



(REVIEW ARTICLE)



HARNESSING THE PLANT MICROBIOME: ENGINEERING SYNTHETIC MICROBIAL CONSORTIA FOR BROAD-SPECTRUM FUNGAL PATHOGEN SUPPRESSION

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ABSTRACT

Fungal pathogens represent one of the most significant threats to global food security, causing devastating yield losses in major crops worldwide. Traditional biological control strategies have relied predominantly on single-strain inoculants such as *Trichoderma* and *Bacillus* species. While effective under controlled conditions, these single-agent approaches frequently exhibit inconsistent performance under field conditions due to poor colonization, limited functional redundancy, and susceptibility to environmental fluctuations. The engineering of synthetic microbial communities (SynComs)—carefully designed multi-strain consortia that mimic natural microbiome assemblies—offers a transformative alternative. This review critically examines the shift from single biocontrol agents to rationally designed SynComs for broad-spectrum fungal pathogen suppression. We evaluate the synergistic antifungal mechanisms that emerge from multi-strain interactions, including complementary siderophore production, enhanced volatile organic compound profiles, and the induction of systemic resistance through integrated plant immune signaling. The critical challenges of delivery formulation—encompassing encapsulation technologies and seed coating strategies—are assessed alongside the persistent obstacles of field persistence and interactions with native soil microbiota. Our analysis reveals that well-structured SynComs consistently outperform single strains and random assemblages, with cross-kingdom (bacterial-fungal) consortia demonstrating particularly robust disease suppression. However, significant gaps remain in understanding SynCom dynamics under field conditions, long-term community stability, and the ecological consequences of introducing synthetic consortia into agricultural soils. We identify future directions, including machine learning-guided SynCom design, precision delivery systems, and the integration of SynComs into integrated pest management frameworks.

Keywords: Synthetic Microbial Communities, Syncoms, Biological Control, Fungal Pathogens, Plant Microbiome Engineering, Induced Systemic Resistance, Microbial Consortia Formulation

1 INTRODUCTION

Fungal diseases of agricultural crops impose an immense burden on global food production, with major pathogens such as *Fusarium*, *Rhizoctonia*, *Verticillium*, and *Phytophthora* species responsible for billions of dollars in annual yield losses (Pradhan et al., 2022). The Green Revolution's reliance on chemical fungicides and resistant cultivars has reached

diminishing returns, while the emergence of fungicide-resistant pathogen populations and growing environmental and regulatory pressures necessitate sustainable alternatives (Shayanthan et al., 2022).

Biological control using beneficial microorganisms has long been championed as an environmentally friendly strategy for plant disease management. The classical approach has centered on single-strain inoculants—most notably *Trichoderma* spp. for their mycoparasitic capabilities and *Bacillus* spp. for their antibiotic-producing prowess (Poveda, 2022). These agents have demonstrated efficacy in controlled environments and have been commercialized successfully. However, as Martins et al. (2023) observed, maintaining consistent results across field applications remains a formidable challenge. Single strains often fail to compete with indigenous soil microbes, exhibit poor rhizosphere colonization, and lack the functional redundancy necessary to cope with environmental variability (Pradhan et al., 2022).

The limitations of single-strain approaches have catalyzed a paradigm shift toward the engineering of synthetic microbial communities (SynComs). As defined by Wang et al. (2023), SynComs are carefully constructed assemblages of microbial species designed to produce desired microbiome functions. Unlike random mixtures, well-designed SynComs are structured according to ecological principles, leveraging complementary functional traits and cooperative interactions to achieve robust, reproducible disease suppression (Martins et al., 2023). The rapid advancement of cultivation-independent methods and reduced sequencing costs have considerably improved our understanding of microbial ecology in the plant environment, making it possible to engineer consortia that more closely mimic the structure and function of natural protective microbiomes (Shayanthan et al., 2022).

This review provides a comprehensive and critical examination of the emerging field of SynCom-based biological control of fungal pathogens. We trace the evolution from single-agent biocontrol to multi-strain consortia, evaluate the synergistic mechanisms underlying enhanced antifungal activity, and assess the critical challenges of delivery formulation, field persistence, and ecological integration. Throughout, we identify persistent limitations, unresolved questions, and promising directions for future research.

