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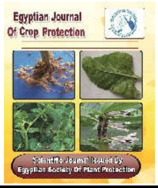

Review

Optimizing Safe and Sustainable Approaches to Manage Fungal Plant Diseases

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ABSTRACT

Fungal phytopathogens pose a significant and escalating threat to global food security, resulting in considerable crop losses and economic burdens while challenging the sustainability of conventional chemical-dependent management practices. This review synthesizes current advancements and challenges in the development of safe, practical strategies to control fungal plant diseases, underscoring the urgent necessity for sustainable alternatives. We examine the potential of biological control agents, host resistance breeding, natural antifungals, nanotechnology, and cultural practices as environmentally friendly solutions, while also highlighting the limitations of synthetic fungicides, which include the development of resistance and ecological detriment. The paper emphasizes the critical importance of Integrated Pest Management in harmonizing these approaches, leveraging synergies among microbial inoculants, genetic innovations, and precision agriculture to diminish dependence on chemical inputs. Despite promising innovations—such as CRISPR-edited crops, RNAi-based fungicides, and nano-formulated biocontrol agents—significant barriers remain, including inconsistent field performance, regulatory challenges, and socioeconomic constraints. We also discuss emerging solutions, encompassing microbiome engineering and climate-resilient biocontrol strains, and underscore the necessity of policy reforms and farmer education to facilitate widespread adoption. Ultimately, this review advocates for a paradigm shift towards ecologically balanced disease management, arguing that the integration of advanced technologies with traditional knowledge can cultivate resilient agricultural systems capable of addressing future food demands while safeguarding ecosystem health. The findings offer a comprehensive roadmap for researchers, policymakers, and practitioners to transition from reactive fungicide use to proactive, sustainable management of fungal pathogens.

Key words: Biological control, Disease management, Fungal phytopathogens, Integrated Pest Management, Sustainable agriculture.

INTRODUCTION

Fungal phytopathogens represent one of the most pervasive and economically devastating threats to global agriculture, undermining food security, destabilizing trade, and imposing heavy financial burdens on farmers worldwide. These pathogens infect crops at every growth stage, causing diseases that lead to 20–30% yield losses in staple crops such as wheat, rice, maize, and potatoes. The Food and Agriculture Organization estimates that plant diseases, predominantly fungal, cost the global economy over $220 billion annually, with resource-limited regions suffering disproportionately due to limited access to effective control measures (Gai and Wang, 2024). Beyond direct agricultural losses, fungal pathogens disrupt ecosystems by altering soil microbiomes, reducing biodiversity, and necessitating intensive chemical interventions that further degrade environmental health (Barros-Rodríguez et al., 2021). For decades, synthetic fungicides (triazoles, strobilurins, benzimidazoles, etc.) have been the cornerstone of fungal disease management due to their rapid action and broad-spectrum efficacy. However, their overuse has precipitated a crisis of diminishing returns: widespread fungicide resistance, particularly in high-risk pathogens like *Botrytis cinerea* (gray mold) and *Zymoseptoria tritici* (Septoria leaf blotch), now renders many conventional chemicals ineffective. Compounding this issue, residual fungicides accumulate in soil and water systems, harming non-target organisms such as pollinators, aquatic life, and beneficial soil microbes critical for nutrient cycling. Human health concerns, including links to carcinogenicity and endocrine disruption, have

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led to stringent regulations and bans on key chemicals like methyl bromide, leaving farmers with fewer tools to combat increasingly aggressive fungal strains (Gikas et al., 2022; Bai et al., 2024; Porter and Collins, 2025).

In response to these challenges, the agricultural scientific community has intensified efforts to develop sustainable, eco-compatible alternatives that align with the principles of integrated pest management (IPM) and One Health. Biological control agents (BCAs), such as *Trichoderma* fungi and *Bacillus* bacteria, exploit natural antagonistic interactions to suppress pathogens while enhancing plant immunity (Khaskheli et al., 2025). Concurrently, advances in genetic engineering—from CRISPR-Cas9-edited resistant crops to RNA interference (RNAi) sprays—offer precision tools to disrupt fungal virulence without chemical residues (Rajput et al., 2021; Gómez-Lama Cabanás and Mercado-Blanco, 2025). Complementing these innovations, traditional knowledge systems contribute plant-derived antifungals (essential oils, aqueous extracts, etc.) and cultural practices (crop rotation, biofumigation, etc.) that reduce pathogen pressure through ecological balance (Panth et al., 2020; Arora et al., 2022). Emerging technologies like nanotechnology further bridge the gap between efficacy and sustainability, enabling targeted delivery of antifungal compounds at reduced dosages (Rajput et al., 2021; Gómez-Lama Cabanás and Mercado-Blanco, 2025).

This review synthesizes contemporary research on these safe and sustainable strategies, evaluating their mechanisms, successes, and limitations in real-world agricultural systems. This paper underscores the urgency of adopting multidisciplinary approaches to fungal disease management by critically analyzing the transition from chemical dependency to integrated solutions. The goal is to mitigate immediate crop losses, preserve ecosystem integrity, and ensure long-term agricultural resilience in climate change, which exacerbates fungal spread and virulence. Through this exploration, we aim to provide a roadmap for researchers, policymakers, and farmers to navigate the complexities of modern phytopathogen control while prioritizing environmental and human health.

MAJOR FUNGAL PHYTOPATHOGENS AND THEIR IMPACT

Fungal phytopathogens affect global agriculture, attacking crops at every stage, from seedling to storage. Among the most destructive field pathogens, *Fusarium graminearum* stands out as the causal agent of *Fusarium* head blight in wheat and barley, capable of reducing yields by 40-60% while contaminating grains with dangerous mycotoxins like deoxynivalenol. This pathogen has shown remarkable adaptability, with new chemotypes emerging in response to fungicide pressure (Mielniczuk and Skwaryło-Bednarz, 2020; Xu et al., 2022). Similarly, *Phytophthora infestans*, the oomycete responsible for potato and tomato late blight, continue to evolve aggressive strains that overcome host resistance, with potential yield losses reaching 100% in conducive environments. The infamous Irish Potato Famine of the 1840s, which caused mass starvation and migration, serves as a historical reminder of this pathogen's destructive potential, while modern outbreaks still cause annual losses exceeding $6 billion worldwide (Narouei-Khandan et al., 2020; Srisawad et al., 2023).

The rust fungi complex (*Puccinia* spp.) presents another formidable challenge to global food security. Wheat stem rust (*Puccinia graminis* f. sp. *tritici*), particularly the Ug99 strain lineage, has spread from East Africa to the Middle East and South Asia, threatening up to 90% of the world's wheat varieties (Gao et al., 2024). Coffee leaf rust (*Hemileia vastatrix*) has similarly devastated Central American production, with regional yield declines of 30-50% since 2012 (Gichuru et al., 2021). Perhaps most alarming is *Magnaporthe oryzae*, the rice blast pathogen, which destroys enough rice annually to feed 60 million people, with yield losses reaching 100% in severe cases (Tan et al., 2023). These field pathogens reduce harvest quantity and compromise quality, as seen with *Fusarium* mycotoxin contamination that renders grain unsuitable for human or animal consumption (Mielniczuk et al., 2020).

Postharvest fungal diseases present an equally significant but often overlooked threat to global food security. *Aspergillus flavus* and *A. parasiticus* contamination of stored maize, peanuts, and tree nuts produce aflatoxins - among the most potent carcinogens known, causing an estimated 25,000-155,000 deaths annually from liver cancer in developing countries (Gong et al., 2024). *Penicillium* spp., including *P. expansum* in apples and *P. digitatum* in citrus, cause devastating postharvest rots, with losses reaching 50% of stored fruit in regions lacking refrigeration. The gray mold fungus *Botrytis cinerea* affects over 200 plant species, causing significant losses in stored grapes, tomatoes, and ornamental crops. These postharvest pathogens thrive in storage environments, where high humidity and inadequate ventilation create ideal conditions for proliferation (Ezzouggari et al., 2024).

The combined impact of these fungal threats extends far beyond agricultural production. Mycotoxin contamination leads to annual global trade losses exceeding $1.4 billion due to rejected shipments. In developing countries, where postharvest infrastructure is often lacking, losses can account for 30-50% of total production (Zhang et al., 2024). The economic burden is particularly severe for smallholder farmers, who may lose their entire harvest to storage molds. Furthermore, climate change exacerbates these challenges, as rising temperatures expand the geographic range of field and storage pathogens while increasing mycotoxin production. For instance, a 2°C temperature rise could increase aflatoxin contamination in maize by 40-50% in key production regions (Mutiga et al., 2019; Kumar et al., 2021; Gullino et al., 2022).

Addressing these multifaceted fungal threats requires an integrated approach from the field to storage. While resistant varieties and biological controls show promise for field diseases, postharvest management demands improved drying technology, storage conditions, and mycotoxin monitoring systems (Zadravec et al., 2022). Developing biofungicides for postharvest applications, such as Cryptococcus yeasts for citrus decay control, is essential in reducing chemical residues. As global trade and climate variability intensify pathogen spread, international cooperation in disease surveillance and management will become increasingly critical to safeguard both food security and public health (Moraes Bazioli et al., 2019; Ramudingana et al., 2025).

CURRENT STRATEGIES FOR MANAGING FUNGAL PHYTOPATHOGENS

1- Chemical Control: Limitations and Emerging Alternatives

Synthetic fungicides have long been the cornerstone of fungal disease management in agriculture, offering rapid and reliable suppression of phytopathogens. Broad-spectrum fungicides, including triazoles (e.g., tebuconazole), strobilurins (e.g., azoxystrobin), and benzimidazoles (e.g., carbendazim), have been widely adopted due to their systemic activity and cost-effectiveness. These chemicals disrupt critical fungal cellular processes—triazoles inhibit ergosterol biosynthesis in cell membranes, strobilurins block mitochondrial respiration, and benzimidazoles interfere with microtubule assembly. Their efficacy in controlling diseases like powdery mildew, rust, and *Botrytis* infections has made them indispensable in intensive farming systems. However, decades of overreliance on chemical controls have led to severe ecological and agronomic consequences that threaten their long-term viability as a management strategy (Bai et al., 2024).

The most pressing issue with chemical fungicides is the rapid evolution of resistance in pathogen populations. *B. cinerea*, the causal agent of gray mold, has developed resistance to all major fungicide classes in key production regions, with some strains exhibiting multiple resistance mechanisms simultaneously (Weber and Petridis, 2023). Similarly, *Z. tritici* has evolved resistance to strobilurins in a few years of widespread use, rendering these compounds ineffective in many areas (Gur et al., 2021). This resistance crisis is compounded by the fact that few new fungicide modes of action have been introduced in recent decades, leaving farmers with dwindling chemical options (Jayawardana and Fernando, 2024). Beyond resistance, synthetic fungicides pose significant environmental hazards, including soil and water contamination. Triazole residues, for instance, persist in agricultural soils for years, disrupting beneficial microbial communities and potentially leaching into groundwater. Aquatic ecosystems are particularly vulnerable, as fungicide runoff has been linked to declines in fish and amphibian populations, while airborne drift affects non-target plants and pollinators (Gikas et al., 2022; Miller et al., 2022).

