OPEN ACCESS Plant Protection, 09 (03) 2025. 753-767 DOI:10.33804/pp.009.03.5828

Check for updates

Available Online at EScience Press

Plant Protection

ISSN: 2617-1287 (Online), 2617-1279 (Print)

http://esciencepress.net/journals/PP

Review Article

# Sustainable Management of Plant Pathogens Using Beneficial Microbes in Dynamic Agroecosystems

**[a]Iram Qadeer, [b]Muhammad Tayyib, [c]Umar Farooq, [d]Naqshe Zuhra, [e]Qurban Ali**

[a] *Department of Zoology, The Government Sadiq College Women University, Bahawalpur, Pakistan.*
[b] *Department of Entomology, University of Agriculture, Faisalabad, Pakistan.*
[c] *Department of Food Science & Technology, Muhammad Nawaz Shareef University of Agriculture, Multan, Pakistan.*
[d] *Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan*
[e] *Entomological Research Institute, Ayub Agricultural Research Institute, Faisalabad, Pakistan.*

**ARTICLE INFO**

***Article history***
*Received: 4th July, 2025*
*Revised: 20th September, 2025*
*Accepted: 27th September, 2025*

***Keywords***
*Plant pathogens*
*Biocontrol, Rhizosphere*
*Pathogenesis*
*Microbiome*
*Consortia*
*Resilience*
*Bioformulation*

**ABSTRACT**

Global agricultural productivity is increasingly threatened by plant pathogens, including fungi, bacteria, viruses, nematodes, and oomycetes, which collectively cause annual crop losses exceeding 20-40%. Prolonged reliance on chemical pesticides has accelerated the evolution of pathogen resistance, disrupted ecological balance, and triggered stricter regulatory controls, underscoring the urgent need for sustainable alternatives. Beneficial microbes such as *Trichoderma*, *Bacillus*, *Pseudomonas*, *Burkholderia*, *Streptomyces*, and arbuscular mycorrhizal fungi represent promising biological agents for plant disease management, particularly within complex and climate-stressed agroecosystems. This review synthesizes their key mechanisms, antibiosis, mycoparasitism, quorum quenching, induced systemic resistance, volatile-mediated inhibition, and biofilm exclusion, with emphasis on field-level outcomes. Advances in microbial consortia and precision delivery technologies are emerging as scalable innovations tailored to soil heterogeneity, crop genotype, and environmental variability. Case studies from India, Kenya, and China highlight the importance of ecological compatibility, local formulation strategies, and farmer participation in enhancing biocontrol efficacy. Nonetheless, inconsistencies in field performance, short shelf life, and regulatory hurdles remain major challenges. Significant knowledge gaps persist in understanding microbe-plant-pathogen-soil interactions under real-world stress conditions. Future directions should integrate omics-driven insights, ecological modeling, and socio-technical adoption frameworks to develop context-specific, climate-resilient biocontrol solutions. Overall, this review positions beneficial microbes not as isolated bio-inputs but as integral, dynamic components of agroecosystem resilience, critical for reducing pesticide dependence and ensuring sustainable disease management in global food systems.

*Corresponding Author: Naqshe Zuhra*
*Email: naqshezuhra@gmail.com*
*© 2025 EScience Press. All rights reserved.*

## INTRODUCTION

Plant pathogens, including fungi, bacteria, viruses, nematodes, and oomycetes, represent a persistent and escalating threat to global food security. These pathogens cause an estimated 20-40% yield loss in staple crops annually, resulting in billions of dollars in economic

damage and exacerbating hunger in vulnerable regions (Singh et al., 2021). Soil-borne pathogens such as *Fusarium oxysporum*, *Rhizoctonia solani*, and *Gaeumannomyces graminis* var. *tritici* are especially destructive due to their long-term survival in soil, ability to colonize root tissues, and disruption of water and nutrient transport (Moura et al., 2022). In addition to causing direct plant mortality, they alter soil microbial communities, impairing long-term soil health and increasing vulnerability to recurrent disease outbreaks.

For decades, synthetic chemical pesticides and fungicides have been the primary means of pathogen control (Ullah et al., 2024). However, this strategy faces major limitations. Intensive and repeated use has driven resistance development through mechanisms such as target site mutation, efflux pump overexpression, and enzymatic detoxification. Resistance to strobilurins and azoles, for example, has been reported in *Botrytis cinerea*, *Alternaria alternata*, and *Fusarium* spp. across multiple cropping systems (Beg et al., 2025). Beyond resistance, chemical controls negatively impact beneficial insects, pollinators, and soil microbes, while contaminating water bodies and contributing to environmental pollution. Stricter regulations on high-risk pesticides and consumer demand for pesticide-free food are accelerating the shift toward biological management of plant diseases (Barwantet al., 2025).

Beneficial microbes, such as plant growth-promoting rhizobacteria (PGPR), endophytes, arbuscular mycorrhizal fungi (AMF), and actinomycetes, offer sustainable alternatives (Agnolucci et al., 2020). These organisms suppress pathogens through multiple mechanisms while enhancing nutrient uptake, stress resilience, and soil health, thereby reducing dependence on synthetic fertilizers (Jehani et al., 2023; Chuong, 2024). For instance, phosphate-solubilizing microbes like *Pseudomonas putida* and *Bacillus megaterium* increase phosphorus availability (Rawat et al., 2021). Although microbial inoculants have shown promise, their performance in open-field conditions remains inconsistent due to ecological complexity, variable soil environments, and formulation challenges.

Modern agroecosystems face compounding stresses. More than one-third of global agricultural soils are moderately to severely degraded through erosion, salinization, and nutrient depletion (Hossain et al., 2020). Climate change further intensifies these stresses by altering rainfall patterns, increasing temperatures, and creating niches for opportunistic pathogens. In sub-Saharan Africa and South Asia, crop yields could decline by up to 50% under current climate trends (Neupane et al., 2022; Wudil et al., 2022; Singh et al., 2023). Monoculture and pesticide overuse accelerate biodiversity loss, destabilizing rhizosphere microbial communities and increasing disease risks (De Groot et al., 2021; Benjamin et al., 2024). Socio-economic barriers, groundwater over-extraction, and salinization further constrain biocontrol adoption (Zeeshan et al., 2023).

Despite progress, critical knowledge gaps remain. Limited understanding of microbial consortia dynamics with native soil communities, crop genotypes, and fluctuating environments hinders scalability. Inoculant efficacy often declines outside controlled conditions due to poor survival or incompatibility with local soils. Advanced omics approaches, metagenomics, transcriptomics, metabolomics, and systems biology, remain underutilized in elucidating plant-microbe-pathogen interactions. Similarly, the integration of microbial strategies with digital agriculture, such as sensor-based disease forecasting and precision delivery, is largely unexplored.

The novelty of this review lies in its systems-level perspective, positioning beneficial microbes not as isolated bio-products but as interactive components of climate-stressed agroecosystems. Unlike conventional reviews emphasizing laboratory-scale mechanisms or single organisms, this synthesis considers ecological, agronomic, and socio-economic factors shaping microbial efficacy. Drawing on case studies from diverse production systems, it critically evaluates both opportunities and limitations of microbial biocontrol. The overarching objective is to synthesize current knowledge on microbial roles in pathogen suppression, assess their performance under real-world field conditions, and identify strategies and innovations that can enhance adoption. Ultimately, this review aims to bridge the gap between experimental findings and scalable, farmer-oriented solutions, providing a roadmap for integrating microbial biocontrol into resilient and sustainable agroecosystems worldwide.

**Mechanisms of disease suppression by beneficial microbes**

Beneficial microbes function not merely as isolated bio-inputs but as integral biological components within the broader agroecosystem. Their ability to suppress plant diseases arises from a combination of direct antagonism, modulation of host immunity, and enhancement of plant

physiological functions. These processes are strongly influenced by soil conditions, crop management practices, and climatic variability (Sheoran et al., 2025). Understanding these mechanisms from a systems perspective is essential for translating microbial efficacy from controlled environments to field-scale applications under climate-stressed conditions.