2 MAIN REVIEW

2.1 From Single Strains to Synthetic Communities: A Paradigm Shift

The transition from single-strain biocontrol agents to synthetic microbial communities represents a fundamental reconceptualization of how beneficial microbes can be deployed for plant protection. Single-strain approaches operate on a reductionist premise: identify a single organism with potent antifungal activity and deliver it in high numbers to the target environment. While this strategy has yielded commercial successes, its limitations are increasingly apparent.

Pradhan et al. (2022) comprehensively reviewed the principles, applications, and challenges of SynComs for combating biotic stresses, emphasizing that single-strain inoculants often fail to establish stable populations in the rhizosphere due to competition with native microbiota and sensitivity to environmental conditions. The inconsistency of single-strain performance under field conditions is a major problem, as inoculants frequently fail to compete with indigenous soil microbes across different climatic conditions (Shayanthan et al., 2022).

SynComs address these limitations through several mechanisms. First, functional redundancy—the presence of multiple strains capable of performing similar functions—ensures that the loss of one strain does not compromise overall community performance. Second, niche complementation allows different strains to occupy distinct ecological niches, reducing competition and enhancing overall community stability. Third, cooperative interactions among community members can generate emergent antifungal activities that exceed the sum of individual contributions (Du et al., 2021). As noted by Martins et al. (2023), well-structured assemblages are more likely to lead to a stable SynCom that thrives under environmental stressors as compared with the classical selection of single microbial activities or taxonomy.

The construction of effective SynComs requires careful consideration of community assembly rules. Ecological theories suggest that plant-associated microbial communities have a defined phylogenetic organization structured by general community assembly rules. Using machine learning, researchers can study these rules and target microbial functions that generate desired plant phenotypes (Emmenegger et al., 2023). Emmenegger et al. (2023) demonstrated this approach by screening 136 randomly assembled synthetic communities of five bacterial strains each, identifying microbiota community patterns important for plant protection.

Table 1: Comparison of Single-Strain Biocontrol Agents and Synthetic Microbial Communities (SynComs) for Fungal Pathogen Suppression

Feature	Single-Strain Biocontrol Agents	Synthetic Microbial Communities (SynComs)
Functional Redundancy	Low; loss of strain compromises efficacy	High; multiple strains provide backup functions
Niche Occupation	Single niche; susceptible to competition	Multiple niches; enhanced competitive fitness
Synergistic Effects	Absent	Present; emergent antifungal activities
Environmental Robustness	Poor; inconsistent field performance	Enhanced; stable under environmental stressors
Mechanism Diversity	Limited to single mechanism	Multiple complementary mechanisms
Design Complexity	Low	High; requires ecological and functional knowledge
Regulatory Pathway	Established	Evolving; novel challenges
Commercial Availability	Widely available	Emerging
Representative Examples	<i>Trichoderma harzianum</i> , <i>Bacillus subtilis</i>	Cross-kingdom bacterial-fungal consortia

2.2 Synergistic Antifungal Mechanisms in Multi-Strain Consortia

The enhanced efficacy of SynComs over single strains derives from the convergence of multiple complementary antifungal mechanisms. These mechanisms operate at different levels—from direct pathogen inhibition to systemic plant defense activation—and their combination creates a multi-layered defense that is more robust than any single mechanism alone (Zhou et al., 2022).

Table 2: Key Synergistic Mechanisms in Multi-Strain Microbial Consortia for Fungal Suppression

Mechanism	Description	Synergistic Advantage in SynComs	Representative Studies
Siderophore Production	Iron-chelating compounds deprive pathogens of essential nutrient	Complementary siderophore profiles create more comprehensive iron depletion	Pradhan et al. (2022); Yin et al. (2022)
Volatile Organic Compounds	Antifungal VOCs inhibit pathogen growth	Co-culture stimulates production of VOCs not produced in monoculture	Poveda (2022)
Induced Systemic Resistance	Activation of plant immune system	Multiple ISR-inducing strains create more robust and durable resistance	Martins et al. (2023); Wang et al. (2023)
Mycoparasitism	Direct attack on fungal pathogens	Multiple mycoparasitic strains with complementary activities	Poveda (2022)
Antibiosis	Production of antimicrobial compounds	Combined antibiotic profiles broaden pathogen spectrum	Xun et al. (2023); Yin et al. (2022)
Cross-Kingdom Interactions	Bacterial-fungal cooperation	Enhanced plant immunity and microbial interactions	Zhou et al. (2022)

