Fungal Allies in Agriculture: A Functional Categorization and Mechanistic Analysis of Beneficial Fungi in Horticultural and Farming Systems

1. A Functional Taxonomy of Beneficial Fungi in Agricultural Ecosystems

1.1 Introduction: The 'Fungal Kingdom' in Agri-Horticultural Systems

Within agricultural and horticultural ecosystems, the Fungi kingdom represents a diverse and foundational component of soil biodiversity, essential for critical ecosystem functions.[1] While often perceived through the narrow lens of either culinary resources or plant pathogens, the vast majority of fungi perform beneficial roles vital for soil health, carbon cycling, nutrient availability, and overall plant productivity.[2] A nuanced understanding of these beneficial fungi, moving beyond simple identification and toward functional roles, is essential for developing sustainable and resilient agricultural systems.[5]

For the practical purposes of horticulture and farming, beneficial fungi can be classified into distinct categories based on their *ecological niche*—that is, *where* they live—and their *primary function* relative to the plant, soil, and broader agroecosystem.[1]

1.2 The Primary Functional Guilds

Analysis reveals four primary functional guilds of beneficial fungi relevant to crop production [4]:

1. **Mycorrhizal Fungi (The Symbiotic Nutrient Foragers):** These fungi form a direct, mutualistic partnership, or symbiosis, with the roots of *living* plants, acting as an extension of the root system.[4]
2. **Endophytic Fungi (The Internal Plant Allies):** This group is defined by its niche. These fungi live asymptomatically *inside* the tissues of host plants (e.g., roots, stems, and leaves), often providing profound benefits from within.[8]
3. **Saprotrophic Fungi (The External Decomposers):** These fungi are the ecosystem's primary recyclers. They acquire nutrients by secreting enzymes to decompose *dead* organic matter, such as leaf litter, crop residues, and compost.[4]
4. **Biocontrol Fungi (The Specialized Protectors):** This is a *functional* designation for fungi whose primary applied role is the suppression of agricultural pests. This group includes entomopathogenic (insect-killing), mycoparasitic (fungus-killing), and nematicidal (nematode-killing) fungi.[5]

The following table provides a comprehensive functional taxonomy to clarify these categories, their ecological roles, and their key functions in agriculture.

1.3 Table 1: A Functional Taxonomy of Beneficial Fungi in Agriculture

Primary Category	**Sub-type / Key Example**	**Ecological Niche (Where they live)**	**Primary Function (What they do)**	**Key Genera**
Mycorrhizal Fungi	Arbuscular Mycorrhizae (AMF)	Obligate symbiont; colonizes root cortex cells of living plants.	Nutrient/water exchange for plant carbon; soil aggregation (Glomalin).	*Glomus*, *Rhizophagus*
	Ectomycorrhizae (EMF)	Symbiont; forms external sheath *around* living plant	Nutrient/water exchange; "mines" organic N for	*Pisolithus*, *Tuber*

		roots.	woody plants.	
Endophytic Fungi	Plant Growth-Promoting (PGPF)	Lives asymptomatically *within* all plant tissues (roots, stems, leaves).	Phytohormone production (auxins, gibberellins); stress tolerance; nutrient solubilization.	*Fusarium*, *Penicillium*
	Biocontrol Endophytes	Lives asymptomatically *within* plant tissues.	Induces Systemic Resistance (ISR); produces anti-herbivore or anti-pathogen metabolites.	*Beauveria*, *Trichoderma*
Saprotrophic Fungi	Decomposers (e.g., White-rot)	Decomposer of *dead* organic matter in soil and compost.	Lignin & cellulose breakdown; nutrient mineralization; soil building.	*Agaricus*, *Coprinus*
Biocontrol Fungi	Entomopathogenic	Parasite of insects.	Kills insect pests by penetrating the cuticle.	*Metarhizium*, *Beauveria*
	Mycoparasitic	Parasite of other fungi.	Kills fungal pathogens via parasitism, antibiosis, and competition.	*Trichoderma*
	Nematicidal	Parasite/preda	Kills	*Purpureocilliu*

		tor of nematodes.	plant-parasitic nematodes via trapping, egg parasitism, or toxins.	*m*

1.4 Functional Overlap: A Core Concept

It is critical to understand that these functional categories are not rigid or mutually exclusive. A single fungal species or even strain can, and often does, occupy multiple niches and perform several functions simultaneously. This "functional duality" is a key component of their value.[13]

For example, fungi in the genus *Trichoderma* are celebrated as a premier **mycoparasitic** biocontrol agent.[14] However, they are also aggressive **saprotrophs** (decomposers) in the soil [11] and are well-documented as **endophytes** that colonize root tissues to promote growth and induce plant defenses.[14]

Similarly, *Beauveria bassiana* and *Metarhizium anisopliae* are famously **entomopathogenic** (insect-killing).[17] Yet, modern research confirms they are also highly effective **endophytes** that live systemically within plant tissues, providing protection from the inside.[10] Therefore, a fungus is defined not just by its species, but by the role it is playing in a specific context.