Direct antagonism, particularly through antibiotic production and parasitism, is among the well-documented modes of microbial disease suppression. Numerous soil-dwelling bacteria and fungi secrete antimicrobial compounds that inhibit pathogen growth or activity, their mode of action and applications were presented in Figure 1. For example, *B. subtilis* and *P. fluorescens* are well-studied for producing lipopeptides and phenazines, respectively, which disrupt pathogen proliferation and reshape rhizosphere interactions (Maurya et al., 2024; Shinde et al., 2025) (Table 1).

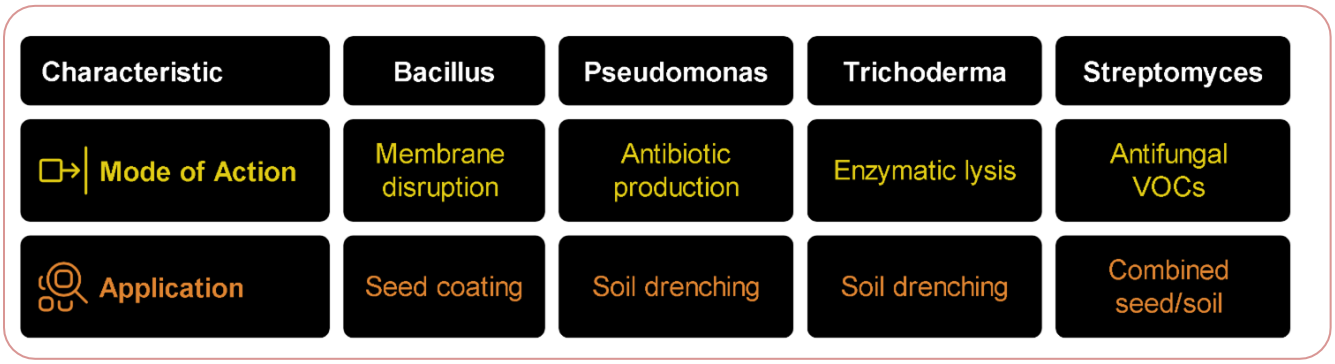



Figure 1. Biocontrol agents: categories, modes of action, and applications.

Parasitic interactions, particularly mycoparasitism, represent an important mechanism of direct antagonism. *Trichoderma harzianum* aggressively parasitizes soil-borne fungal pathogens such as *F. oxysporum* by coiling around their hyphae, penetrating the fungal cell wall through the action of chitinases and glucanases, and disrupting cellular integrity (Mukherjee et al., 2022). In tomato fields across central India, soil application of *T. harzianum* reduced *Fusarium* wilt incidence by more than 60% and increased marketable yield by 25% under both irrigated and drought-prone conditions (Pothiraj et al., 2021; Abbas Almajed, 2024). Microscopic observations confirmed the formation of haustoria-like structures that extract nutrients from the target pathogen, further weakening its ability to colonize host roots. Similarly, *Streptomyces lydicus*, an actinomycete, exhibits dual activity through antibiotic secretion and parasitism; in greenhouse trials with cucumber, seed treatment with *S. lydicus* reduced damping-off incidence by 70% and significantly enhanced seedling vigor (Hassan et al., 2021; Wang et al., 2022). However, the effectiveness of these mechanisms varies across agroecological zones, being strongly influenced by soil pH, temperature, organic matter content, and interactions with native microbiota, highlighting the need for context-specific formulations.

Beyond direct pathogen suppression (Figure 2), many beneficial microbes enhance plant defense through induced systemic resistance (ISR). ISR is a priming process in which non-pathogenic microbes prepare plant defense pathways, enabling faster and stronger responses to pathogen attack (Zhu et al., 2022). Unlike systemic acquired resistance (SAR), which is salicylic acid (SA)-dependent and triggered by infection, ISR operates primarily through jasmonic acid (JA) and ethylene (ET) signaling and can be induced without pathogenic stimuli (Kamle et al., 2020). ISR, mediated through JA-ET pathways, involves regulators such as MYB72 and small RNAs, thereby enhancing defense readiness (Thomas and Singh, 2021; Sharma et al., 2023; Abdolmaleky et al., 2025). Field trials validate the relevance of ISR: in eastern China, *B. amyloliquefaciens* FZB42 reduced downy mildew severity in cucumber by 45% while increasing pathogenesis-related protein expression and peroxidase activity (Mirzwa-Mróz et al., 2024). Similarly, *T. asperellum* T34 induced robust ISR in tomato, lowering *Fusarium* wilt incidence by 40-60%, depending on soil type and moisture (Sehim et al., 2023). ISR not only improves disease resistance but also optimizes metabolic allocation, as defense responses are activated only when required, conserving energy and supporting growth under stress.

Table 1. Mechanisms of disease suppression by beneficial microbes and their reported outcomes.

| Mechanism | Example microbes | Compounds/ Processes | Reported outcomes | References |
|---|---|---|---|---|
| Antibiotic production | *B. subtilis* | Surfactin, iturin, fengycin (lipopeptides) | Disrupt fungal membranes; sheath blight incidence ↓ 30%, fungicide use ↓ 33% in rice | Shinde et al., 2025; Afzal et al., 2025 |
| | *P. fluorescens* | 2,4-DAPG, phenazine, pyoluteorin | Broad-spectrum antifungal & antibacterial activity; microbiome shifts toward suppressive state | Maurya et al., 2024 |
| Mycoparasitism | *Trichoderma harzianum* | Chitinases, glucanases; hyphal coiling | Fusarium wilt ↓ 60%, tomato yield ↑ 25% | Pothiraj et al., 2021; Mukherjee et al., 2022 |
| | *Streptomyces lydicus* | Antibiotic secretion + hyphal penetration | Damping-off ↓ 70%, seedling vigor ↑ in cucumber | Hassan et al., 2021; Wang et al., 2022 |
| Induced systemic resistance (ISR) | *P. fluorescens* WCS417r | JA/ET signaling; MYB72, iron homeostasis; small RNA regulation | ISR in *Arabidopsis thaliana* → resistance to *P. syringae*, *B. cinerea* | Kamle et al., 2020; Thomas and Singh, 2021; Sharma et al., 2023; Abdolmaleky et al., 2025 |
| | *B. amyloliquefaciens* FZB42 | PR protein expression; peroxidase activity | Downy mildew ↓ 45% in cucumber | Mirzwa-Mróz et al., 2024 |
| | *T. asperellum* T34 | JA/ET-mediated ISR | Fusarium wilt ↓ 40–60% in tomato (field- and soil-dependent) | Sehim et al., 2023 |
| Nutrient mobilization & stress tolerance | *Azospirillum brasilense*, *Rhizobium* spp. | Biological N fixation | >60 Mt N $yr^{-1}$ contributed globally; reduces fertilizer dependency | Soumare et al., 2020 |
| | *B.megaterium*, *P. putida* | Phosphate solubilization | Available P ↑ up to 70% in P-deficient soils | Chen et al., 2023 |
| | Arbuscular mycorrhizal fungi (AMF) | Hyphal extension into soil pores | Root biomass ↑; water use efficiency ↑ under drought/salinity | — |
| | *Azospirillum* + *Bacillus* consortia with AMF | Phytohormone production (IAA, cytokinins, gibberellins); antioxidative enzymes (SOD, catalase) | Improved yield & drought resilience in maize; ROS protection under stress | Saberi-Riseh et al., 2020; Agbodjato, 2024 |

Indirect disease suppression is equally important and is often mediated through enhanced plant vigor, nutritional status, and tolerance to abiotic stress. Microbial inoculants improve nutrient availability by fixing nitrogen, solubilizing phosphorus, producing phytohormones, and activating antioxidative defenses (Soumare et al., 2020; Chen et al., 2023). AMF further enhance nutrient and water uptake by extending hyphal networks into soil pores inaccessible to roots, particularly under drought and salinity stress, and promote greater root biomass and water-use efficiency. Beneficial microbes also produce indole-3-acetic acid (IAA), cytokinins, and gibberellins,

which stimulate root growth, delay senescence, and increase photosynthetic efficiency. In maize fields in Kenya, inoculation with a consortium of *Azospirillum*, *Bacillus*, and AMF increased yields and improved drought resilience under rainfed conditions (Agbodjato and Babalola, 2024). Moreover, several strains of *Bacillus* and *Pseudomonas* enhance antioxidative enzyme activity, including superoxide dismutase (SOD) and catalase, thereby protecting plants from reactive oxygen species (ROS)-induced oxidative stress (Saberi-Riseh et al., 2020). These physiological improvements indirectly suppress pathogens by strengthening host resilience, especially in degraded or climate-stressed environments.