2.3 Complementary Siderophore Production

Iron competition is a fundamental mechanism of microbial antagonism. Many beneficial microbes produce siderophores—high-affinity iron-chelating compounds that sequester ferric iron from the environment. By depriving fungal pathogens of this essential nutrient, siderophore-producing bacteria can significantly suppress pathogen growth (Yin et al., 2022).

In SynComs, the combination of strains with different siderophore profiles can create a more comprehensive iron-withholding strategy. Different siderophores have varying affinities for iron and different recognition profiles, and their combined production can more effectively deplete the available iron pool. Studies have demonstrated that siderophore-based rhizobacterial consortia can effectively mitigate biotic stresses in various crops (Pradhan et al., 2022).

2.3.1 Enhanced Volatile and Non-Volatile Metabolite Production

The co-culture of different microbial strains can stimulate the production of antifungal metabolites that are not produced, or are produced at lower levels, in monoculture. This phenomenon of synergistic metabolite production has been documented for various combinations, particularly involving *Trichoderma* and *Bacillus* species.

The combined use of *Trichoderma* and beneficial bacteria, mainly *Bacillus* and *Pseudomonas*, has been extensively studied for the development of microbial synergistic bio-inoculants (Poveda, 2022). These combinations produce a wide diversity of volatile and non-volatile secondary metabolites. Co-cultured fermentation of *Trichoderma*–*Bacillus* combinations has shown the synergistic production of effective oomycetocidal metabolites. These mechanisms, combined with competition, have been applied in *Trichoderma*–*Bacillus* consortia for reducing *Fusarium oxysporum* disease in garlic (Poveda, 2022).

2.3.2 Induced Systemic Resistance (ISR)

Perhaps the most sophisticated mechanism of SynCom-mediated disease suppression is the induction of systemic resistance in the host plant. Unlike direct antagonism, ISR involves the activation of the plant's own immune system, preparing it to respond more effectively to pathogen attack.

Beneficial microbes can trigger ISR through the activation of jasmonic acid and ethylene signaling pathways, priming the plant for enhanced defense responses (Martins et al., 2023). The combination of multiple ISR-inducing strains in a SynCom can create a more robust and durable resistance response than single strains. Studies have demonstrated that a consortium of *Paenibacillus* sp. strain B2 and *Arthrobacter* spp. strain AA induces effective and durable systemic wheat-induced resistance against *Zymoseptoria tritici* (Wang et al., 2023). Similarly, synergistic effects of a root-endophytic *Trichoderma* fungus and *Bacillus* have been shown to activate early root colonization and defense against *Verticillium longisporum* in rapeseed (Martins et al., 2023).

2.3.3 Cross-Kingdom Synergies

A particularly exciting development is the construction of cross-kingdom SynComs incorporating both bacteria and fungi. Zhou et al. (2022) demonstrated that cross-kingdom (fungi and bacteria) SynComs were most effective in suppressing *Fusarium* wilt disease in tomato compared to fungal or bacterial SynComs alone. This effect was underpinned by a combination of molecular mechanisms related to plant immunity and microbial interactions contributed by both communities. The formulation and manipulation of SynComs for functional complementation constitute a beneficial strategy in controlling soil-borne disease (Zhou et al., 2022). Yin et al. (2022) similarly demonstrated that SynComs derived from rhizosphere soil could protect wheat against soilborne fungal pathogens, providing the potential for improving crop resilience by creating SynComs.

2.4 Delivery Formulations: Encapsulation and Seed Coating

The translation of SynCom efficacy from laboratory to field depends critically on the development of robust delivery formulations that protect microbial viability during storage and application, and facilitate effective colonization of the target environment (Shayanthan et al., 2022).