Human health concerns further limit the appeal of chemical fungicides. Many widely used compounds, such as mancozeb and chlorothalonil, are classified as probable carcinogens or endocrine disruptors, raising alarms about chronic exposure among farmworkers and consumers. Regulatory agencies have increasingly restricted or banned high-risk fungicides—the European Union's withdrawal of chlorothalonil in 2019 and the pending phase-out of mancozeb exemplify this trend (Lori et al., 2021; Lazarević-Pašti et al., 2025). These restrictions leave farmers with fewer tools to combat aggressive pathogens, particularly in high-value crops like grapes and potatoes where fungal pressure is intense. Additionally, the high cost of developing and registering new fungicides (exceeding $250 million per product) discourages innovation, creating a gap between emerging resistance and the availability of effective alternatives (Tsalidis, 2022; Porter and Collins, 2025).

2- Biological Control: Harnessing Nature's Defenses for Sustainable Phytopathogen Management

Biological control represents a paradigm shift in plant disease management, moving beyond chemical suppression to exploit the complex ecological interactions between micro-organisms, plants, and pathogens. This approach utilizes beneficial microbes, naturally occurring compounds, and plant defense mechanisms to create an inhospitable environment for fungal phytopathogens while promoting agroecosystem health (Palmieri et al., 2022). Unlike broad-spectrum fungicides that indiscriminately eliminate harmful and beneficial organisms, BCAs function through targeted competition, antibiosis, parasitism, and systemic resistance induction (Manzar et al., 2022). Among the most extensively studied BCAs are filamentous fungi from the *Trichoderma* genus, which employ a remarkable array of antagonistic strategies. *Trichoderma* spp. actively colonize the rhizosphere, outcompeting pathogens for space and nutrients while secreting cell wall-degrading enzymes such as chitinases and β-1,3-glucanases that directly lyse fungal hyphae (Maciag et al., 2023). These mycoparasites demonstrate particular efficacy against soil-borne and air-borne pathogens, reducing disease incidence by 60-80% in crops ranging from vegetables to cereals. In Tunisia and Iraq, greenhouse trials have shown that *Trichoderma*-based seed treatments can suppress many post-harvest diseases in tomato fruits by 75%, outperforming chemical fungicides in long-term soil health improvement (Guzmán-Guzmán et al., 2023).

Bacterial biocontrol agents offer complementary modes of action, with *Bacillus* spp. and *Pseudomonas* spp. leading commercial development. *B. subtilis* strains produce cyclic lipopeptides (e.g., surfactin, iturin, etc.) that disrupt fungal membrane integrity, demonstrating broad-spectrum activity against powdery mildew and *B. cinerea*. Meanwhile, *P. fluorescens* utilizes iron competition through siderophore production, effectively starving pathogens of this essential micronutrient (Lastochkina et al., 2019). Perhaps most valuable is the ability of these bacteria to induce systemic acquired resistance in plants by priming jasmonic acid and salicylic acid pathways. This "vaccination effect" has been documented in grapevines treated with *Bacillus* preparations, which exhibit enhanced defense responses against subsequent *Plasmopara viticola* infections. The commercial success of bacterial BCAs is evident in products like Serenade® (*B. subtilis* QST713) and Sonata® (*B. pumilus*), which now account for over 30% of the organic disease control market (Valenzuela Ruiz et al., 2024).

The integration of fungal and bacterial biocontrols with cultural practices creates synergistic disease suppression systems. For instance, the combination of *Trichoderma* inoculants with compost amendments in tomato production has shown 90% control of *Alternaria* spp. and *Botrytis* spp., compared to 50-60% for either treatment alone (Karačić et al., 2024). This enhancement occurs because organic matter provides a substrate for antagonist proliferation while improving soil structure. Similarly, intercropping systems incorporating aromatic plants like basil or marigold boost the efficacy of *Pseudomonas* BCAs by releasing volatile organic compounds that disorient pathogen chemotaxis (Xu et al., 2025). Emerging research on endophytic biocontrol agents—microbes that colonize plant tissues without causing disease—opens new possibilities for internal protection. The endophyte *Acremonium strictum*, for example, systemically colonizes wheat plants and produces antifungal alkaloids that reduce *Fusarium* severity by 40-50% (Morales-Cedeño et al., 2023).

Despite these successes, biological control faces challenges in consistency and adoption. Performance variability under field conditions remains a significant hurdle, as environmental factors like soil pH, moisture, and temperature dramatically influence microbial activity. A 2023 meta-analysis revealed that *Bacillus*-based treatments showed 30% greater efficacy in controlled environments than open-field applications (Elhjouji et al., 2025). Formulation technology addresses this limitation through innovations in microencapsulation and carrier materials that protect microbes from environmental stress. Another barrier is the slower onset of action compared to chemical fungicides, requiring precise timing of applications before disease pressure escalates. Educational initiatives for farmers are critical to overcoming the "expectation gap"—understanding that biocontrols work preventatively rather than as rescue treatments. Regulatory frameworks also need adaptation, as current pesticide evaluation protocols designed for synthetic chemicals often fail to assess the ecological benefits of BCAs (Mikiciuk et al., 2024; Díaz-Rodríguez et al., 2025).

The future of biological control lies in customized microbial consortia tailored to specific pathosystems. Advances in microbiome sequencing enable the design of synthetic communities combining nutrient-cycling, pathogen-antagonistic, and plant growth-promoting strains. Coupled with nanotechnology delivery systems and precision application equipment, next-generation biocontrol strategies promise to transform plant disease management into a sustainable practice that works with, rather than against, natural ecosystems. As research unravels the intricate signaling networks between plants and their microbial allies, biological control is poised to move from a complementary alternative to the foundation of 21st-century integrated pest management systems (Nchu, 2024; Tyagi et al., 2024).

3- Host Resistance and Genetic Innovations: Revolutionizing Phytopathogen Management

Developing disease-resistant crops through genetic innovation represents one of the most sustainable and economically viable strategies for managing fungal phytopathogens. Unlike chemical controls that require repeated applications and lose efficacy to resistance, host-plant resistance provides durable protection by leveraging the plant's defense mechanisms. Traditional breeding has long been the cornerstone of this approach, with landmark successes such as the incorporation of the Sr31 stem rust resistance gene into wheat varieties during the mid-20th century, which protected global wheat production for decades. However, the emergence of virulent fungal strains like Ug99, which overcame Sr31 and related genes, exposed the limitations of conventional breeding—a process that often requires 8–12 years to develop a resistant cultivar. Modern genetic technologies are dramatically accelerating this timeline while expanding the arsenal of resistance mechanisms available to plant breeders (Leonova et al., 2020; Plotnikova et al., 2022; Gao et al., 2024; Wei et al., 2024).

CRISPR-Cas9 gene editing has emerged as a transformative tool for engineering disease resistance without introducing foreign DNA, thus bypassing the regulatory hurdles associated with transgenic crops. Researchers have used CRISPR to knockout susceptibility (S) genes in plants—genes that pathogens exploit for infection. For example, the inactivation of the MLO gene in wheat and barley confers broad-spectrum resistance to powdery mildew by preventing fungal penetration, mimicking naturally occurring mutations that have remained effective for centuries. Similarly, CRISPR-mediated editing of the EDR1 gene in Arabidopsis enhances resistance to

Golovinomyces cichoracearum by hyperactivating salicylic acid defense pathways (Leal et al., 2024; Bayır et al., 2025). Beyond knockouts, precision editing enables the insertion of resistance (R) genes from wild crop relatives into elite cultivars. The Pi21 gene from wild rice, when introduced into commercial varieties through marker-assisted selection, provides durable resistance to *Magnaporthe oryzae* without yield penalties—a critical advancement given that rice blast disease destroys 10–30% of global rice production annually (Tavakoli et al., 2021; Mohr et al., 2022).

RNA interference technology offers another innovative approach: silencing essential fungal genes during infection. Unlike genetic modification of host plants, RNAi can be applied as a topical spray—a breakthrough that avoids GMO regulations while providing targeted protection. BioClay™ technology, which delivers double-stranded RNA molecules layered onto clay nanoparticles, has shown remarkable success in field trials against *F. graminearum*. The RNAi molecules silence fungal genes involved in ergosterol biosynthesis, reducing disease severity by 70–90% in wheat and barley (Basso et al., 2025). This approach is particularly valuable for combating mycotoxin-producing fungi, as it can specifically target toxin biosynthesis pathways without affecting beneficial endophytes. The first commercial RNAi-based fungicide, BioDirect, is currently undergoing regulatory review and could revolutionize the management of stubborn pathogens like *B. cinerea*, which has developed resistance to all major chemical classes (Menezes et al., 2022; Islam et al., 2025).

The integration of high-throughput phenotyping and genomic selection has further enhanced resistance-breeding programs. Drones equipped with multispectral sensors can now identify subtle resistance traits in field trials by detecting early physiological responses to fungal infection, such as changes in leaf temperature or chlorophyll fluorescence. These technologies, combined with genome-wide association studies (GWAS), have accelerated the identification of novel resistance loci in crop wild relatives—a critical resource as fungal pathogens evolve to overcome deployed R genes (Xu et al., 2023; Tsonev et al., 2024). Researchers discovered a new broad-spectrum resistance gene (Sr62) from wild emmer wheat that remains effective against all known stem rust races, including Ug99. Marker-assisted backcrossing allowed its incorporation into elite wheat lines in 4 years, compared to the decade typically required through conventional breeding (Karelov et al., 2022; Gao et al., 2024; Li et al., 2024).

Despite these advances, challenges remain in ensuring genetic resistance's durability and ecological compatibility. Pathogens can rapidly evolve to overcome single-gene resistance through mutation or recombination, as demonstrated by the quick breakdown of Bs2-mediated resistance to *Xanthomonas* in peppers (Tóth et al., 2023). Stacking multiple R genes with different mechanisms of action—a strategy now feasible through gene editing—helps mitigate this risk. Another concern is the potential fitness cost associated with resistance traits; some edited wheat lines with enhanced chitinase expression show reduced growth under low-disease pressure. Ongoing research into "decoy" resistance strategies, where plants express modified versions of pathogen targets that trigger immune responses without supporting fungal growth, may address this limitation (Li et al., 2023; Chang et al., 2025).

The future of host resistance lies in innovative deployment strategies that integrate genetic innovations with ecological knowledge. Regional gene deployment programs, where different resistance combinations are planted in adjacent areas, can slow pathogen adaptation while maintaining high yields (Gao et al., 2024). Digital agriculture tools will be crucial in monitoring pathogen populations and recommending optimal resistance gene combinations. As climate change alters pathogen geographic ranges and life cycles, the dynamic nature of gene editing and RNAi technologies positions them as essential tools for developing climate-resilient crops (Wei et al., 2024; Chang et al., 2025). By moving beyond the pesticide paradigm and harnessing the plant's innate immune potential, genetic innovations offer a sustainable path toward reducing agriculture's reliance on chemical inputs while ensuring global food security in the face of evolving fungal threats (Islam et al., 2025).