Taken together, these findings highlight the multifaceted roles of beneficial microbes in plant health, extending beyond pathogen suppression to improved nutrition, stress tolerance, and systemic defense priming. Their effectiveness, however, remains context-dependent, with variability in survival, delivery, and environmental adaptation posing key challenges. Integrating mechanistic insights with systems-level field validation will be essential to develop regionally tailored microbial consortia and optimize their application for sustainable crop protection.

**Key beneficial microbial groups and their functions**

Plant-beneficial microbial consortia provide distinct yet interconnected functions that enhance plant health, suppress pathogens, and strengthen agroecosystem resilience. Unlike isolated bioagents, these microbes act within complex soil-plant-microbe networks shaped by environmental conditions, crop type, and management practices. Understanding the microbial taxa involved and how their functions vary under field conditions is essential for developing robust, ecologically based disease management strategies.

Fungal biocontrol agents, particularly species of *Trichoderma*, are among the most widely studied and applied in sustainable agriculture. These fungi suppress plant pathogens through multiple mechanisms, including mycoparasitism, enzyme-mediated cell wall degradation, antibiotic production, and activation of host immune responses (Chen et al., 2020; Torres-Rodriguez, 2024). *T. harzianum* and *T. viride* secrete chitinases, glucanases, and proteases that degrade the cell walls of pathogens such as *F. oxysporum* and *R. solani* (Ghasemi et al., 2020). Beyond direct antagonism, *Trichoderma* species induce systemic resistance (ISR) in host plants through jasmonic acid (JA) and ethylene (ET)-mediated pathways (Figure 2). Certain strains also control plant-parasitic nematodes by producing nematotoxic metabolites or parasitizing nematode eggs (Tariq Javeed et al., 2021). Their broad-spectrum efficacy further extends to insect pests, where volatile organic compounds (VOCs) deter oviposition and feeding (Kumar et al., 2023).

Endophytic fungi, asymptomatic colonizers of living plant tissues, also serve as effective biocontrol agents and stress modulators (Yasin et al., 2025). These fungi establish mutualistic associations with their hosts and produce bioactive metabolites that suppress pathogens at infection sites, compete for internal niches, and modulate plant hormone signaling (Table 2). They provide systemic protection and are particularly valuable in perennial crops, where long-term associations mitigate seasonal stress fluctuations.

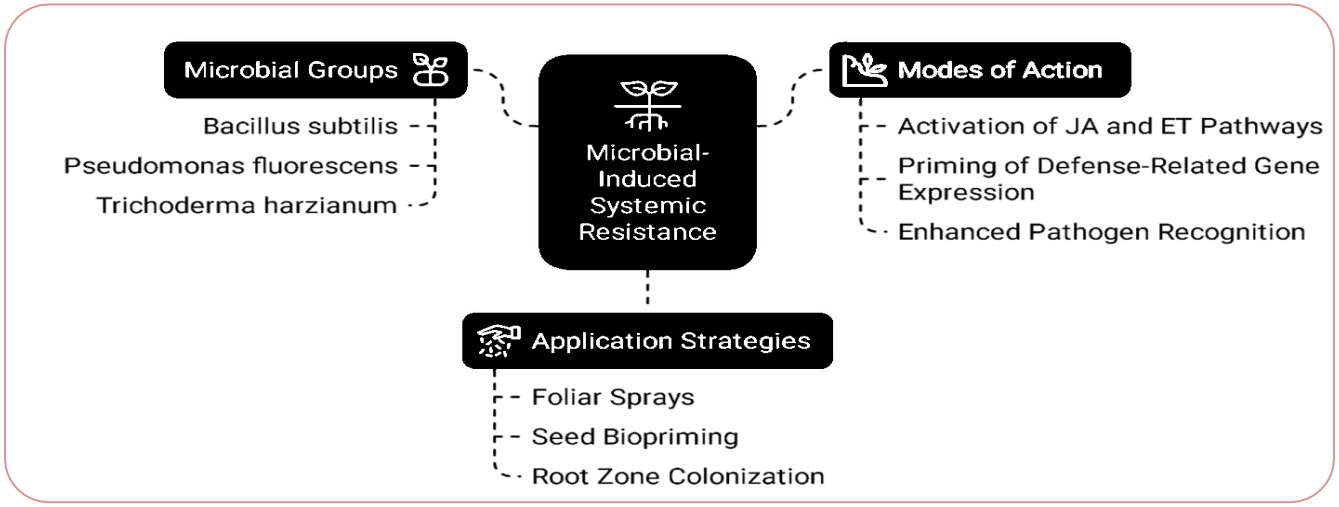



Figure 2. Microbe-induced systemic resistance in plants.

Table 2. Key beneficial microbial groups, their functions, and field outcomes.

| Microbial Group | Mode of Action | Crop/System | Quantitative Outcome | References |
|---|---|---|---|---|
| *Trichoderma* spp. (*T. harzianum, T. viride*) | Secretion of chitinases, glucanases, proteases (mycoparasitism, enzyme degradation) | *Fusarium oxysporum*, *Rhizoctonia solani* | Pathogen cell wall degradation; strong antagonism | Ghasemi et al., 2020 |
| *T. asperellum* | Induction of systemic resistance (JA/ET pathways; PR-1, PDF1.2 upregulation) | Cucumber, Chickpea | Enhanced tolerance to biotic & abiotic stresses | Yadav et al., 2023 |
| *Trichoderma* spp. | Nematode suppression via nematotoxic compounds, egg parasitism | Multiple crops | Reduced plant-parasitic nematode incidence | Tariq Javeed et al., 2021 |
| *Trichoderma* spp. (applied via composts/seed/foliar) | Biocontrol integration | Vegetable systems (Colombia, India) | Fungicide use reduced by up to 50% | Kumar et al., 2023 |
| Endophytic fungi (*Piriformospora indica*) | Stress tolerance (antioxidants, SA signaling) | Desert plants (salinity, drought) | Improved stress tolerance; reduced root pathogens | Li et al., 2023 |
| *F. solani* (endophytic) | Competition, secondary metabolites | Grapevine | Reduced *Botrytis cinerea* incidence; improved phenolic profiles | Jelenić et al., 2021; Tahir et al., 2024 |
| PGPR (*Bacillus* spp.) | Antibiotic production (iturin, fengycin); pathogen inhibition | Rice paddies | Reduced sheath blight; higher grain yield | Modi and Jha, 2022 |
| *P. fluorescens* | Antibiotics (DAPG, pyoluteorin); ISR | General | Enhanced ISR, pathogen suppression | Gade and Koche, 2022 |
| *Pseudomonas* spp. | Root rot suppression; drought tolerance | Maize, Tomato (East Africa) | +30% early root biomass; reduced root rot | Olowe et al., 2022; Jarrar Ahmed et al., 2024; Benaissa et al., 2025 |
| PGPR (*B. firmus*, *P. chlororaphis*) | Nematicidal activity (HCN, proteases) | Various crops | Reduced nematode incidence | Sun et al., 2024 |
| AMF | Symbiosis: hyphal networks improve nutrient uptake | Maize (Sub-Saharan Africa) | +60% P uptake; +35% yield (under drought) | Adeyemi et al., 2021 |
| AMF | Drought & salinity tolerance (osmolytes, antioxidants) | Multiple crops | Improved resilience to stress | Begum et al., 2020; Pratama Hamzah et al., 2024 |
| AMF-rich soils | Competitive exclusion; improved rhizosphere | Vineyards (Europe) | Reduced *Pythium*, *Phytophthora*; improved vine vigor | Cataldo et al., 2021 |
| Consortia (*Azospirillum*, *Bacillus*, *Trichoderma*, AMF) | Multi-mechanistic biofertilizer | Soybean (Brazil Cerrado) | ↑ Yields, ↓ disease, ↑ soil C across seasons | Pagano et al., 2017; |