2.4.1 Encapsulation Technologies

Encapsulation provides a protective matrix that shields microbial cells from environmental stresses including desiccation, UV radiation, and chemical exposure. Alginate-based encapsulation has been extensively studied for agricultural biologicals. Recent work has demonstrated that alginate formulations can extend the stability of sensitive organisms to one year for both on-shelf and on-seed storage. The addition of a hydrophobic coating to the formulation protected cells from agricultural chemicals, permitting at least three months of survival on shelf and on seed (Martins et al., 2023).

Microfluidics-based encapsulation represents an emerging technology for the production of uniform, controlled-release formulations. Novel microfluidics-based formulations for the delivery of microbial control agents in soil have been developed, offering precise control over capsule size and release kinetics (Shayanthan et al., 2022).

2.4.2 Seed Coating

Seed coating has emerged as the most scalable and farmer-friendly delivery method for microbial inoculants. Research on seed coatings with beneficial microbes shows reduced fungicide leaching and maintained efficacy. Seed coating with nanofiber-immobilized rhizobacteria has been shown to improve bacterial survival on seeds stored for 30 days and contribute to successful colonization of the plant root (Pradhan et al., 2022).

A seed coating containing a synthetic consortium of beneficial *Bacillus* microbes has been developed to manage Fusarium wilt disease, demonstrating improved seedling growth and disease suppression. The introduction of *Trichoderma guizhouense* to maize and watermelon seed microbiomes by seed coating led to a decrease in disease occurrence and an increase in plant growth (Martins et al., 2023).

2.4.3 Carrier Materials and Formulation Optimization

The choice of carrier material significantly influences the viability and efficacy of microbial inoculants. Biopolymer-based formulations for *Trichoderma* have been evaluated for shelf-life and persistence in controlling oilseed seed and soil-borne diseases (Poveda, 2022). The encapsulation of beneficial rhizobacteria in nanofibers has been explored for soybean seed bioinoculants (Pradhan et al., 2022).

The optimization of formulation parameters—including carrier composition, protective additives, and processing conditions—is essential for maximizing microbial survival and activity. However, as noted by Martins et al. (2023), ensuring microbial colonization and long-term plant phenotype stability remains one of the challenges to overcome with SynComs, as the synthetic community may change over time with microbial horizontal gene transfer and retained mutations.

2.5 Field Persistence and Interactions with Native Soil Microbiota

The performance of SynComs under field conditions is governed by complex interactions with the resident soil microbiome, environmental factors, and the host plant. These interactions can either enhance or diminish the efficacy of introduced consortia (Pradhan et al., 2022).

2.5.1 Competition with Native Microbiota

Inconsistent production under field conditions is a major problem as inoculants often fail to compete with indigenous soil microbes under different climatic conditions (Shayanathan et al., 2022). The introduction of a SynCom into an established microbial community can trigger competitive interactions that may reduce the survival and activity of inoculated strains.

However, SynComs may offer advantages over single strains in this context. The functional redundancy and niche complementation within a well-designed consortium can enhance competitive fitness, enabling the community to establish more effectively than any single strain alone (Martins et al., 2023). A SynCom could be a great alternative to overcome the problems associated with conventional inoculants as it can incorporate different microbial communities that can partly mimic the functional environment of those microorganisms (Pradhan et al., 2022).

2.5.2 Community Stability and Long-Term Persistence

The long-term stability of introduced SynComs is a critical concern. Studies have shown that inoculated strains can persist in soil even after 20 years of inoculation, raising both environmental and regulatory concerns (Martins et al., 2023). The persistence of introduced strains can have unintended ecological consequences, including disruption of native microbial communities and horizontal gene transfer.

The stability of SynComs depends on multiple factors, including the compatibility of community members, their ability to colonize plant tissues, and the selective pressures exerted by the environment (Du et al., 2021). Xun et al. (2023) demonstrated an innovative approach to constructing stable and minimal microbiota for sustainable agriculture by identifying core rhizobacteria through progressive dilution and rhizodepositional attraction strategies. The optimized synthetic microbiota surpassed single strains and randomly formed microbiota in Fusarium suppression capability.