4- Natural Antifungals and Cultural Practices: Ecological Approaches to Phytopathogen Management

Using plant-derived antifungal compounds and agronomic practices represents a time-tested yet increasingly sophisticated approach to managing fungal diseases in agriculture. These strategies work harmoniously with ecological principles, offering sustainable alternatives to synthetic fungicides while enhancing soil health and crop resilience. Botanical antifungals derive their potency from complex secondary metabolites that plants have evolved as natural defense mechanisms. Among the most extensively studied are neem (*Azadirachta indica*) extracts, which contain azadirachtin—a limonoid compound that disrupts fungal membrane integrity and inhibits spore germination (McLaughlin et al., 2023; Rasiukevičiūtė et al., 2025). Research has demonstrated neem oil's efficacy against powdery mildews in cucurbits and *Alternaria* spp. in tomatoes, achieving 60–80% disease suppression while leaving no toxic residues. Similarly, essential oils from thyme (*Thymus vulgaris*), clove (*Syzygium aromaticum*), and oregano (*Origanum vulgare*) rich in thymol, eugenol, and carvacrol exhibit broad-spectrum activity against *B. cinerea* and *F. oxysporum* through multiple modes of action, including mitochondrial dysfunction and reactive oxygen species generation. These compounds are particularly valuable in organic production systems and postharvest applications, where a 0.5% thyme oil emulsion has shown comparable efficacy to synthetic fungicides in controlling *Penicillium* rot in citrus fruits (Kosakowska et al., 2024; Mihaylova et al., 2025). Hajji-Hedfi et al. (2024a) explored the antifungal and phytochemical properties of three forest plants (*Eucalyptus globulus*, *Pistacia lentiscus*, and *Juniperus phoenicea*) against apple diseases caused by *Colletotrichum gloeosporioides* and *Alternaria alternata*. *E. globulus* aqueous extracts exhibited the highest total polyphenol and flavonoid content and the most potent antioxidant activity. Phytochemical analysis revealed common phenolic acids and flavonoids in all three plants. *E. globulus* essential oil demonstrated the most effective *in vitro* fungistatic activity, while it's aqueous extract and essential oil significantly inhibited mycelial growth and spore germination. Preventive treatments with *E. globulus* extracts on inoculated apples resulted in the lowest disease severity and lesion size, suggesting its promising potential for managing apple anthracnose and Alternaria rot.

Hajji-Hedfi et al. (2024b) investigated the potential of *Capsicum annuum* seed aqueous extract, combined with salicylic acid, to combat *B. cinerea*, the cause of gray mold in tomatoes. Phytochemical analysis revealed various bioactive compounds in the extract. In vitro, a 60% extract concentration most effectively inhibited fungal growth. In vivo, the combined treatment of tomato seeds significantly reduced gray mold damage and improved seedling growth parameters. Similarly, applying the combined treatment preventively to tomato fruits inoculated with *B. cinerea* resulted in the lowest disease severity, favorably influenced physicochemical and morphometrical attributes, and enhanced defense-related enzyme activity. These findings suggest that the combined application of pepper seed extract and salicylic acid offers a promising and eco-friendly alternative to chemical fungicides for sustainable tomato cultivation.

The biopolymer chitosan, derived from crustacean shells, exemplifies how waste products can be repurposed for disease control. When applied as a foliar spray or seed coating, chitosan forms a physical barrier against fungal penetration and primes plant defense responses by upregulating pathogenesis-related proteins and phenylpropanoid pathway enzymes (Toma et al., 2025). In rice paddies, chitosan treatments reduce *Magnaporthe oryzae* infections by 40–60% while enhancing silica deposition in cell walls—a dual mechanism that chemical fungicides cannot replicate (Younas et al., 2024). Field trials with chitosan nanoparticles loaded with cinnamon oil have demonstrated synergistic effects, achieving 90% inhibition of *Aspergillus flavus* in maize storage and addressing pre- and postharvest contamination risks. These natural compounds are increasingly formulated with adjuvants to improve rain fastness and leaf adhesion, overcoming early limitations of rapid environmental degradation (Phan et al., 2025).

Complementing botanical antifungals, cultural practices manipulate the agroecosystem to create unfavorable conditions for pathogens while promoting crop health. Crop rotation remains one of the most effective strategies against soil-borne fungi; rotating cereals with non-host legumes reduces *Fusarium* inoculum by 70–90% over three growing seasons. The practice disrupts pathogen life cycles while improving soil nitrogen content—a stark contrast to monoculture systems where *Fusarium* populations can persist for decades. Intercropping takes this further by creating physical barriers to spore dispersal; for example, planting garlic between strawberry rows emits allicin vapors that suppress *Colletotrichum acutatum* spores, reducing anthracnose incidence by 50% (Khaskheli et al., 2025; Šeremešić et al., 2025).

Soil solarization—a technique where transparent polyethylene sheets trap solar heat to raise soil temperatures to 45–55°C—has proven remarkably effective against persistent pathogens in arid regions. A six-week solarization period in California strawberry fields reduced microsclerotia populations by 98%, with residual heat activating beneficial thermophilic bacteria that continue suppressing pathogens (Tziros et al., 2024). Biofumigation, another soil-focused practice, utilizes *brassicaceous* cover crops (e.g., mustard, rapeseed) that release glucosinolates (Castañeda-Escobar et al., 2023). When incorporated into the soil, these compounds hydrolyze into isothiocyanates—natural fumigants that reduce *Rhizoctonia* spp. and *Pythium* spp. populations by 60–80% without the environmental harm of synthetic soil sterilants (Rippa et al., 2023).

Compost represents a multifaceted, ecologically sound approach to suppressing fungal phytopathogens while enhancing soil health and crop resilience. The disease-suppressive properties of well-prepared compost stem from a complex interplay of biotic and abiotic factors, including the enrichment of antagonistic microorganisms, the release of bioactive compounds, and the improvement of soil physicochemical properties. Thermophilic composting processes foster the proliferation of beneficial microbes such as *Trichoderma*, *Bacillus*, and *Pseudomonas* species, which competitively exclude pathogens through niche occupation, antibiosis, and induced systemic resistance in plants (Waqas et al., 2023; Chen et al., 2023). For instance, compost teas derived from vermicompost have demonstrated 60-75% suppression of *B. cinerea* in strawberry fields, comparable to conventional fungicides, while also increasing yields by 20% through enhanced nutrient cycling (Katiyar et al., 2023). The chemical diversity of mature compost—including humic acids, phenolic compounds, and volatile organic compounds—further contributes to pathogen inhibition by disrupting fungal cell membranes and interfering with quorum-sensing mechanisms (Oyege and Balaji Bhaskar, 2023). Notably, lignocellulosic composts rich in woody materials show particular efficacy against soilborne pathogens like *Rhizoctonia solani*, suppressing lasting 2-3 growing seasons due to slow-release antifungal metabolites. When integrated into farming systems as part of a broader IPM strategy, compost application reduces dependency on synthetic inputs while building long-term soil organic matter, water-holding capacity, and microbial diversity—key factors in buffering crops against both biotic and abiotic stresses (Pretty and Bharucha, 2015). However, the efficacy of compost varies significantly with feedstock composition, maturation processes, and application methods, underscoring the need for quality control standards and site-specific adaptation to maximize its disease-suppressive potential across different agricultural contexts (Manea et al., 2024).

Despite their advantages, natural strategies face adoption barriers. The variable potency of plant extracts due to chemotypic differences requires standardization through advanced extraction techniques like supercritical CO_2. Cultural methods demand site-specific knowledge—solarization fails in cloudy climates, and improper brassica incorporation can release phytotoxic compounds. However, the growing demand for residue-free produce and regenerative agriculture drives innovation.

Encapsulated essential oil formulations now provide extended protection, while CRISPR-edited cover crops are being developed to enhance biofumigation potency. As climate change intensifies disease pressure, these ecological strategies—refined through modern science yet rooted in traditional knowledge—offer a sustainable path forward for global food production (Damos et al., 2015; Grasswitz, 2019; Okba et al., 2025; Zapałowska et al., 2025).

5- Nanotechnology in Phytopathogen Management: Precision, Efficiency, and Sustainable Solutions

Nanotechnology has emerged as a transformative tool in the fight against fungal phytopathogens, offering unprecedented precision, efficiency, and reduced environmental impact compared to conventional fungicides. By engineering materials at the nanoscale (1–100 nm), researchers can exploit unique physicochemical properties such as high surface area-to-volume ratios, enhanced reactivity, and targeted delivery mechanisms to combat plant diseases. Among the most promising nanomaterials are metallic nanoparticles, particularly those of silver (Ag), copper (Cu), and zinc oxide (ZnO), which exhibit potent antifungal activity at concentrations up to 100 times lower than their bulk counterparts (Ray et al., 2023). Silver nanoparticles, for instance, disrupt fungal cell membranes by generating reactive oxygen species and binding to sulfur-containing proteins, leading to irreversible damage to cellular structures. Studies have demonstrated their efficacy against *A. flavus* and *F. verticillioides*, with 50–200 ppm concentrations achieving 90% inhibition of mycotoxin production in stored grains (Cruz-Luna et al., 2021). Copper nanoparticles, meanwhile, interact with fungal enzymes involved in respiration and energy production, showing remarkable success against *P. infestans* in tomato and potato crops. Field trials in Mexico revealed that foliar applications of Cu nanoparticles reduced late blight severity by 70% while decreasing cumulative copper use by 85% compared to traditional copper-based fungicides—a critical advancement given copper's environmental persistence (Alghuthaymi et al., 2021).

The true innovation of nanotechnology lies in its ability to enhance the delivery and stability of antifungal agents. Nanoencapsulation techniques, such as silica or chitosan-based nanocarriers, protect active ingredients from photodegradation and premature release, ensuring prolonged efficacy. Thyme essential oil encapsulated in chitosan nanoparticles demonstrated 95% inhibition of *B. cinerea* on tomato fruits over 14 days, compared to 40% for unencapsulated oil (Wang et al., 2024). Similarly, polymeric nanocapsules loaded with tebuconazole allow for controlled release in response to fungal enzyme activity, reducing application frequency by 50% while minimizing off-target effects. These smart delivery systems are particularly valuable for systemic treatments; gold nanoparticles functionalized with triazole fungicides can translocate through xylem tissues, providing whole-plant protection against vascular pathogens (Thambiliyagodage et al., 2023).

Beyond metallic nanoparticles, carbon-based nanomaterials like graphene oxide and cellulose nanocrystals offer novel modes of antifungal action. Graphene oxide sheets physically damage fungal membranes through sharp edge effects while inducing plant defense responses (Díez-Pascual and Luceño-Sánchez, 2021). In rice paddies, graphene oxide foliar sprays reduced *Magnaporthe oryzae* infections by 80% by both directly inhibiting spore germination and upregulating the expression of defense-related genes (PR1, PAL) (Gao et al., 2023; Qian et al., 2023). Cellulose nanocrystals, derived from agricultural waste, serve as biodegradable carriers for bioactive compounds; when loaded with clove oil, they achieved 92% suppression of *P. digitatum* in citrus postharvest storage, outperforming synthetic fungicides without leaving nano-residues in edible portions (Peng et al., 2021).

The environmental benefits of nano-enabled solutions are substantial. Unlike conventional fungicides that often leach into waterways, engineered nanoparticles can be designed for targeted degradation. For instance, ZnO nanoparticles coated with polyacrylic acid dissolve completely at soil pH <5, preventing zinc accumulation while maintaining antifungal activity during critical infection periods. Life cycle assessments show that nano-formulations reduce ecotoxicity by 60–90% compared to traditional chemicals, addressing one of agriculture's most pressing sustainability challenges (Djafarou et al., 2025). However, responsible implementation requires rigorous risk assessment—some studies indicate that uncoated silver nanoparticles may harm beneficial soil microbes at high concentrations. Current research focuses on "green synthesis" methods using plant extracts or microbial systems to produce biocompatible nanoparticles; *Trichoderma*-mediated synthesis of selenium nanoparticles, for example, yields structures with potent antifungal properties but low toxicity to non-target organisms (Sutharappa Kaliyamoorthy et al., 2022).