PGPR include diverse genera such as *Bacillus*, *Pseudomonas*, *Azospirillum*, and *Serratia*, each contributing to plant health through nutrient mobilization, growth promotion, and pathogen suppression. *B. subtilis* and *B. amyloliquefaciens* produce a wide range of antimicrobial compounds, including iturin and fengycin, which inhibit fungal growth and disrupt pathogen biofilms. Similarly, *P. fluorescens* secretes DAPG and pyoluteorin, which not only suppress pathogens but also induce systemic resistance (ISR) in plants (Gade and Koche, 2022). PGPR also synthesize phytohormones such as IAA, gibberellins, and cytokinins that stimulate root elongation and branching, thereby enhancing water and nutrient uptake. Certain strains of *S. marcescens* and *A. brasilense* additionally exhibit quorum-quenching activity, disrupting the signaling pathways of pathogenic bacteria and biofilm-forming fungi. Collectively, these functions highlight the potential of PGPR as central components of integrated nutrient and pest management systems.

AMF represent another important group of beneficial microbes, forming symbiotic associations with nearly 80% of terrestrial plants. Their extraradical hyphae increase the effective absorptive surface area for phosphorus, zinc, and other immobile nutrients (Shahzad et al., 2020; Wahab et al., 2023). AMF also enhance drought and salinity tolerance by regulating stomatal conductance, promoting osmolyte accumulation, and activating antioxidant defense systems (Begum et al., 2020; Pratama Hamzah et al., 2024). However, AMF effectiveness is influenced by soil disturbance, crop rotation history, and host plant genotype. Conservation agriculture practices such as minimal tillage, cover cropping, and organic amendments significantly enhance AMF colonization and persistence.

More recently, microbial consortia, formulations combining PGPR, AMF, endophytes, and biocontrol fungi, have been developed to exploit complementary mechanisms (Vishwakarma et al., 2020; Fatima et al., 2024). These consortia mimic the diversity of natural microbial communities and demonstrate greater functional stability under variable field conditions (Pagano et al., 2017; Procópio and Barreto, 2021). Such synergistic approaches are particularly valuable in dynamic agroecosystems, where microbial resilience is crucial for sustaining crop health under environmental stress.

**Microbe–pathogen targeting strategies in crop protection**

The selection of beneficial microbes for targeted disease management is guided by their distinct biochemical attributes and ecological compatibility with both crop physiology and pathogen biology. This approach enables precise, mechanism-driven suppression of plant diseases, as summarized in Table 3.

*B. subtilis* is particularly effective against damping-off diseases in cucumber, commonly caused by *Pythium* spp. and *R. solani*. Its efficacy is attributed to the production of potent lipopeptides, surfactin, iturin, and fengycin, that disrupt pathogen membranes and inhibit spore germination. Furthermore, *B. subtilis* primes plant immunity by inducing systemic resistance (ISR) during early seedling establishment (Abbas et al., 2019; Mohanan et al., 2025).

*P. fluorescens* is well-suited for foliar application in rice against *Xanthomonas oryzae* pv. *oryzae*, the causal agent of bacterial leaf blight. It produces the antibiotic 2,4-diacetylphloroglucinol (DAPG), suppresses epiphytic pathogen colonization, and activates plant defense gene expression via jasmonate- and ethylene-mediated signaling pathways (Ngalimat et al., 2021).

*T. harzianum* is widely applied to manage *F. oxysporum* in various crops through aggressive mycoparasitism. This involves hyphal coiling, enzymatic degradation of pathogen cell walls (via chitinases and glucanases), and the production of secondary metabolites that suppress pathogen proliferation while improving root vigor (Dutta et al., 2023; Usman et al., 2024).

*Burkholderia cepacia* is used against *Fusarium* wilt in banana plantations due to its ability to disrupt pathogen quorum sensing, thereby reducing virulence gene expression. Furthermore, it forms biofilms on root surfaces, serving as both a physical and chemical barrier that prevents pathogen entry and promotes niche exclusion (Ganesh et al., 2020; Shahid, 2024).

*Streptomyces griseoviridis* is employed for the management of *R. solani*-induced sheath blight in rice. It acts by releasing antifungal volatile organic compounds (VOCs), such as geosmin and methylisoborneol, and by establishing strong rhizosphere colonization, which creates a protective microbial shield around plant roots (Akber and Fang, 2024).

These microbe-pathogen pairings illustrate the strategic deployment of microbial agents, not as broad-spectrum solutions, but as finely tuned biological interventions tailored to specific crop-pathogen systems within their ecological and physiological contexts.

Table 3. Mechanism-guided field applications of beneficial microorganisms against crop pathogens.

| Mechanism | Crop | Microbe | Application Strategy | Trial Type | Results | Reference |
|---|---|---|---|---|---|---|
| ISR induction, Lipopeptide production | Cucumber | *Bacillus subtilis* | Seed coating | Field | Reduced damping-off by 70%, 33% fungicide reduction | (Bakr et al., 2025; Chowdhury et al., 2015) |
| Antibiotic production (DAPG), Defense gene activation | Rice | *Pseudomonas fluorescens* | Foliar spray | Field | Reduced bacterial leaf blight by 50% | (Mehmood et al., 2023; Teja et al., 2025) |
| Mycoparasitism, Enzymatic degradation of pathogens | Tomato | *Trichoderma harzianum* | Soil drenching | Field | Fusarium wilt suppressed by 60% | (Mohanan et al., 2025) |
| Quorum sensing inhibition, Biofilm formation | Banana | *Burkholderia cepacia* | Root inoculation | Field | Fusarium wilt reduced by 63% | (Nakkeeran et al., 2021) |
| Volatile production, Rhizosphere colonization | Rice | *Streptomyces griseoviridis* | Seed + Soil application | Field | Sheath blight control improved by 40% | (Khan et al., 2023) |

**Case studies highlighting microbial biocontrol successes**

Recent case studies from different regions of the world demonstrate the effectiveness of microbial biocontrol agents in suppressing plant pathogens through diverse mechanisms. In Germany, *B. velezensis* FZB42 effectively suppressed *R. solani* in plants by producing lipopeptides such as surfactin and fengycin, which disrupted fungal membranes and triggered induced systemic resistance (ISR) via jasmonic acid signaling (Borriss, 2020). In Canada, *P. chlororaphis* PA23 controlled *Sclerotinia sclerotiorum* in canola through the production of phenazine-1-carboxylic acid and hydrogen cyanide, demonstrating strong antibiosis and efficient rhizosphere colonization (Athukorala et al., 2010). A study in India developed a synthetic microbial consortium of *T. harzianum*, *B. subtilis*, and *P. fluorescens* to manage tomato root rot, where synergistic interactions enhanced mycoparasitism, nutrient competition, and ISR, reducing disease severity by 70% (Sharma et al., 2020). In China, *S. griseoviridis* was applied in rice fields to suppress sheath blight through the production of antifungal volatiles and siderophores, while also improving plant vigor (Xu et al., 2019). Similarly, in banana plantations, strains of the *B. cepacia* complex were employed to control *F. oxysporum* f. sp. *cubense* via quorum-sensing interference and biofilm formation, thereby reducing pathogen colonization (Ismaila et al., 2023). These examples highlight how country-specific applications of microbial agents, each utilizing distinct biochemical and ecological mechanisms, can provide scalable and sustainable solutions for plant disease management.