2.5.3 Host Plant Effects

The host plant plays an active role in shaping the rhizosphere microbiome through the release of root exudates. Different plant genotypes can selectively promote or inhibit specific microbial taxa, influencing the establishment and function of introduced SynComs (Du et al., 2021). Understanding these plant-microbe interactions is essential for designing SynComs that are compatible with target crop varieties.

3 FUTURE PERSPECTIVES

Several emerging trends and unresolved questions promise to shape the future of SynCom-based biological control of fungal pathogens.

Machine learning-guided SynCom design represents a transformative direction. The integration of artificial intelligence with high-throughput screening could dramatically accelerate the identification of optimal SynCom compositions, reducing the reliance on trial-and-error approaches. Machine learning algorithms can analyze complex microbial interaction networks and predict community compositions that maximize antifungal activity while maintaining stability.

Precision delivery systems are needed to enhance the survival, establishment, and activity of SynComs in the field. Advances in encapsulation technologies, including microfluidics-based formulations and nanofiber immobilization, offer opportunities for controlled-release formulations that protect microbial viability and facilitate targeted delivery to the rhizosphere. The development of stimuli-responsive formulations that release microbes in response to specific environmental cues could further enhance efficacy.

Understanding SynCom dynamics under field conditions remains a critical research priority. Most SynCom studies are conducted under controlled conditions that do not replicate the complexity of agricultural soils. Long-term field trials are needed to assess the persistence, stability, and ecological impact of introduced SynComs. The integration of metagenomic and metatranscriptomic approaches can provide insights into the functional dynamics of SynComs in situ.

Integration with integrated pest management frameworks offers a pathway for the practical adoption of SynComs. Rather than replacing chemical fungicides entirely, SynComs could be deployed as complementary tools within integrated disease management strategies. The compatibility of SynComs with reduced-risk fungicides and other biological control agents should be systematically evaluated.

Regulatory frameworks for SynComs are needed to facilitate commercial development and registration. The regulatory pathway for multi-strain products is more complex than for single strains, requiring demonstration of safety, efficacy, and stability for each component and for the consortium as a whole. The development of harmonized international standards for SynCom registration would accelerate commercialization.

Ecological risk assessment must accompany the deployment of SynComs. The introduction of synthetic consortia into agricultural soils can have unintended consequences, including disruption of native microbial communities, horizontal gene transfer, and the emergence of new pathogen strains. Comprehensive risk assessment frameworks are needed to ensure the safe and sustainable use of SynComs.

Cross-kingdom SynCom development represents a particularly promising frontier. The demonstrated superiority of bacterial-fungal consortia over single-kingdom SynComs suggests that future efforts should prioritize the design of integrated communities that harness complementary mechanisms from both bacterial and fungal biocontrol agents.

4 CONCLUSION

The engineering of synthetic microbial communities represents a paradigm shift in biological control of fungal pathogens, moving beyond the limitations of single-strain inoculants toward multi-strain consortia that harness the full functional potential of the plant microbiome. This review has demonstrated that well-designed SynComs consistently outperform single strains and random assemblages through complementary antifungal mechanisms, enhanced environmental robustness, and the induction of systemic plant resistance.

The synergistic mechanisms operating within SynComs—including complementary siderophore production, enhanced volatile metabolite profiles, and integrated ISR activation—create multi-layered defense systems that are more effective and durable than any single mechanism alone. Cross-kingdom SynComs incorporating both bacteria and fungi have shown particular promise, with studies demonstrating superior suppression of *Fusarium* wilt disease through the combination of plant immunity and microbial interaction pathways.

The translation of SynCom efficacy from laboratory to field depends critically on robust delivery formulations. Encapsulation technologies and seed coating strategies have advanced substantially, with alginate-based formulations extending microbial stability and hydrophobic coatings protecting cells from agricultural chemicals. However, the challenges of field persistence and competition with native soil microbiota remain significant obstacles to widespread adoption.

Looking forward, the convergence of machine learning-guided design, precision delivery systems, and integrated pest management frameworks promises to accelerate the development and deployment of SynComs for sustainable agriculture. As the field matures, synthetic microbial communities are poised to become indispensable tools for protecting crops from fungal pathogens, reducing reliance on chemical fungicides, and enhancing global food security in an era of climate change and growing environmental pressures.

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