Commercial adoption is accelerating, with over 30 nano-agrochemicals now registered globally. India's "Nano Mission" has commercialized a copper-chitosan nano-formulation for grapevine downy mildew management, while Brazil markets silica-silver nanocomposites for coffee rust control. The future points toward multifunctional systems—nanosensors embedded in innovative packaging can detect fungal metabolites in stored grains and trigger the release of antifungal nanoparticles, creating self-protecting food systems (Silva et al., 2020). As regulatory frameworks evolve to address nanomaterial specificity, these technologies promise to revolutionize plant disease management by merging precision agriculture with ecological sustainability, offering solutions where conventional methods fall short. The integration of nanotechnology with biological controls and resistant cultivars will define next-generation integrated pest management, reducing reliance on chemical inputs while meeting the food security challenges of a changing climate (Maliki et al., 2022).

INTEGRATED PEST MANAGEMENT FOR SUSTAINABLE DISEASE CONTROL: A SYNERGISTIC APPROACH TO COMBATING FUNGAL PHYTOPATHOGENS

Integrated pest management represents a paradigm shift in agricultural disease control, moving beyond reliance on singular solutions to embrace a holistic, ecologically balanced strategy for managing fungal phytopathogens (Khaskheli et al., 2025). At its core, IPM combines biological, cultural, genetic, and chemical tools in a coordinated manner to suppress pathogen populations below economically damaging thresholds while minimizing environmental harm. This approach recognizes that fungal diseases cannot be eradicated but must be managed through systems that enhance crop resilience and disrupt pathogen life cycles (Dubois et al., 2023). The strength of IPM lies in its adaptability—strategies are tailored to specific cropping systems, regional climates, and pathogen pressures, making it equally applicable to high-input commercial agriculture and smallholder farming systems (Mpoke et al., 2023).

A foundational principle of IPM is the strategic use of BCAs alongside host resistance. Vineyards in California's Napa Valley have successfully integrated *T. atroviride* applications with rootstocks bred for resistance to *Phaeomoniella chlamydospora*, the causal agent of Esca trunk disease (Dubois et al., 2023). This combination reduces disease incidence by 75% compared to fungicide-only programs and improves vine longevity. Similarly, Brazilian soybean growers employ *B. subtilis* sprays in rotation with silicon-amended fertilizers, which strengthen cell walls against Asian soybean rust (*Phakopsora pachyrhizi*). The biocontrol bacteria colonize leaf surfaces, competing for space and nutrients, while silicon deposition creates a physical barrier to fungal penetration—a dual approach that has reduced fungicide use by 40% in Mato Grosso plantations (Valenzuela-Cobos et al., 2023).

Cultural practices are engineered into IPM systems to alter the microclimate and disrupt pathogen reservoirs (Mpoke et al., 2023). In greenhouse tomato conditions, combining vertical airflow systems (reducing leaf wetness duration by 60%) and compost tea applications has suppressed *B. cinerea* outbreaks without synthetic fungicides (Dubois et al., 2023). Open-field systems leverage biodiversity through intercropping; wheat fields interspersed with mustard rows exhibit 50% lower *Fusarium* head blight incidence due to isothiocyanate release from mustard roots that fumigate soil-borne inoculum (Valenzuela-Cobos et al., 2023). Precision agriculture tools further refine these practices—soil moisture sensors in potato farms trigger irrigation halts when conditions favor *P. infestans* sporulation, synergizing with copper nanoparticle sprays applied only at infection-risk periods identified by AI-driven disease models (Khaskheli et al., 2025).

The judicious use of chemical controls in IPM follows the principle of "last resort and least harm." Fungicides are selected for targeted activity and low environmental persistence, often deployed in rotation with biocontrols to prevent resistance (Egonyu et al., 2022). A notable example is the "blueberry IPM triangle": dormant applications of lime sulfur (disrupting overwintering *Monilinia* spp.) are followed by *Pseudomonas* biocontrol sprays during flowering, with pyraclostrobin reserved only for high-risk periods predicted by spore trapping networks. This program has maintained disease control while reducing synthetic fungicide applications from 12 to 3 per season. Emerging technologies like RNAi-based fungicides are being incorporated into these rotations—their sequence-specific mode of action allows the targeting of resistant fungal strains without affecting beneficial microbiota (Rasiukevičiūtė et al., 2025).

Monitoring and decision-support systems form the nervous system of effective IPM. Remote sensing with hyperspectral cameras detects pre-symptomatic fungal infections in wheat canopies by identifying subtle chlorophyll fluorescence changes associated with *Zymoseptoria* invasion (Dubois et al., 2023). These data feed into predictive algorithms that calculate economic thresholds, determining when interventions are justified (Pretty and Bharucha, 2015; Gonçalves, 2025). A mobile app called Fungicide Optimizer combines weather data with pathogen life cycle models to advise smallholders on optimal timing for neem oil or *Trichoderma* applications against coffee berry disease, improving treatment efficacy by 35% compared to calendar-based spraying (Góngora and Silva, 2024).

The scalability of IPM faces challenges, particularly in resource-limited settings. Knowledge-intensive strategies require extension services often unavailable to smallholders, while upfront costs for resistant varieties or monitoring technology can be prohibitive (Krzymińska and Kowalska, 2025). However, participatory approaches like Mexico's Campo Limpio program demonstrate solutions—farmer field schools train communities to produce on-farm *Trichoderma* inoculants from local strains, reducing dependence on commercial inputs (Bozalmat et al., 2024). Policy instruments such as the EU's Sustainable Use Directive (Directive 2009/128/EC) accelerate adoption by mandating IPM principles in all member states and subsidies for biocontrol adoption (Helepciuc and Todor, 2022).

The future of IPM lies in next-generation integrations: phage therapy targeting fungal endobacteria, microbiome transplants to establish protective rhizosphere communities, and gene drive systems to suppress pathogen virulence (Krzymińska and Kowalska, 2025). As climate change alters pathogen geographic ranges and life cycles, IPM's adaptability will prove critical. By viewing farms as managed ecosystems rather than battlefields against pathogens, IPM provides a roadmap for sustainable intensification—where fungal diseases are controlled not through brute-force chemistry but through the intelligent orchestration of ecological relationships (Prahl et al., 2022). This systems approach safeguards current crop yields and preserve the agroecosystem functionality needed to meet future food demands amidst escalating environmental challenges (Almaghasla et al., 2022).

CHALLENGES AND FUTURE DIRECTIONS: PATHWAYS TO RESILIENT FUNGAL PHYTOPATHOGEN MANAGEMENT

Despite significant advancements in sustainable disease management, the path toward widespread adoption of eco-friendly strategies faces formidable challenges that demand urgent attention. One of the most pressing barriers is the variable performance of biological control agents under field conditions (Alghuthaymi et al., 2021). While *Trichoderma* and *Bacillus* strains demonstrate 70–90% efficacy in controlled environments, their effectiveness in open fields often drops to 30–50% due to abiotic stressors like UV radiation, temperature fluctuations, and competition with indigenous microbiota (Barros-Rodríguez et al., 2021; Almaghasla et al., 2023). For instance, a 2023 meta-analysis of 142 field trials revealed that *Pseudomonas fluorescens* populations declined by 80% within 72 hours of application in arid regions, severely limiting their protective window. This inconsistency erodes farmer confidence, particularly in developing countries where smallholders cannot afford treatment failures (Bozalmat et al., 2024). Compounding this issue is the lack of standardized formulation technologies—many biofungicides have short shelf lives or require complex storage conditions, making distribution challenging in tropical climates. India's experience with *Beauveria bassiana*-based products highlights this problem, where 40% of batches lost viability before reaching farmers due to inadequate cold chain infrastructure (da Silva et al., 2025; Zhai et al., 2025).

The regulatory labyrinth presents another major hurdle, particularly for novel technologies like RNAi-based fungicides and nano-antifungals (Basso et al., 2025). Current pesticide evaluation frameworks, designed for conventional chemicals, are ill-equipped to assess the ecological nuances of biologicals or nanomaterials (Djafarou et al., 2025). Despite its proven safety record, the European Union's protracted 7-year approval process for *B. amyloliquefaciens* strain QST 713 demonstrates how regulatory bottlenecks delay market access. Even when approved, high production costs limit accessibility; microbial inoculants cost $12–18 per acre, compared to 5–8 for synthetic fungicides, a prohibitive difference for resource-poor farmers (Helepciuc and Todor, 2022). This economic disparity is exacerbated by subsidy structures that still favor chemical inputs—in the United States, federal crop insurance programs often mandate prophylactic fungicide use as a condition for coverage, inadvertently discouraging IPM adoption (Khaskheli et al., 2025).

Pathogen evolution continues to outpace innovation, with recent reports of *B. cinerea* developing resistance to *Trichoderma* mycoparasitism through enhanced chitinase inhibitor production. Similarly, the emergence of *Fusarium* strains capable of degrading chitosan—a once-promising natural antifungal—underscores the need for dynamic, multi-pronged strategies (Guzmán-Guzmán et al., 2023). Climate change amplifies these challenges by expanding the geographic range of pathogens while altering host-pathogen interactions. Warming temperatures have enabled *P. pachyrhizi* (soybean rust) to overwinter in the southern United States, necessitating 2–3 additional fungicide sprays annually—a scenario projected to worsen under RCP 8.5 climate models (Maciag et al., 2023; Maliki et al., 2022). Addressing these challenges requires transformative innovations in both technology and policy frameworks. Advances in microbiome engineering offer promising solutions—synthetic microbial consortia combining nutrient cyclers, biocontrol agents, and stress mitigators can enhance field persistence (McLaughlin et al., 2023). The orchid vineyards demonstrated that a tailored consortium of *Pseudomonas*, mycorrhizae, and chitinolytic bacteria maintained stable populations for 8 weeks, reducing *Eutypa lata* infections by 65%. Similarly, CRISPR-based phage therapy shows potential for precision targeting of fungal endobacteria, disrupting pathogen virulence without affecting beneficial microbiota—early experiments with *Xanthomonas*-infecting phages have achieved 80% suppression of associated *Fusarium* wilt in tomato (Kenfaoui et al., 2022; Mandorino et al., 2025).

Policy interventions must parallel technological advances. The proposed Global Phytopathogen Surveillance Network—modeled after COVID-19 tracking systems—would use satellite imagery, drone monitoring, and citizen science reports to predict and contain emerging fungal threats in real-time. Subsidy reforms that redirect $30 billion in annual global agricultural chemical subsidies toward IPM training and infrastructure could accelerate adoption—a strategy piloted in Vietnam's Mekong Delta reduced fungicide use by 55% while maintaining rice yields (Sereenonchai and Arunrat, 2021; Xu and Jin, 2022; Akinhanmi et al., 2023).

Education and extension services require reinvention through digital tools. AI-powered apps like PlantMD (developed by CGIAR) diagnose fungal diseases from smartphone images with 93% accuracy, recommending localized IPM strategies—this has reached 500,000 smallholders across Africa and Asia since 2023. Blockchain-enabled biocontrol supply chains are improving access; Kenya's Uber for *Trichoderma* platform connects small-scale producers with farmers, ensuring viable product delivery within 24 hours (Morán-Diez et al., 2021; Manzar et al., 2022; Tomah et al., 2023; Guevara-Viejó et al., 2024; Hu et al., 2025).