**Challenges in utilizing beneficial microbes for plant disease control**

The limited success of microbial inoculants in agriculture cannot be attributed solely to technological bottlenecks but is also constrained by fundamental ecological principles governing microbial survival, competition, and interactions within the soil-plant system (Mikiciuk et al., 2024; Qasim and Abdulla Falah, 2024). From a technological perspective, poor shelf life, unstable formulations, and inefficient delivery systems reduce viable propagule density before microbes even reach the rhizosphere. In addition, regulatory delays and inadequate quality control further restrict farmer access (Mawar et al., 2021; Teixidó et al., 2022; Borges-García, 2024). For example, many beneficial microbes, particularly Gram-negative bacteria and mycorrhizal fungi, are highly sensitive to desiccation, UV radiation, and oxidative stress (Radi et al., 2025). In India, commercial *Bacillus* formulations retained only 40-60% viability after six months under ambient conditions, substantially reducing their field efficacy (Mawar et al., 2021). Encapsulation technologies, such as alginate beads and starch matrices, can improve stability, but their high costs and limited scalability hinder large-scale application (Jarman et al., 2023).

Ecological constraints represent more intrinsic biological challenges. Effective colonization requires compatibility with native soil microbiomes, which often outcompete or suppress introduced strains, particularly in degraded or chemically intensive soils with disrupted

microbial networks. Rhizosphere variability across crop species and cultivars further complicates establishment. For instance, PGPR strains that colonize wheat efficiently may fail in maize due to differences in root exudate chemistry (Nair et al., 2023). These dynamics emphasize the importance of ecological compatibility rather than focusing solely on improving delivery methods.

Socio-economic and institutional barriers also limit adoption. Globally, more than 70% of smallholder farmers lack reliable access to microbial biocontrol products due to weak distribution networks, insufficient storage infrastructure, and inadequate extension services. In sub-Saharan Africa, fewer than 10% of farmers use microbial inoculants, largely because of limited awareness and the absence of localized field trials (Koskey et al., 2021). Regulatory and intellectual property constraints further compound these challenges. Microbial biopesticides are often regulated under the same framework as synthetic chemicals, requiring 3-5 years and up to US$2 million in data generation per product. This regulatory burden discourages small biotech firms and public research institutions from developing microbial solutions (Borges-García, 2024). Moreover, the absence of harmonized international approval systems restricts commercialization, as strains developed in Latin America or Asia often cannot be marketed in Europe or North America without mutual recognition agreements (Anand et al., 2022). Table 4 summarizes the key research gaps, future perspectives, and technological innovations required to overcome these barriers and enhance the reliability of microbial biocontrol in agriculture.

Table 4. Research gaps, future perspectives, and innovations.

| Research Gaps | Future Perspectives | Innovations |
|---|---|---|
| Inconsistent performance of microbial inoculants under field conditions due to environmental variability (moisture, temperature, pH) (Rodrigues et al., 2023) | Development of crop-specific and site-adapted microbial consortia tailored to local agroecological conditions. | Advanced encapsulation and formulation technologies (e.g., alginate beads, biochar, nanocarriers) to improve shelf life and field viability. |
| Limited understanding of interactions between microbes, native microbiomes, plant genotypes, and pathogens in real-world systems (Nair et al., 2023) | Integration of beneficial microbe compatibility traits into crop breeding programs to enhance host colonization and efficacy. | Microbial engineering and synthetic biology to enhance ISR signaling, metabolite production, and stress tolerance traits. |
| Poor microbial colonization in degraded or chemically treated soils due to disrupted native microbiota (O'Callaghan et al., 2022) | Participatory co-design of microbial strategies with farmers and extension services to align practices with local knowledge and cropping systems. | Precision delivery systems such as seed priming, root-zone inoculation, and sensor-guided foliar sprays for optimized timing and placement. |
| Genotype-dependent variability in microbe–host compatibility reduces reproducibility across different crop species and cultivars (Qasim and Abdulla Falah, 2024) | Breeding crops that support beneficial microbial colonization by selecting for favorable root exudate profiles and symbiosis-related traits. | Integration of microbial applications with digital tools like disease forecasting models, drones, and IoT-based environmental monitoring platforms. |
| Weak regulatory frameworks and lack of harmonized biosafety protocols delay product registration and commercialization (Borges-García, 2024) | Creation of fast-track, risk-based regulatory pathways and international standardization to ease approval and cross-border movement of microbial bio-products. | Establishment of community-scale microbial production units and local biolabs to decentralize availability, especially in resource-limited or smallholder-dominated regions. |
| Lack of quality control, short shelf life, and sensitivity of microbial formulations to storage and transport conditions (Mawar et al., 2021; Teixidó et al., 2022) | Long-term ecological monitoring of microbe-based products to ensure safety, persistence, and resilience under diverse cropping systems and environmental stressors. | Use of multi-functional microbial consortia mimicking natural microbiomes to achieve stability, redundancy, and broader spectrum disease suppression under field variability. |
| Socio-economic constraints, limited farmer access, and lack of localized trials hinder adoption (Koskey et al., 2021; Manono et al, 2025) | Strengthening extension services and local supply chains to ensure accessibility for smallholder farmers. | Development of affordable, farmer-friendly formulations and on-farm bio-labs for local production. |

## Conclusion

The increasing vulnerability of global food systems to plant pathogens, driven by climate change, land degradation, monoculture intensification, and pesticide overuse, necessitates a paradigm shift from reactive chemical control to ecologically sustainable, microbe-based disease management. This review highlights that beneficial microbes, including *Trichoderma*, *Bacillus*, *Pseudomonas*, *Burkholderia*, *Streptomyces*, arbuscular mycorrhizal fungi (AMF), and endophytes, not only suppress a wide spectrum of plant pathogens through mechanisms such as mycoparasitism, induced systemic resistance (ISR), antibiosis, quorum quenching, and volatile-mediated inhibition, but also enhance plant nutrient uptake, stress tolerance, and overall agroecosystem resilience. Case studies from India, Kenya, Brazil, China, and Germany demonstrate that the success of microbial biocontrol depends on the ecological adaptability of the microbe, delivery method, host crop compatibility, and active community participation.

Despite this potential, large-scale deployment in open-field, dynamic agroecosystems remains constrained by inconsistent performance, formulation instability, limited shelf life, and variable host-microbe-soil interactions. These challenges are further compounded by chemical-driven degradation of native microbiota, regulatory hurdles, and restricted access for smallholder farmers. To unlock the full potential of microbial biocontrol, future research must close existing knowledge gaps using multi-omics approaches, systems biology, and long-term field validation. Innovations in synthetic microbial consortia, crop genotype, microbiome matching, and precision delivery platforms are critical to ensuring consistent efficacy and ecological integration. Moreover, convergence with digital agriculture, incorporating environmental sensors, disease forecasting models, and AI-guided applications, offers unprecedented opportunities for targeted, adaptive plant protection.

This review advocates a systems-level approach, repositioning beneficial microbes not merely as single-mode biopesticides but as integral components of resilient, context-specific solutions that safeguard both agricultural productivity and ecological integrity.

## Authors' Contributions

All authors contributed equally in collecting, organizing and compiling the literature.

## Research Funding

This research did not receive any grant from funding agencies.

## Conflict of Interest

The authors declare no conflict of interest.

## Sustainable Development Goals Targeted

SDG 2: Zero Hunger
SDG 3: Good Health and Well-being
SDG 6: Clean Water and Sanitation
SDG 12: Responsible Consumption and Production

## References

Abbas Almajed, A., 2024. Antifungal activity of clove essential oil-based nanoemulsion against tomato fusarium wilt and potential toxicity on male albino rats. Journal of Global Innovations in Agricultural Sciences, 1019-1035.

Abbas, A., Khan, S.U., Khan, W.U., Saleh, T.A., Khan, M.H.U., Ullah, S., Ali, A., Ikram, M., 2019. Antagonist effects of strains of *Bacillus* spp. against *Rhizoctonia solani* for their protection against several plant diseases: Alternatives to chemical pesticides. Comptes Rendus Biologies 342 (5-6), 124-135.

Abdolmaleky, H.M., Nohesara, S., Zhou, J.-R., Thiagalingam, S., 2025. Epigenetics in evolution and adaptation to environmental challenges: pathways for disease prevention and treatment. Epigenomics, 1-17.

Adeyemi, N.O., Atayese, M.O., Sakariyawo, O.S., Azeez, J.O., Olubode, A.A., Ridwan, M., Adebiyi, A., Oni, O., Ibrahim, I., 2021. Influence of different arbuscular mycorrhizal fungi isolates in enhancing growth, phosphorus uptake and grain yield of soybean in a phosphorus deficient soil under field conditions. Communications in Soil Science and Plant Analysis 52 (10), 1171-1183.

Afzal, M., Tan, X., Fang, M.L., Zeng, D., Huang, M., Chen, X., Zhang, X., Tan, Z., 2025. Chitosan-silver nanoparticles and *Bacillus tequilensis* modulate antioxidant pathways and microbiome dynamics for sheath blight resistance in rice. Plant Stress, 100917.

Agbodjato, N.A., Babalola, O.O., 2024. Promoting sustainable agriculture by exploiting plant growth-promoting rhizobacteria (PGPR) to

improve maize and cowpea crops. PeerJ 12, e16836.

Agnolucci, M., Avio, L., Palla, M., Sbrana, C., Turrini, A., Giovannetti, M., 2020. Health-promoting properties of plant products: the role of mycorrhizal fungi and associated bacteria. Agronomy 10 (12), 1864.

Akber, M.A., Fang, X., 2024. Research progress on diseases caused by the soil-borne fungal pathogen *Rhizoctonia solani* in alfalfa. Agronomy 14 (7), 1483.

Anand, U., Vaishnav, A., Sharma, S.K., Sahu, J., Ahmad, S., Sunita, K., Suresh, S., Dey, A., Bontempi, E., Singh, A.K., 2022. Current advances and research prospects for agricultural and industrial uses of microbial strains available in world collections. Science of the Total Environment 842, 156641.

Athukorala, S.N., Fernando, W.D., Rashid, K.Y., de Kievit, T., 2010. The role of volatile and non-volatile antibiotics produced by *Pseudomonas chlororaphis* strain PA23 in its root colonization and control of *Sclerotinia sclerotiorum*. Biocontrol Science and Technology 20 (8), 875-890.

Bakr, R., Abdelmoteleb, A., Mendez-Trujillo, V., Gonzalez-Mendoza, D., Hewedy, O., 2025. The potential of beneficial microbes for sustainable alternative approaches to control phytopathogenic diseases. Microbiology Research 16 (5), 105.

Barwant, M.M., Ogidi, O.I., Yogita, C., Munje, R., 2025. Study of consumers choices on pesticides use and sustainability. In: The Interplay of Pesticides and Climate Change: Environmental Dynamics and Challenges. Springer Nature Switzerland, Cham, pp. 469-516.

Beg, M.A., Aktaruzzaman, M., Lewis, K.J., Oliver, J.E., 2025. Fungicide resistance profiles of *Alternaria* spp. associated with fruit rot of blueberry in Georgia, USA. Frontiers in Plant Science 16, 1524586.

Begum, N., Ahanger, M.A., Zhang, L., 2020. AMF inoculation and phosphorus supplementation alleviates drought induced growth and photosynthetic decline in *Nicotiana tabacum* by up-regulating antioxidant metabolism and osmolyte accumulation. Environmental and Experimental Botany 176, 104088.

Benaissa, O., Taoussi, M., Legrifi, I., Belabess, Z., Lazraq, A., Lahlali, R., 2025. Strengthening tomato resilience: harnessing microbial consortia to overcome biotic and abiotic stress. Phyton 94 (5), 1453.

Benjamin, J., Oyedokun, D.O., Oziegbe, E.V., Oni, J., Ogundare, E.B., Ujah, G.O., Adebayo, A., 2024. Cereal production in Africa: the threat of current plant pathogens in changing climate - a review. Discover Agriculture 2 (1), 33.

Borges-García, M., 2024. Yam biotechnology innovation: a contribution to local food sovereignty. Journal of Global Innovations in Agricultural Sciences, 1011-1018.

Borriss, R., 2020. Phytostimulation and biocontrol by the plant-associated *Bacillus amyloliquefaciens* FZB42: an update. In: Phyto-microbiome in stress regulation, pp. 1-20.

Cataldo, E., Fucile, M., Mattii, G.B., 2021. A review: Soil management, sustainable strategies and approaches to improve the quality of modern viticulture. Agronomy 11 (11), 2359.

Chen, J., Vallikkannu, M., Karuppiah, V., 2020. Systemically induced resistance against maize diseases by *Trichoderma* spp. In: *Trichoderma*: host pathogen interactions and applications, pp. 111-123.

Chen, Z., Wang, L., Cardoso, J.A., Zhu, S., Liu, G., Rao, I.M., Lin, Y., 2023. Improving phosphorus acquisition efficiency through modification of root growth responses to phosphate starvation in legumes. Frontiers in Plant Science 14, 1094157.

Chowdhury, S.P., Hartmann, A., Gao, X., Borriss, R., 2015. Biocontrol mechanism by root-associated *Bacillus amyloliquefaciens* FZB42 - a review. Frontiers in Microbiology 6, 780.

Chuong, N.V., 2024. Efficiency of Enterobacter asburiae and vermicompost on the peanut growth and yield. Journal of Global Innovations in Agricultural Sciences 12 (3), 563-574.

De Groot, G.S., Aizen, M.A., Sáez, A., Morales, C.L., 2021. Large-scale monoculture reduces honey yield: The case of soybean expansion in Argentina. Agriculture, Ecosystems & Environment 306, 107203.

Dutta, P., Mahanta, M., Singh, S.B., Thakuria, D., Deb, L., Kumari, A., Upamanya, G.K., Boruah, S., Dey, U., Mishra, A., 2023. Molecular interaction between plants and Trichoderma species against soil-borne plant pathogens. Frontiers in Plant Science 14, 1145715.

Fatima, S.S., Amjad Ali, M., Jabran, M., Nabeel Afzal, M., Abbas, A., 2024. Comparative study of bio-control agents against *Fusarium* wilt in okra caused by *Fusarium oxysporum* pv. *vasinfectum*. Phytopathogenomics and Disease Control 3 (2), 213-220.

Gade, R., Koche, M.D., 2022. Enhancing the growth and disease suppression ability of Pseudomonas fluorescens, 351-368. In: New and Future Developments in Microbial Biotechnology and Bioengineering. Elsevier.

Ganesh, P.S., Vishnupriya, S., Vadivelu, J., Mariappan, V., Vellasamy, K.M., Shankar, E.M., 2020. Intracellular survival and innate immune evasion of *Burkholderia cepacia*: improved understanding of quorum sensing-controlled virulence factors, biofilm, and inhibitors. Microbiology and Immunology 64 (2), 87-98.

Ghasemi, S., Safaie, N., Shahbazi, S., Shams-Bakhsh, M., Askari, H., 2020. The role of cell wall degrading enzymes in antagonistic traits of *Trichoderma virens* against *Rhizoctonia solani*. Iranian Journal of Biotechnology 18 (4), e2333.

Hassan, M., Ahmed, H., Kamel, S., Abd El-Hamed, W., Yousef, H., 2021. Biological control of damping-off and root rot disease caused by *Rhizoctonia solani* on cucumber plants. Fayoum Journal of Agricultural Research and Development 35 (3), 525-541.

Hossain, A., Krupnik, T.J., Timsina, J., Mahboob, M.G., Chaki, A.K., Farooq, M., Bhatt, R., Fahad, S., Hasanuzzaman, M., 2020. Agricultural land degradation: processes and problems undermining future food security, 17-61. In: Environment, Climate, Plant and Vegetation Growth. Springer.