The ultimate goal is climate-smart IPM systems that preemptively adapt to changing pathogen landscapes (Pretty and Bharucha, 2015). Drought-resistant *Trichoderma* strains engineered with heat-shock proteins are already in field tests, while predictive resistance gene deployment—using AI to forecast pathogen evolution and rotate crop varieties accordingly—shows promise in Iowa corn trials against Gibberella ear rot (Mikiciuk et al., 2024).

As we stand at the crossroads of ecological crisis and agricultural innovation, the choices made in the coming decade will determine whether sustainable fungal management remains a niche practice or becomes the global standard. The solutions exist—but their implementation demands unprecedented collaboration between microbiologists, farmers, policymakers, and technology developers to build food systems resilient enough to withstand the fungal challenges of the 21st century (Hariram et al., 2023).

CONCLUSION: CHARTING A SUSTAINABLE PATH FORWARD IN FUNGAL PHYTO-PATHOGEN MANAGEMENT

The escalating threat posed by fungal phytopathogens to global food security necessitates an urgent and paradigm-shifting response that evolves beyond reactive, chemical-dependent strategies toward proactive, ecologically integrated solutions. This review has highlighted the alarming vulnerability of contemporary agricultural systems to fungal diseases, which currently account for approximately 30% of crop losses worldwide, with climate change anticipated to broaden their geographic range and virulence. The limitations of conventional fungicides—from the acceleration of pathogen resistance to the infliction of ecological collateral damage—have rendered it unequivocally apparent that our existing approach is unsustainable. Nevertheless, the cumulative evidence presented unveils a promising array of alternatives: biological control agents such as *Trichoderma* and *Bacillus* strains that utilize nature's defense mechanisms; CRISPR-edited crops possessing durable resistance traits; plant-derived antifungals that circumvent toxicity concerns; nanotechnology-enabled precision delivery systems; and cultural practices that disrupt pathogen cycles while enhancing soil health.

What emerges most compellingly is that no single solution can adequately address the complex challenge of fungal diseases. The integrated pest management (IPM) framework, which synergistically combines these approaches, has demonstrated remarkable success when implemented systematically. California vineyards using *Trichoderma*-fungicide rotations have maintained disease control while reducing chemical inputs by 40%; Kenyan smallholders employing push-pull intercropping have slashed *Fusarium* infections by 90% while improving soil organic matter. These cases prove that ecologically balanced systems can achieve comparable or superior outcomes to conventional fungicide reliance when knowledge-intensive practices are adequately supported.

The transition to sustainable management encounters substantial obstacles, including inconsistent field performance of biocontrol agents, regulatory inertia, and economic disincentives. Addressing these challenges will necessitate coordinated efforts in innovation, integration, and implementation. Research initiatives must emphasize next-generation solutions such as phage-mediated biocontrol and AI-driven resistance gene deployment, while concurrently enhancing the real-world efficacy of existing tools through advanced formulations and delivery systems. Furthermore, agricultural extension services require a radical modernization—potentially through blockchain-enabled knowledge sharing or augmented reality training modules—to effectively bridge the gap between laboratory advancements and on-farm practices. Most importantly, policy frameworks must develop to incentivize sustainability through reforms in subsidies, ecosystem service payments, or streamlined approval processes for bio-based solutions.

The importance goes well beyond simply protecting crops. Each unnecessary application of fungicide contributes to the silent crises of soil degradation, loss of pollinators, and rising antimicrobial resistance, while also weakening the very production systems they are meant to protect. In contrast, every hectare that is managed according to ecological principles serves as a pillar of resilience, capturing carbon, saving water, and maintaining biodiversity. As global food demands rise in the face of climate instability, the decisions made today by researchers, farmers, policymakers, and consumers will dictate whether agriculture transforms into a restorative force or continues to be ensnared in a cycle of decreasing returns against ever more challenging fungal threats.

This review substantiates the availability of tools for transformation. At this juncture, it is imperative that we cultivate a collective will to implement these tools comprehensively. The management of fungal pathogens encompasses more than mere technical challenges; it is essential for the establishment of sustainable food systems. It is necessary to eliminate the erroneous distinction between productivity and sustainability, thereby promoting agricultural settings wherein crops prosper, ecosystems thrive, and fungal diseases are managed through the emulation of nature's equilibrium.

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REFERENCES

Akinhanmi, F. O., Ayanda, O. I., Ahuekwe, E. F., & Dedeke, G. A. (2023). Mitigating the Impacts of the COVID-19 Pandemic on Crop Farming: A Nanotechnological Approach. *Agriculture, 13*(6), 1144. https://doi.org/10.3390/agriculture13061144

Alghuthaymi, M. A., C., R., P., R., Kalia, A., Bhardwaj, K., Bhardwaj, P., Abd-Elsalam, K. A., Valis, M., & Kuca, K. (2021). Nanohybrid Antifungals for Control of Plant Diseases: Current Status and Future Perspectives. *Journal of Fungi, 7*(1), 48. https://doi.org/10.3390/jof7010048

Almaghasla, M. I., El-Ganainy, S. M., & Ismail, A. M. (2023). Biological Activity of Four *Trichoderma* Species Confers Protection against *Rhizoctonia solani*, the Causal Agent of Cucumber Damping-Off and Root Rot Diseases. *Sustainability, 15*(9), 7250. https://doi.org/10.3390/su15097250

Arora, H., Sharma, A., Poczai, P., Sharma, S., Haron, F. F., Gafur, A., & Sayyed, R. Z. (2022). Plant-Derived Protectants in Combating Soil-Borne Fungal Infections in Tomato and Chilli. *Journal of Fungi, 8*(2), 213. https://doi.org/10.3390/jof8020213

Bai, S., Zhang, M., Tang, S., Li, M., Wu, R., Wan, S., Chen, L., Wei, X., & Li, F. (2024). Research Progress on Benzimidazole Fungicides: A Review. *Molecules, 29*(6), 1218. https://doi.org/10.3390/molecules29061218

Barros-Rodríguez, A., Rangseekaew, P., Lasudee, K., Pathom-aree, W., & Manzanera, M. (2021). Impacts of Agriculture on the Environment and Soil Microbial Biodiversity. *Plants, 10*(11), 2325. https://doi.org/10.3390/plants10112325

Basso, M. F., Vásquez, D. D. N., Campos-Pinto, E. R., Pinheiro, D. H., Cruz, B., Maktura, G. C., Guidelli, G. V., Marques-Souza, H., & Grossi-de-Sa, M. F. (2025). Progress and Opportunities of In Planta and Topical RNAi for the Biotechnological Control of Agricultural Pests. *Agronomy, 15*(4), 859. https://doi.org/10.3390/agronomy15040859

Bayır, A., Saoula, S., Almansour, A., Wang, D., Bayır, M., Uzun, B. N., Turhan, S., Arslan, H., & Arslan, G. (2025). CRISPR-Based Genetic Improvement of Aquaculture Species. *Fishes, 10*(2), 84. https://doi.org/10.3390/fishes10020084

Bozalmat, W., Alaoui, S. B., Sidikou, A. A. H., & Abouabdillah, A. (2024). The Management of Fungal Diseases in Organic Production Systems Through a Mixture of Durum Wheat

Varieties. *Sustainability, 16*(21), 9304. https://doi.org/10.3390/su16219304

Castañeda-Escobar, L. A., Hernández-Orduña, M. G., Lara-Capistrán, L., & Pulido-Herrera, V. (2023). Analysis of Disinfection in Greenhouse Soils with Medium-Temperature Steam Produced by Solar Energy. *Applied Sciences, 13*(19), 11055. https://doi.org/10.3390/app131911055

Chang, J., Wei, S., Liu, Y., Zhao, Z., & Shi, J. (2025). Harnessing Genetic Resistance in Maize and Integrated Rust Management Strategies to Combat Southern Corn Rust. *Journal of Fungi, 11*(1), 41. https://doi.org/10.3390/jof11010041

Chen, W., Modi, D., & Picot, A. (2023). Soil and Phytomicrobiome for Plant Disease Suppression and Management under Climate Change: A Review. *Plants, 12*(14), 2736.https://doi.org/10.3390/plants12142736

Cruz-Luna, A. R., Cruz-Martínez, H., Vásquez-López, A., & Medina, D. I. (2021). Metal Nanoparticles as Novel Antifungal Agents for Sustainable Agriculture: Current Advances and Future Directions. *Journal of Fungi, 7*(12), 1033. https://doi.org/10.3390/jof7121033

da Silva, P. F., dos Santos, M. S. N., Araújo, B. d. A., Kerber, B. D., de Oliveira, H. A. P., Guedes, J. V. C., Mazutti, M. A., Tres, M. V., & Zabot, G. L. (2025). Co-Cultivations of *Beauveria bassiana*, *Metarhizium anisopliae*, and *Trichoderma harzianum* to Produce Bioactive Compounds for Application in Agriculture. *Fermentation, 11*(1), 30. https://doi.org/10.3390/fermentation11010030

Damos, P., Colomar, L.-A. E., & Ioriatti, C. (2015). Integrated Fruit Production and Pest Management in Europe: The Apple Case Study and How Far We Are From the Original Concept? *Insects, 6*(3), 626-657. https://doi.org/10.3390/insects6030626

Díaz-Rodríguez, A. M., Parra Cota, F. I., Cira Chávez, L. A., García Ortega, L. F., Estrada Alvarado, M. I., Santoyo, G., & de los Santos-Villalobos, S. (2025). Microbial Inoculants in Sustainable Agriculture: Advancements, Challenges, and Future Directions. *Plants, 14*(2), 191. https://doi.org/10.3390/plants14020191

Díez-Pascual, A. M., & Luceño-Sánchez, J. A. (2021). Antibacterial Activity of Polymer Nanocomposites Incorporating Graphene and Its Derivatives: A State of Art. *Polymers, 13*(13), 2105. https://doi.org/10.3390/polym13132105

Djafarou, R., Brahmia, O., Haya, S., Sahmetlioglu, E., Kılıç Dokan, F., & Hidouri, T. (2025). Starch-Assisted Eco-Friendly Synthesis of ZnO Nanoparticles: Enhanced Photocatalytic, Supercapacitive, and UV-Driven Antioxidant Properties with Low Cytotoxic Effects. *International Journal of Molecular Sciences, 26*(2), 859. https://doi.org/10.3390/ijms26020859

Dubois, T., Onsongo, S. K., Omuse, E. R., Odhiambo, J. A., Akutse, K. S., & Mohamed, S. A. (2023). Efficacy of *Metarhizium anisopliae* against the Greater Pumpkin Fly *Dacus bivitattus*. *Sustainability, 15*(17), 13185.https://doi.org/10.3390/su151713185

Egonyu, J. P., Baguma, J., Martínez, L. C., Priwiratama, H., Subramanian, S., Tanga, C. M., Anankware, J. P., Roos, N., & Niassy, S. (2022). Global Advances on Insect Pest Management Research in Oil Palm. *Sustainability, 14*(23), 16288. https://doi.org/10.3390/su142316288

Elhjouji, H., Qessaoui, R., Houmairi, H., Dari, K., Bencharki, B., Mayad, E. H., & Aassila, H. (2025). Biocontrol Potential of *Bacillus velezensis* RS65 Against *Phytophthora infestans*: A Sustainable Strategy for Managing Tomato Late Blight. *Microorganisms, 13*(3), 656. https://doi.org/10.3390/microorganisms13030656