Ismaila, A.A., Ahmad, K., Siddique, Y., Wahab, M.A.A., Kutawa, A.B., Abdullahi, A., Zobir, S.A.M., Abdu, A., Abdullah, S.N.A., 2023. *Fusarium* wilt of banana: current update and sustainable disease control using classical and essential oils approaches. Horticultural Plant Journal 9 (1), 1-28.

Jarman, A., Thompson, J., McGuire, E., Reid, M., Rubsam, S., Becker, K., Mitcham, E., 2023. Postharvest technologies for small-scale farmers in low- and middle-income countries: a call to action. Postharvest Biology and Technology 206, 112491.

Jarrar Ahmed, M., Shoaib, A., Malik, B., 2024. Biocontrol potential of *Pseudomonas syringae* against emerging phyto-fungal pathogens. Phytopathogenomics and Disease Control 3 (2), 95-100.

Jehani, M., Singh, S., Kumar, D., Kumar, G., 2023. *Azospirillum* - A free-living nitrogen-fixing bacterium, 285-308. In: Rhizobiome. Elsevier.

Jelenić, J., Ćosić, J., Velki, M., Ilić, J., 2021. Endophytic *Fusarium* spp. affect yield, but can they be a solution for *Botrytis* control in vineyard production? Fungal Ecology 54, 101114.

Kamle, M., Borah, R., Bora, H., Jaiswal, A.K., Singh, R.K., Kumar, P., 2020. Systemic acquired resistance (SAR) and induced systemic resistance (ISR): role and mechanism of action against phytopathogens, 457-470. In: Fungal Biotechnology and Bioengineering. Springer.

Khan, S., Srivastava, S., Karnwal, A., Malik, T., 2023. *Streptomyces* as a promising biological control agent for plant pathogens. Frontiers in Microbiology 14, 1285543.

Koskey, G., Mburu, S.W., Awino, R., Njeru, E.M., Maingi, J.M., 2021. Potential use of beneficial microorganisms for soil amelioration, phytopathogen biocontrol, and sustainable crop production in smallholder agroecosystems. Frontiers in Sustainable Food Systems 5, 606308.

Kumar, V., Koul, B., Taak, P., Yadav, D., Song, M., 2023. Journey of *Trichoderma* from pilot scale to mass production: a review. Agriculture 13 (10), 2022.

Li, L., Feng, Y., Qi, F., Hao, R., 2023. Research progress of *Piriformospora indica* in improving plant growth and stress resistance. Journal of Fungi 9 (10), 965.

Manono, B.O., Khan, S., Kithaka, K.M., 2025. A review of the socio-economic, institutional, and biophysical factors influencing smallholder farmers' adoption of climate smart agricultural practices in Sub-Saharan Africa. Earth 6 (2), 48.

Maurya, S., Thakur, R., Vighnesh, R., Suresh, S., Dang, A., Raj, D., Srivastava, S., 2024. Eco-friendly management of plant pathogens through secondary metabolites released by Fluorescent Pseudomonads. J. Pure Appl. Microbiol. 18(3), 1471-1488.

Mawar, R., Manjunatha, B., Kumar, S., 2021. Commercialization, diffusion and adoption of bioformulations for sustainable disease management in Indian arid agriculture: prospects and challenges. Circular Economy and

Sustainability 1 (4), 1367-1385.

Mehmood, N., Saeed, M., Zafarullah, S., Hyder, S., Rizvi, Z.F., Gondal, A.S., Jamil, N., Iqbal, R., Ali, B., Ercisli, S., 2023. Multifaceted impacts of plant-beneficial *Pseudomonas* spp. in managing various plant diseases and crop yield improvement. ACS Omega 8 (25), 22296-22315.

Mikiciuk, G., Miller, T., Kisiel, A., Cembrowska-Lech, D., Mikiciuk, M., Łobodzińska, A., Bokszczanin, K., 2024. Harnessing beneficial microbes for drought tolerance: A review of ecological and agricultural innovations. Agriculture 14 (12), 2228.

Mirzwa-Mróz, E., Zieniuk, B., Yin, Z., Pawełkowicz, M., 2024. Genetic insights and molecular breeding approaches for downy mildew resistance in cucumber (*Cucumis sativus* L.): current progress and future prospects. International Journal of Molecular Sciences 25 (23), 12726.

Modi, K., Jha, S., 2022. *Bacillus* consortia as a sustainable approach for plant growth promotion in rice (*Oryza sativa* L.). Current Agriculture 39, 28-49.

Mohanan, A., Nigam, R., Yeliya, P., Daniel, G.R., Devi, N.O., Sahu, R., Mohapatra, D., Sahoo, L., 2025. The role of plant microbiomes in suppressing soilborne pathogens: a review. Journal of Advances in Microbiology 25 (5), 160-178.

Moura, A.B., Backhouse, D., de Souza Júnior, I.T., Gomes, C.B., 2022. Soilborne pathogens, 199-224. In: Subsoil Constraints for Crop Production. Springer.

Mukherjee, P.K., Mendoza-Mendoza, A., Zeilinger, S., Horwitz, B.A., 2022. Mycoparasitism as a mechanism of *Trichoderma*-mediated suppression of plant diseases. Fungal Biology Reviews 39, 15-33.

Nakkeeran, S., Rajamanickam, S., Saravanan, R., Vanthana, M., Soorianathasundaram, K., 2021. Bacterial endophytome-mediated resistance in banana for the management of Fusarium wilt. 3 Biotech 11 (6), 267.

Neupane, D., Adhikari, P., Bhattarai, D., Rana, B., Ahmed, Z., Sharma, U., Adhikari, D., 2022. Does climate change affect the yield of the top three cereals and food security in the world? Earth 3 (1), 45-71.

Ngalimat, M.S., Mohd Hata, E., Zulperi, D., Ismail, S.I., Ismail, M.R., Mohd Zainudin, N.A.I., Saidi, N.B., Yusof, M.T., 2021. Plant growth-promoting bacteria as an emerging tool to manage bacterial rice pathogens. Microorganisms 9 (4), 682.

O'Callaghan, M., Ballard, R.A., Wright, D., 2022. Soil microbial inoculants for sustainable agriculture: Limitations and opportunities. Soil Use and Management 38 (3), 1340-1369.

Olowe, O.M., Nicola, L., Asemoloye, M.D., Akanmu, A.O., Babalola, O.O., 2022. Trichoderma: Potential bio-resource for the management of tomato root rot diseases in Africa. Microbiological Research 257, 126978.

Pagano, M.C., Correa, E.J.A., Duarte, N.F., Yelikbayev, B., O'Donovan, A., Gupta, V.K., 2017. Advances in eco-efficient agriculture: the plant-soil mycobiome. Agriculture 7 (2), 14.

Pothiraj, G., Hussain, Z., Singh, A.K., Solanke, A.U., Aggarwal, R., Ramesh, R., Shanmugam, V., 2021. Characterization of *Fusarium* spp. inciting vascular wilt of tomato and its management by a *Chaetomium*-based biocontrol consortium. Frontiers in Plant Science 12, 748013.

Pratama Hamzah, A.H., Heryadi, D.Y., Pramono, S.A., 2024. Production-optimization of biosurfactant from mangrove sediment bacteria using media salinity, differences in carbon source concentration and pH levels. Journal of Global Innovations in Agricultural Sciences 12 (2), 391-398.

Procópio, L., Barreto, C., 2021. The soil microbiomes of the Brazilian Cerrado. Journal of Soils and Sediments 21, 2327-2342.

Qasim Hasan, A., Abdulla Falah, M., 2024. Impact of pesticide use on farmers' health condition: case control design. Journal of Global Innovations in Agricultural Sciences 12 (1), 169-174.

Radi, H., Koufan, M., Belkoura, I., Koussa, T., Mazri, M.A., 2025. In vitro mycorrhization for plant propagation and enhanced resilience to environmental stress: a review. Plants 14 (14), 2097.