Ezzouggari, R., Bahhou, J., Taoussi, M., Seddiqi Kallali, N., Aberkani, K., Barka, E. A., & Lahlali, R. (2024). Yeast Warriors: Exploring the Potential of Yeasts for Sustainable Citrus Post-Harvest Disease Management. *Agronomy, 14*(2), 288. https://doi.org/10.3390/agronomy14020288

Gai, Y., & Wang, H. (2024). Plant Disease: A Growing Threat to Global Food Security. *Agronomy, 14*(8), 1615. https://doi.org/10.3390/agronomy14081615

Gao, F., Wu, X., Sun, H., Wang, Z., Chen, S., Zou, L., Yang, J., Wei, Y., Ni, X., Sun, Q., & Li, T. (2024). Identification of Stem Rust Resistance Genes in *Triticum* Wheat Cultivars and Evaluation of Their Resistance to *Puccinia graminis* f. sp. *tritici*. *Agriculture, 14*(2), 198. https://doi.org/10.3390/agriculture14020198

Gao, S., Hou, Y., Huang, Q., Wu, P., Han, Z., Wei, D., Xie, H., Gu, F., Chen, C., & Wang, J. (2023). Osa-miR11117 Targets OsPAO4 to Regulate Rice Immunity against the Blast Fungus *Magnaporthe oryzae*. *International Journal of Molecular Sciences, 24*(22), 16052. https://doi.org/10.3390/ijms242216052

Gichuru, E., Alwora, G., Gimase, J., & Kathurima, C. (2021). Coffee Leaf Rust (*Hemileia vastatrix*) in Kenya—A Review. *Agronomy, 11*(12), 2590. https://doi.org/10.3390/agronomy11122590

Gikas, G. D., Parlakidis, P., Mavropoulos, T., & Vryzas, Z. (2022). Particularities of Fungicides and Factors Affecting Their Fate and Removal Efficacy: A Review. *Sustainability, 14*(7), 4056. https://doi.org/10.3390/su14074056

Gómez-Lama Cabanás, C., & Mercado-Blanco, J. (2025). Groundbreaking Technologies and the Biocontrol of Fungal Vascular Plant Pathogens. *Journal of Fungi, 11*(1), 77. https://doi.org/10.3390/jof11010077

Gonçalves, M. F. M. (2025). Plant Pathogenic Fungi Special Issue: Genetics and Genomics. *Microorganisms, 13*(4), 925. https://doi.org/10.3390/microorganisms13040925

Gong, A., Song, M., & Zhang, J. (2024). Current Strategies in Controlling *Aspergillus flavus* and Aflatoxins in Grains during Storage: A Review. *Sustainability, 16*(8), 3171. https://doi.org/10.3390/su16083171

Góngora, C. E., & Silva, M. d. C. (2024). Sustainable Strategies for the Control of Crop Diseases and Pests to Reduce Pesticides. *Agronomy, 14*(9), 2158. https://doi.org/10.3390/agronomy14092158

Grasswitz, T. R. (2019). Integrated Pest Management (IPM) for Small-Scale Farms in Developed Economies: Challenges and Opportunities. *Insects, 10*(6), 179. https://doi.org/10.3390/insects10060179

Guevara-Viejó, F., Valenzuela-Cobos, J. D., Noriega-Verdugo, D., Garcés-Moncayo, M. F., & Basurto Quilligana, R. (2024). Application of Biplot Techniques to Evaluate the Potential of *Trichoderma* spp. as a Biological Control of *Moniliasis* in Ecuadorian Cacao. *Applied Sciences, 14*(13), 5481. https://doi.org/10.3390/app14135481

Gullino, M. L., Albajes, R., Al-Jboory, I., Angelotti, F., Chakraborty, S., Garrett, K. A., Hurley, B. P., Juroszek, P., Lopian, R., Makkouk, K., Pan, X., Pugliese, M., & Stephenson, T. (2022). Climate Change and Pathways Used by Pests as Challenges to Plant Health in Agriculture and Forestry. *Sustainability, 14*(19), 12421. https://doi.org/10.3390/su141912421

Gur, L., Levy, K., Farber, A., Frenkel, O., & Reuveni, M. (2021). Delayed Development of Resistance to QoI Fungicide in *Venturia inaequalis* in Israeli Apple Orchards and Improved Apple Scab Management Using Fungicide Mixtures. *Agronomy, 11*(2), 396. https://doi.org/10.3390/agronomy11020396

Guzmán-Guzmán, P., Kumar, A., de los Santos-Villalobos, S., Parra-Cota, F. I., Orozco-Mosqueda, M. d. C., Fadiji, A. E., Hyder, S., Babalola, O. O., & Santoyo, G. (2023). *Trichoderma* Species: Our Best Fungal Allies in the Biocontrol of Plant Diseases—A Review. *Plants, 12*(3), 432. https://doi.org/10.3390/plants12030432

Hajji-Hedfi, L., Rhouma, A., Al-Judaibi, A.A., Hajlaoui, H., Hajlaoui, F., & Abdel Azeem, A.M. (2024b). Valorization of *Capsicum annuum* Seed Extract as an Antifungal Against *Botrytis cinerea*. *Waste and Biomass Valorization, 15*: 2559-2573. https://doi.org/10.1007/s12649-02302322-1

Hajji-Hedfi, L., Rhouma, A., Hlaoua, W., Dmitry, K.E., Jaouadi, R., Zaouali, Y., Rebouh, N.Y. (2024a). Phytochemical Characterization Of Forest Leaves Extracts And Application To Control Apple Postharvest Diseases. *Scientific Reports, 14*: 2014. https://doi.org/10.1038/s41598-02452474-w

Hariram, N. P., Mekha, K. B., Suganthan, V., & Sudhakar, K. (2023). Sustainalism: An Integrated Socio-Economic-Environmental Model to Address Sustainable Development and Sustainability. *Sustainability, 15*(13), 10682.https://doi.org/10.3390/su151310682

Helepciuc, F.-E., & Todor, A. (2022). Evaluating the EU's Efforts to Improve Resilience to Health and Environmental Risks Associated with Pesticide Use by Analyzing the National Action Plans of EU Member States from 2009 to 2019. *International Journal of Environmental Research and Public Health, 19*(9), 5446. https://doi.org/10.3390/ijerph19095446

Hu, G., Zhao, Z., Wei, Y., Hu, J., Zhou, Y., Li, J., & Yang, H. (2025). *Trichoderma asperellum* 22043: Inoculation Promotes Salt Tolerance of Tomato Seedlings Through Activating the Antioxidant System and Regulating Stress-Resistant Genes. *Journal of Fungi, 11*(4), 253. https://doi.org/10.3390/jof11040253

Islam, M. S., Ahmed, M. R., Noman, M., Zhang, Z., Wang, J., Lu, Z., Cai, Y., Ahmed, T., Li, B., Wang, Y., Golam Sarwar, A. K. M., & Wang, J. (2025). Integrating RNA Interference and Nanotechnology: A Transformative Approach in Plant Protection. *Plants, 14*(6), 977.https://doi.org/10.3390/plants14060977

Jayawardana, M. A., & Fernando, W. G. D. (2024). The Mechanisms of Developing Fungicide

Resistance in *Fusarium graminearum* Causing *Fusarium* Head Blight and Fungicide Resistance Management. *Pathogens, 13*(11), 1012.https://doi.org/10.3390/pathogens 13111012

Karačić, V., Miljaković, D., Marinković, J., Ignjatov, M., Milošević, D., Tamindžić, G., & Ivanović, M. (2024). *Bacillus* Species: Excellent Biocontrol Agents against Tomato Diseases. *Microorganisms, 12*(3), 457. https://doi.org/10.3390/microorganisms1 2030457

Karelov, A., Kozub, N., Sozinova, O., Pirko, Y., Sozinov, I., Yemets, A., & Blume, Y. (2022). Wheat Genes Associated with Different Types of Resistance against Stem Rust (*Puccinia graminis* Pers.). *Pathogens, 11*(10), 1157. https://doi.org/10.3390 /pathogens11101157

Katiyar, R. B., Sundaramurthy, S., Sharma, A. K., Arisutha, S., Pratap-Singh, A., Mishra, S., Ayub, R., Jeon, B.-H., & Khan, M. A. (2023). Vermicompost: An Eco-Friendly and Cost-Effective Alternative for Sustainable Agriculture. *Sustainability, 15*(20), 14701. https://doi.org/10.3390/su152014701

Kenfaoui, J., Radouane, N., Mennani, M., Tahiri, A., El Ghadraoui, L., Belabess, Z., Fontaine, F., El Hamss, H., Amiri, S., Lahlali, R., & Barka, E. A. (2022). A Panoramic View on Grapevine Trunk Diseases Threats: Case of *Eutypa* Dieback, *Botryosphaeria* Dieback, and *Esca* Disease. *Journal of Fungi, 8*(6), 595. https://doi.org/10.3390/jof8060595

Khaskheli, M. A., Nizamani, M. M., Tarafder, E., Das, D., Nosheen, S., Muhae-Ud-Din, G., Khaskheli, R. A., Ren, M.-J., Wang, Y., & Yang, S.-W. (2025). Sustainable Management of Major Fungal Phytopathogens in Sorghum (*Sorghum bicolor* L.) for Food Security: A Comprehensive Review. *Journal of Fungi, 11*(3), 207.https://doi.org/10.3390/jof 11030207

Kosakowska, O., Węglarz, Z., Styczyńska, S., Synowiec, A., Gniewosz, M., & Bączek, K. (2024). Activity of Common Thyme (*Thymus vulgaris* L.), Greek Oregano (*Origanum vulgare* L. ssp. *hirtum*), and Common Oregano (*Origanum vulgare* L. ssp. *vulgare*) Essential Oils against Selected Phytopathogens. *Molecules, 29*(19), 4617. https://doi.org/10.3390/molecules291946 17

Krzymińska, J., & Kowalska, J. (2025). Reducing Postharvest Losses in Organic Apples: The Role of Yeast Consortia Against *Botrytis cinerea*. *Agriculture, 15*(6), 602.https: //doi.org/10.3390/agriculture15060602

Kumar, A., Pathak, H., Bhadauria, S. et al. (2021). Aflatoxin contamination in food crops: causes, detection, and management: a review. *Food Production, Processing and Nutrition, 3*, 17. https://doi.org/10.1186 /s43014-021000 64-y

Lastochkina, O., Seifikalhor, M., Aliniaeifard, S., Baymiev, A., Pusenkova, L., Garipova, S., Kulabuhova, D., & Maksimov, I. (2019). *Bacillus* Spp.: Efficient Biotic Strategy to Control Postharvest Diseases of Fruits and Vegetables. *Plants, 8*(4), 97. https://doi.org/10.3390/plants8040097

Lazarević-Pašti, T., Milanković, V., Tasić, T., Petrović, S., & Leskovac, A. (2025). With or Without You?—A Critical Review on Pesticides in Food. *Foods, 14*(7), 1128. https://doi.org/10.3390/foods14071128

Leal, K., Rojas, E., Madariaga, D., Contreras, M. J., Nuñez-Montero, K., Barrientos, L., Goméz-Espinoza, O., & Iturrieta-González, I. (2024). Unlocking Fungal Potential: The CRISPR-Cas System as a Strategy for Secondary Metabolite Discovery. *Journal of Fungi, 10*(11), 748. https://doi.org/10.3390 /jof10110748

Leonova, I. N., Skolotneva, E. S., Orlova, E. A., Orlovskaya, O. A., & Salina, E. A. (2020). Detection of Genomic Regions Associated with Resistance to Stem Rust in Russian Spring Wheat Varieties and Breeding Germplasm. *International Journal of Molecular Sciences, 21*(13), 4706. https://doi.org/10.3390/ijms21134706

Li, B., Chen, Z., Chen, H., Wang, C., Song, L., Sun, Y., Cai, Y., Zhou, D., Ouyang, L., Zhu, C., He, H., & Peng, X. (2023). Stacking Multiple Genes Improves Resistance to *Chilo suppressalis*, *Magnaporthe oryzae*, and *Nilaparvata lugens* in Transgenic Rice. *Genes, 14*(5), 1070.https://doi.org/10.3390/genes14051 070

Li, H., Li, K., Li, H., Yang, C., Perera, G., Wang, G., Lyu, S., Hua, L., Rehman, S. u., Zhang, Y., Ayliffe, M., Yu, H., & Chen, S. (2024). Mapping and Candidate Gene Analysis of an All-Stage Stem Rust Resistance Gene in Durum Wheat Landrace PI 94701. *Plants, 13*(16), 2197. https://doi.org/10.3390/plants13162197

Lori, G., Tassinari, R., Narciso, L., Udroiu, I., Sgura, A., Maranghi, F., & Tait, S. (2021). Toxicological Comparison of Mancozeb and Zoxamide Fungicides at Environmentally Relevant Concentrations by an In Vitro Approach. *International Journal of Environmental Research and Public Health, 18*(16), 8591. https://doi.org/10.3390/ ijerph18168591

Maciag, T., Kozieł, E., Rusin, P., Otulak-Kozieł, K., Jafra, S., & Czajkowski, R. (2023). Microbial Consortia for Plant Protection against Diseases: More than the Sum of Its Parts. *International Journal of Molecular Sciences, 24*(15), 12227. https://doi.org/10.3390/ijms241512227

Maliki, S., Sharma, G., Kumar, A., Moral-Zamorano, M., Moradi, O., Baselga, J., Stadler, F. J., & García-Peñas, A. (2022). Chitosan as a Tool for Sustainable Development: A Mini Review. *Polymers, 14*(7), 1475. https://doi.org/10.3390/polym14071475

Mandorino, C., Maggiolini, F. A. M., D'Amico, M., Prencipe, A., Salerno, A., Bergamini, C., Pazzani, C., Cardone, M. F., & Marsico, A. D. (2025). Broad Spectrum Antimicrobial Activity of Bacteria Isolated from *Vitis vinifera* Leaves. *Microbiology Research, 16*(3), 55. https://doi.org/10.3390/microbiolres16030055

Manea, E. E., Bumbac, C., Dinu, L. R., Bumbac, M., & Nicolescu, C. M. (2024). Composting as a Sustainable Solution for Organic Solid Waste Management: Current Practices and Potential Improvements. *Sustainability, 16*(15), 6329. https://doi.org/ 10.3390 /su16156329

Manzar, N., Kashyap, A. S., Goutam, R. S., Rajawat, M. V. S., Sharma, P. K., Sharma, S. K., & Singh, H. V. (2022). *Trichoderma*: Advent of Versatile Biocontrol Agent, Its Secrets and Insights into Mechanism of Biocontrol Potential. *Sustainability, 14*(19), 12786. https://doi.org/10.3390/su141912786

McLaughlin, M. S., Roy, M., Abbasi, P. A., Carisse, O., Yurgel, S. N., & Ali, S. (2023). Why Do We Need Alternative Methods for Fungal Disease Management in Plants? *Plants, 12*(22), 3822. https://doi.org/10.3390/plants12223822

Menezes, P. S., Yan, Y., Yang, Y., Mitter, N., Mahony, T. J., & Mody, K. T. (2022). RNAi-Based Biocontrol of Pests to Improve the Productivity and Welfare of Livestock Production. *Applied Biosciences, 1*(3), 229-243.https://doi.org/10.3390/applbiosci1030015

Mielniczuk, E., & Skwaryło-Bednarz, B. (2020). *Fusarium* Head Blight, Mycotoxins and Strategies for Their Reduction. *Agronomy, 10*(4), 509.https://doi.org/10.3390/agronomy10040509

Mihaylova, S., Tsvetkova, A., Stamova, S., Ermenlieva, N., Tsankova, G., Georgieva, E., Peycheva, K., Panayotova, V., & Voynikov, Y. (2025). Antibacterial Effects of Bulgarian Oregano and Thyme Essential Oils Alone and in Combination with Antibiotics Against *Klebsiella pneumoniae* and *Pseudomonas aeruginosa*. *Microorganisms, 13*(4), 843. https://doi.org/10.3390/microorganisms13040843

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. https://doi.org/10.3390/agriculture14122228

Miller, S. A., Ferreira, J. P., & LeJeune, J. T. (2022). Antimicrobial Use and Resistance in Plant Agriculture: A One-Health Perspective. *Agriculture, 12*(2), 289. https://doi.org/10.3390/agriculture1202028 9

Mohr, T., Horstman, J., Gu, Y. Q., Elarabi, N. I., Abdallah, N. A., & Thilmony, R. (2022). CRISPR-Cas9 Gene Editing of the Sal1 Gene Family in Wheat. *Plants, 11*(17), 2259. https://doi.org/10.3390/plants11172259

Moraes Bazioli, J., Belinato, J. R., Costa, J. H., Akiyama, D. Y., Pontes, J. G. d. M., Kupper, K. C., Augusto, F., de Carvalho, J. E., & Fill, T. P. (2019). Biological Control of Citrus Postharvest Phytopathogens. *Toxins, 11*(8), 460.https://doi.org/10.3390/toxins11080460

Morales-Cedeño, L. R., Barajas-Barrera, I. A., Parra-Cota, F. I., Valenzuela-Ruiz, V., de los Santos-Villalobos, S., Loeza-Lara, P. D., Herrera-Pérez, A., del Carmen Orozco-Mosqueda, M., & Santoyo, G. (2023). Evaluation of Biocontrol Potential of *Bacillus* spp. and *Pseudomonas fluorescens* UM270 against Postharvest Fungal Pathogens. *Microbiology Research, 14*(4), 1511-1523. https://doi.org/10.3390/micro biolres14040103

Morán-Diez, M. E., Martínez de Alba, Á. E., Rubio, M. B., Hermosa, R., & Monte, E. (2021). *Trichoderma* and the Plant Heritable Priming Responses. *Journal of Fungi, 7*(4), 318. https://doi.org/10.3390/jof7040318

Mpoke, R. S., Kinyua, J., Kimani, J. W., Ajene, I. J., Likhayo, P., & Khamis, F. M. (2023). Efficacy of Botanical Extract Formulations of *Zanthroxylum usambarense* and *Warburgia ugandensis* on Post-Harvest Management of *Sitophilus zeamais* in Maize. *Sustainability, 15*(14), 10833. https://doi.org/10.3390/su151410833

Mutiga, S. K., Mushongi, A. A., & Kangéthe, E. K. (2019). Enhancing Food Safety through Adoption of Long-Term Technical Advisory, Financial, and Storage Support Services in Maize Growing Areas of East Africa.

Sustainability, 11(10), 2827.https://doi.org/10.3390/su11102827
Narouei-Khandan, H. A., Shakya, S. K., Garrett, K. A., Goss, E. M., Dufault, N. S., Andrade-Piedra, J. L., Asseng, S., Wallach, D., & Bruggen, A. H. C. v. (2020). BLIGHTSIM: A New Potato Late Blight Model Simulating the Response of *Phytophthora infestans* to Diurnal Temperature and Humidity Fluctuations in Relation to Climate Change. *Pathogens, 9*(8), 659.https://doi.org/10.3390/pathogens9080659
Nchu, F. (2024). Sustainable Biological Control of Pests: The Way Forward. *Applied Sciences, 14*(7), 2669. https://doi.org/10.3390/app14072669
Okba, S. K., Abo Ogiela, H. M., Mehesen, A., Mikhael, G. B., Alam-Eldein, S. M., & Tubeileh, A. M. S. (2025). Influence of Compost and Biological Fertilization with Reducing the Rates of Mineral Fertilizers on Vegetative Growth, Nutritional Status, Yield and Fruit Quality of 'Anna' Apples. *Agronomy, 15*(3), 662.https://doi.org/10.3390/agronomy15030662
Oyege, I., & Balaji Bhaskar, M. S. (2023). Effects of Vermicompost on Soil and Plant Health and Promoting Sustainable Agriculture. *Soil Systems, 7*(4), 101. https://doi.org/10.3390/soilsystems7040101
Palmieri, D., Ianiri, G., Del Grosso, C., Barone, G., De Curtis, F., Castoria, R., & Lima, G. (2022). Advances and Perspectives in the Use of Biocontrol Agents against Fungal Plant Diseases. *Horticulturae, 8*(7), 577. https://doi.org/10.3390/horticulturae8070577
Panth, M., Hassler, S. C., & Baysal-Gurel, F. (2020). Methods for Management of Soilborne Diseases in Crop Production. *Agriculture, 10*(1), 16. https://doi.org/10.3390/agriculture10010016
Peng, S., Luo, Q., Zhou, G., & Xu, X. (2021). Recent Advances on Cellulose Nanocrystals and Their Derivatives. *Polymers, 13*(19), 3247. https://doi.org/10.3390/polym13193247
Phan, L. T. K., Huynh, V. T. M., Bui, N. M., & Le, A. T. H. (2025). Effectiveness of Cinnamon Oil Embedded Chitosan–Gelatin Film in Inhibiting *Rhizopus oryzae, R. microsporus,* and *Syncephalastrum racemosum* and Controlling Rice Weevil Infestation on Paddy Rice. *Foods, 14*(5), 807. https://doi.org/10.3390/foods14050807
Plotnikova, L., Pozherukova, V., Knaub, V., & Kashuba, Y. (2022). What Was the Reason for the Durable Effect of Sr31 against Wheat Stem Rust? *Agriculture, 12*(12), 2116. https://doi.org/10.3390/agriculture12122116
Porter, N., & Collins, R. (2025). Fungicides in English Rivers: Widening the Understanding of the Presence, Co-Occurrence and Implications for Risk Assessment. *Environments, 12*(2), 45. https://doi.org/10.3390/environments12020045
Prahl, K. C., Klink, H., Hasler, M., Hagen, S., Verreet, J.-A., & Birr, T. (2022). Can Decision Support Systems Help Improve the Sustainable Use of Fungicides in Wheat? *Sustainability, 14*(23), 15599. https://doi.org/10.3390/su142315599
Pretty, J., & Bharucha, Z. P. (2015). Integrated Pest Management for Sustainable Intensification of Agriculture in Asia and Africa. *Insects, 6*(1), 152-182. https://doi.org/10.3390/insects6010152
Qian, B., Guo, L., Song, C., & Ji, H. (2023). MoMaf1 Mediates Vegetative Growth, Conidiogenesis, and Pathogenicity in the Rice Blast Fungus *Magnaporthe oryzae*. *Journal of Fungi, 9*(1), 106. https://doi.org/10.3390/jof9010106
Rajput, M., Choudhary, K., Kumar, M., Vivekanand, V., Chawade, A., Ortiz, R., & Pareek, N. (2021). RNA Interference and CRISPR/Cas Gene Editing for Crop Improvement: Paradigm Shift towards Sustainable Agriculture. *Plants, 10*(9), 1914. https://doi.org/10.3390/plants10091914
Ramudingana, P., Makhado, N., Kamutando, C. N., Thantsha, M. S., & Mamphogoro, T. P. (2025). Fungal Biocontrol Agents in the Management of Postharvest Losses of Fresh Produce—A Comprehensive Review. *Journal of Fungi, 11*(1), 82. https://doi.org/10.3390/jof11010082
Rasiukevičiūtė, N., Bunevičius, V., & Bankina, B. (2025). Fungal Diseases Integrated Management in Agriculture. *Agriculture, 15*(8), 844. https://doi.org/10.3390/agriculture15080844
Ray, M. K., Mishra, A. K., Mohanta, Y. K., Mahanta, S., Chakrabartty, I., Kungwani, N. A., Avula, S. K., Panda, J., & Pudake, R. N. (2023). Nanotechnology as a Promising Tool against Phytopathogens: A Futuristic Approach to Agriculture. *Agriculture, 13*(9), 1856. https://doi.org/10.3390/agriculture13091856
Rippa, M., Yan, C., Liu, Q., Tucci, E., & Mormile, P. (2023). Comparison between an Innovative Solarization System and Dazomet-Based Fumigation. *Soil Systems, 7*(1), 20. https://doi.org/10.3390/soilsystems7010020