Rawat, P., Das, S., Shankhdhar, D., Shankhdhar, S., 2021. Phosphate-solubilizing microorganisms: mechanism and their role in phosphate solubilization and uptake. Journal of Soil Science and Plant Nutrition 21 (1), 49-68.

Rodrigues, A.O., May De Mio, L.L., Soccol, C.R., 2023. *Trichoderma* as a powerful fungal disease control agent for a more sustainable and healthy agriculture: recent studies and molecular insights. Planta 257 (2), 31.

Saberi-Riseh, R., Fathi, F., Moradzadeh-Eskandari, M., 2020. Effect of some *Pseudomonas fluorescens* and

*Bacillus subtilis* strains on osmolytes and antioxidants of cucumber under salinity stress. Journal of Crop Protection 9 (1), 1-16.

Sehim, A.E., Hewedy, O.A., Altammar, K.A., Alhumaidi, M.S., Abd Elghaffar, R.Y., 2023. *Trichoderma asperellum* empowers tomato plants and suppresses *Fusarium oxysporum* through priming responses. Frontiers in Microbiology 14, 1140378.

Shahid, R., 2024. CRISPR and agriculture: transforming crop science through precision genetics and sustainable practices - a review. Journal of Global Innovations in Agricultural Sciences, 1147-1157.

Shahzad, F., Asghar, H.N., Mushtaq, Z., Hadayat, A., Zuhra, N., Ahmad, R., Ali, M.A., 2020. Role of endomycorrhizae, rhizobacteria and compost to improve phosphorus availability in onion. Journal of Plant Nutrition 43 (9), 1283-1295.

Sharma, I., Kashyap, S., Agarwala, N., 2023. Biotic stress-induced changes in root exudation confer plant stress tolerance by altering rhizospheric microbial community. Frontiers in Plant Science 14, 1132824.

Sharma, P., Jambhulkar, P., Raja, M., Sain, S., Javeria, S., 2020. *Trichoderma* spp. in consortium and their rhizospheric interactions, 267-292. In: *Trichoderma*: Host Pathogen Interactions and Applications. Springer, Singapore.

Sheoran, A.R., Lakra, N., Saharan, B.S., Luhach, A., Kumar, R., Seth, C.S., Duhan, J.S., 2025. Enhancing plant disease resistance: insights from biocontrol agent strategies. Journal of Plant Growth Regulation 44 (2), 436-459.

Shinde, S.S., Gaonkar, V.V., Mukadam, H.M., Gaikwad, S.V., 2025. *Bacillus subtilis*: a biological marvel in the domain of agriculture and environmental science. Environmental Research Communications 7 (1), 015009.

Singh, B.K., Delgado-Baquerizo, M., Egidi, E., Guirado, E., Leach, J.E., Liu, H., Trivedi, P., 2023. Climate change impacts on plant pathogens, food security and paths forward. Nature Reviews Microbiology 21 (10), 640-656.

Singh, V.K., Singh, R., Kumar, A., Bhadouria, R., 2021. Current status of plant diseases and food security, 19-35. In: Food Security and Plant Disease Management. Elsevier, Amsterdam.

Soumare, A., Diedhiou, A.G., Thuita, M., Hafidi, M., Ouhdouch, Y., Gopalakrishnan, S., Kouisni, L., 2020. Exploiting biological nitrogen fixation: a route towards a sustainable agriculture. Plants 9 (8), 1011.

Sun, W., Shahrajabian, M.H., Soleymani, A., 2024. The roles of plant-growth-promoting rhizobacteria (PGPR)-based biostimulants for agricultural production systems. Plants 13 (5), 613.

Tahir, M.N., Habib, A., Ali, A., 2024. Management of fusarium wilt disease in sesame (*Sesamum indicum*) through seed treatment and soil amendment. Phytopathogenomics and Disease Control 3 (2), 261-266.

Tariq Javeed, M., Farooq, T., Al-Hazmi, A.S., Hussain, M.D., Rehman, A.U., 2021. Role of *Trichoderma* as a biocontrol agent (BCA) of phytoparasitic nematodes and plant growth inducer. Journal of Invertebrate Pathology 183, 107626.

Teixidó, N., Usall, J., Torres, R., 2022. Insight into a successful development of biocontrol agents: Production, formulation, packaging, and shelf life as key aspects. Horticulturae 8 (4), 305.

Teja, B.S., Jamwal, G., Gupta, V., Verma, M., Sharma, A., Sharma, A., Pandit, V., 2025. Biological control of bacterial leaf blight (BLB) in rice – A sustainable approach. Heliyon 11(2).

Thomas, L., Singh, I., 2021. Microbe-mediated biotic stress signaling and resistance mechanisms in plants, 297-334. In: Plant Stress Biology: Strategies and Trends. Springer, Singapore.

Torres-Rodriguez, J.A., 2024. Chitosan: biocontrol of *Moniliophthora roreri* and a biostimulant of *Theobroma cacao* L. Journal of Global Innovations in Agricultural Sciences, 993-1001.

Ullah, N., Ahmed, B., Waris, M., Yousuf, S., 2024. In-vitro management of *Erwinia amylovora* caused by fire blight of apple with synthetic chemicals. Phytopathogenomics and Disease Control 3 (2), 87-93.

Usman, H.M., Iffat, A., Shafique, T., 2024. Insights into *Fusarium* spp. associated with dry root rot of citrus and its management. Phytopathogenomics and Disease Control, 241-249.

Vishwakarma, K., Kumar, N., Shandilya, C., Mohapatra, S., Bhayana, S., Varma, A., 2020. Revisiting plant-microbe interactions and microbial consortia application for enhancing sustainable agriculture: A review. Frontiers in Microbiology 11, 560406.

Wahab, A., Muhammad, M., Munir, A., Abdi, G., Zaman, W., Ayaz, A., Khizar, C., Reddy, S.P.P., 2023. Role of

arbuscular mycorrhizal fungi in regulating growth, enhancing productivity, and potentially influencing ecosystems under abiotic and biotic stresses. Plants 12 (17), 3102.

Wang, M., Li, J., Cong, W., Zhang, J., 2022. Antimicrobial mechanism and secondary metabolite profiles of biocontrol agent *Streptomyces lydicus* M01 based on ultra-high-performance liquid chromatography connected to a quadrupole time-of-flight mass spectrometer analysis and genome sequencing. Frontiers in Microbiology 13, 908879.

Wudil, A.H., Usman, M., Rosak-Szyrocka, J., Pilař, L., Boye, M., 2022. Reversing years for global food security: A review of the food security situation in Sub-Saharan Africa (SSA). International Journal of Environmental Research and Public Health 19 (22), 14836.

Xu, T., Cao, L., Zeng, J., Franco, C.M., Yang, Y., Hu, X., Liu, Y., Wang, X., Gao, Y., Bu, Z., 2019. The antifungal action mode of the rice endophyte *Streptomyces hygroscopicus* OsiSh-2 as a potential biocontrol agent against the rice blast pathogen. Pesticide Biochemistry and Physiology 160, 58-69.

Yadav, M., Divyanshu, K., Dubey, M.K., Rai, A., Kumar, S., Tripathi, Y.N., Shukla, V., Upadhyay, R.S., 2023. Plant growth promotion and differential expression of defense genes in chilli pepper against *Colletotrichum truncatum* induced by *Trichoderma asperellum* and *T. harzianum*. BMC Microbiology 23 (1), 54.

Yasin, S.M., Syam'un, E., Rasyid, B., 2025. Endophytic bacteria in highland and its ability to enhance plant growth environment. Journal of Global Innovations in Agricultural Sciences, 671-679.

Zeeshan, M., Mukhtar, T., Inam-ul-Haq, M., Asad, M.J., 2023. Incidence, characterization and pathogenic variability of *Fusarium oxysporum* in the Punjab province of Pakistan. International Journal of Phytopathology 12 (1), 19-29.

Zhu, L., Huang, J., Lu, X., Zhou, C., 2022. Development of plant systemic resistance by beneficial rhizobacteria: Recognition, initiation, elicitation and regulation. Frontiers in Plant Science 13, 952397.