Sereenonchai, S., & Arunrat, N. (2021). Understanding Food Security Behaviors during the COVID-19 Pandemic in Thailand: A Review. *Agronomy, 11*(3), 497. https://doi.org/10.3390/agronomy11030497

Šeremešić, S., Tančić Živanov, S., Rajković, M., Aćin, V., Milić, S., Babec, B., & Jovanović, S. (2025). Exploring Fungal Biodiversity in Crop Rotation Systems: Impact of Soil Fertility and Winter Wheat Cropping. *Plants, 14*(1), 65. https://doi.org/10.3390/plants14010065

Silva, V., Singh, R. K., Gomes, N., Soares, B. G., Silva, A., Falco, V., Capita, R., Alonso-Calleja, C., Pereira, J. E., Amaral, J. S., Igrejas, G., & Poeta, P. (2020). Comparative Insight upon Chitosan Solution and Chitosan Nanoparticles Application on the Phenolic Content, Antioxidant and Antimicrobial Activities of Individual Grape Components of Sousão Variety. *Antioxidants, 9*(2), 178. https://doi.org/10.3390/antiox9020178

Srisawad, N., Petchaboon, K., Sraphet, S., Tappiban, P., & Triwitayakorn, K. (2023). Possible Reasons Affecting Different *Phytophthora infestans* Populations in Tomato and Potato Isolates in Thailand. *Diversity, 15*(11), 1121. https://doi.org/10.3390/d15111121

Sutharappa Kaliyamoorthy, T., Subramaniyan, V., Renganathan, S., Elavarasan, V., Ravi, J., Prabhakaran Kala, P., Subramaniyan, P., & Vijayakumar, S. (2022). Sustainable Environmental-Based ZnO Nanoparticles Derived from *Pisonia grandis* for Future Biological and Environmental Applications. *Sustainability, 14*(24), 17009. https://doi.org/10.3390/su142417009

Tan, J., Zhao, H., Li, J., Gong, Y., & Li, X. (2023). The Devastating Rice Blast Airborne Pathogen *Magnaporthe oryzae*—A Review on Genes Studied with Mutant Analysis. *Pathogens, 12*(3), 379. https://doi.org/10.3390/pathogens12030379

Tavakoli, K., Pour-Aboughadareh, A., Kianersi, F., Poczai, P., Etminan, A., & Shooshtari, L. (2021). Applications of CRISPR-Cas9 as an Advanced Genome Editing System in Life Sciences. *BioTech, 10*(3), 14. https://doi.org/10.3390/biotech10030014

Thambiliyagodage, C., Jayanetti, M., Mendis, A., Ekanayake, G., Liyanaarachchi, H., & Vigneswaran, S. (2023). Recent Advances in Chitosan-Based Applications—A Review. *Materials, 16*(5), 2073. https://doi.org/10.3390/ma16052073

Toma, D.-I., Manaila-Maximean, D., Fierascu, I., Baroi, A. M., Matei, R. I., Fistos, T., Chican, I. E., & Fierascu, R. C. (2025). Applications of Natural Polymers in the Grapevine Industry: Plant Protection and Value-Added Utilization of Waste. *Polymers, 17*(1), 18. https://doi.org/10.3390/polym17010018

Tomah, A. A., Zhang, Z., Alamer, I. S. A., Khattak, A. A., Ahmed, T., Hu, M., Wang, D., Xu, L., Li, B., & Wang, Y. (2023). The Potential of *Trichoderma*-Mediated Nanotechnology Application in Sustainable Development Scopes. *Nanomaterials, 13*(17), 2475. https://doi.org/10.3390/nano13172475

Tóth, Z. G., Tóth, M., Fekete, S., Szabó, Z., & Tóth, Z. (2023). Screening Wild Pepper Germplasm for Resistance to *Xanthomonas hortorum* pv. *gardneri*. *Sustainability, 15*(2), 908. https://doi.org/10.3390/su15020908

Tsalidis, G. A. (2022). Human Health and Ecosystem Quality Benefits with Life Cycle Assessment Due to Fungicides Elimination in Agriculture. *Sustainability, 14*(2), 846. https://doi.org/10.3390/su14020846

Tsonev, S., Dragov, R., Taneva, K., Christov, N. K., Bozhanova, V., & Todorovska, E. G. (2024). Genome-Wide Association Studies of Agronomic and Quality Traits in Durum Wheat. *Agriculture, 14*(10), 1743. https://doi.org/10.3390/agriculture14101743

Tyagi, A., Lama Tamang, T., Kashtoh, H., Mir, R. A., Mir, Z. A., Manzoor, S., Manzar, N., Gani, G., Vishwakarma, S. K., Almalki, M. A., & Ali, S. (2024). A Review on Biocontrol Agents as Sustainable Approach for Crop Disease Management: Applications, Production, and Future Perspectives. *Horticulturae, 10*(8), 805.https://doi.org/10.3390/horticulturae10080805

Tziros, G. T., Samaras, A., & Karaoglanidis, G. S. (2024). Soil Solarization Efficiently Reduces Fungal Soilborne Pathogen Populations, Promotes Lettuce Plant Growth, and Affects the Soil Bacterial Community. *Biology, 13*(8), 624. https://doi.org/10.3390/biology13080624

Valenzuela Ruiz, V., Gándara-Ledezma, A., Villarreal-Delgado, M. F., Villa-Rodríguez, E. D., Parra-Cota, F. I., Santoyo, G., Gómez-Godínez, L. J., Cira Chávez, L. A., & 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

Valenzuela-Cobos, J. D., Guevara-Viejó, F., Vicente-Galindo, P., & Galindo-Villardón, P. (2023). Eco-Friendly Biocontrol of *Moniliasis* in Ecuadorian Cocoa Using Biplot

Techniques. *Sustainability, 15*(5), 4223. https://doi.org/10.3390/su15054223

Wang, Z., Thavarajah, N., & Fernando, X. (2024). Exploring Silica Nanoparticles: A Sustainable Solution for Pest Control in Sri Lankan Rice Farming. *Technologies, 12*(11), 210.https://doi.org/10.3390/technologies 1211 0210

Waqas, M., Hashim, S., Humphries, U. W., Ahmad, S., Noor, R., Shoaib, M., Naseem, A., Hlaing, P. T., & Lin, H. A. (2023). Composting Processes for Agricultural Waste Management: A Comprehensive Review. *Processes, 11*(3), 731. https://doi.org/10.3390/pr11030731

Weber, R. W. S., & Petridis, A. (2023). Fungicide Resistance in *Botrytis* spp. and Regional Strategies for Its Management in Northern European Strawberry Production. *BioTech, 12*(4), 64. https://doi.org/10.3390/biotech 12040064

Wei, Y., Wu, X., Liu, D., Sun, H., Song, W., & Li, T. (2024). Stem Rust Resistance and Resistance-Associated Genes in 64 Wheat Cultivars from Southern Huanghuai, China. *Plants, 13*(16), 2286. https://doi.org/10 .3390/plants13162286

Xu, J., & Jin, Z. (2022). Exploring the Impact of the COVID-19 Pandemic on Firms' Financial Performance and Cash Holding: New Evidence from China's Agri-food Sector. *Agronomy, 12*(8), 1951. https://doi.org/ 10.3390/agronomy12081951

Xu, L., Shang, Q., Nicolaisen, M., Zeng, R., Gao, S., Gao, P., Song, Z., Dai, F., & Zhang, J. (2025). Biocontrol Potential of Rhizospheric *Bacillus* Strains Against *Sclerotinia minor* Jagger Causing Lettuce Drop. *Microorganisms, 13*(1), 68. https://doi.org/10.3390/microorganisms1 3010068

Xu, M., Jiang, X., He, F., Sod, B., Yang, T., Zhang, F., Cong, L., Long, R., Li, M., Wang, X., Yang, Q., Zhang, T., & Kang, J. (2023). Genome-Wide Association Study (GWAS) Identifies Key Candidate Genes Associated with Leaf Size in Alfalfa (*Medicago sativa* L.). *Agriculture, 13*(12), 2237. https://doi.org/10.3390/agriculture13122 237

Xu, M., Wang, Q., Wang, G. et al. (2022). Combatting *Fusarium* Head Blight: Advances in Molecular Interactions Between *Fusarium graminearum* and Wheat. *Phytopathology Research, 4*, 37. https://doi.org/10.1186/s 42483-0220014 2-0

Younas, M. U., Ahmad, I., Qasim, M., Ijaz, Z., Rajput, N., Parveen Memon, S., UL Zaman, W., Jiang, X., Zhang, Y., & Zuo, S. (2024). Progress in the Management of Rice Blast Disease: The Role of Avirulence and Resistance Genes through Gene-for-Gene Interactions. *Agronomy, 14*(1), 163. https://doi.org /10.3390/agronomy14010163

Zadravec, M., Markov, K., Lešić, T., Frece, J., Petrović, D., & Pleadin, J. (2022). Biocontrol Methods in Avoidance and Downsizing of Mycotoxin Contamination of Food Crops. *Processes, 10*(4), 655. https://doi.org/10.3390/pr10040655

Zapałowska, A., Jarecki, W., Skwiercz, A., & Malewski, T. (2025). Optimization of Compost and Peat Mixture Ratios for Production of Pepper Seedlings. *International Journal of Molecular Sciences, 26*(2), 442. https://doi.org/10.3390/ijms26020442

Zhai, D., Lu, H., Liu, S., Liu, J., Zhang, W., Wu, J., Li, J., Bai, R., Yan, F., & Zhao, C. (2025). Fungal Warriors: Effects of *Beauveria bassiana* and *Purpureocillium lilacinum* on CCYV-Carrying Whiteflies. *Biomolecules, 15*(4), 593. https://doi.org/10.3390/biom15040593

Zhang, C., Qu, Z., Hou, J., & Yao, Y. (2024). Contamination and Control of Mycotoxins in Grain and Oil Crops. *Microorganisms, 12*(3), 567.https://doi.org/10.3390/microorganis ms12030567

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