2. The Mycorrhizal Symbiosis: Engineering the Plant-Soil Interface

2.1 Defining the "Mycorrhiza": A Foundational Symbiosis

The "mycorrhiza," or "fungus-root" [19], represents a foundational mutualism that has been co-evolving with plants for over 400 million years.[8] This symbiosis is ubiquitous, formed by approximately 90% of all land plants.[4]

The relationship is a "barter" system: the plant, through photosynthesis, supplies the fungus with carbon (sugars), and in return, the fungus acts as a vast subterranean foraging network, delivering minerals, nutrients, and water to the plant roots.[4] This creates an intricate information and nutrient exchange system, often called the "wood wide web," that links plants and soil.[22]

2.2 Arbuscular Mycorrhizal Fungi (AMF): The Universal Symbionts

Arbuscular Mycorrhizal Fungi (AMF) are the most common and agriculturally significant type, forming associations with approximately 80% of terrestrial plants, including the majority of horticultural vegetables (e.g., tomatoes, corn), row crops, and grasses.[11]

- **Niche:** AMF are *obligate symbionts*, meaning they cannot complete their life cycle without a living host plant.[29]
- **Mechanism:** AMF hyphae penetrate the root and grow *into* the root cortex cells, penetrating the cell membrane (but not the cytoplasm) to form highly branched, tree-like structures called "arbuscules".[30] These arbuscules are the primary sites of the bidirectional nutrient exchange. The fungi also form "vesicles," which are storage structures within the root.[19]
- **Horticultural Exceptions:** A critical consideration for farm management is that a few major crop families do *not* form mycorrhizal associations. These include the **Brassicaceae** (e.g., cabbage, broccoli, canola, mustard, and radish) and the **Chenopodiaceae** (e.g., spinach, beets, and chard).[11] Applying AMF inoculants to these crops will have no effect.

2.3 Ectomycorrhizal Fungi (EMF): The Woody Crop Specialists

Ectomycorrhizal Fungi (EMF) are dominant symbionts for many woody plants, accounting for about 3% of mycorrhizal associations.[19]

- **Niche:** In contrast to AMF, EMF hyphae do *not* penetrate the root cells. Instead, they form a thick fungal "sheath" or "mantle" that completely *surrounds* the root tip. From this sheath, hyphae grow *between* the root cells to form a network known as the "Hartig net," which is the site of nutrient exchange.[19]
- **Horticultural Relevance:** This category is crucial for many horticultural tree crops,

including nut trees (e.g., pecan, hazelnut [19]), and in forestry (e.g., pines).[4]
- **AMF vs. EMF Functional Distinction:** The choice between AMF and EMF inoculants is not interchangeable; it is entirely crop-dependent. Furthermore, EMF possess a specialized function that AMF lack, which is derived from their saprotrophic ancestors: the ability to "mine" nutrients, particularly nitrogen, directly from complex organic matter.[32] While AMF are superior at "foraging" for mineral nutrients in the soil solution, EMF can secrete enzymes to decompose organic matter and unlock the nutrients (especially N) bound within it, giving them a significant competitive advantage in nutrient-poor forest soils.[32]

2.4 Core Function: Nutrient Mobilization and Uptake (The Phosphorus Pathway)

The primary benefit of mycorrhizae is the vast enhancement of nutrient uptake. The fungal hyphal network is significantly finer than plant root hairs [11] and extends far beyond the root's "nutrient depletion zone" (the area of soil immediately surrounding the root from which nutrients have been removed).[28]

This "virtual root system" [21] is especially critical for the uptake of **Phosphorus (P)**, a key macronutrient that is highly immobile in soil.[22] The fungi are not just passive pipes; they actively facilitate P acquisition, particularly from *insoluble* sources that would otherwise be unavailable to the plant.[35] For example, in one study, inoculation with the AMF *G. intraradices* increased the phosphorus concentration in plants grown in P-deficient soil by 107%.[36]

This symbiosis fundamentally alters the plant's own energy economy. Plants normally exude energy-intensive *phosphatase enzymes* to liberate P from soil. Research shows that AMF-inoculated plants *significantly decrease* their own production of these enzymes.[36] The fungal partner effectively "outsources" this P-scavenging function. This frees up significant plant energy (carbon), allowing the plant to *reallocate* its resources, investing *less* in its below-ground root biomass and *more* into its above-ground shoot biomass, which directly translates to increased crop yield.[35] The network also enhances the uptake of other vital nutrients, including Nitrogen (N), Potassium (K), Zinc (Zn), Manganese (Mn), and Copper (Cu).[19]

2.5 Core Function: Water Relations and Soil Structure Engineering

Mycorrhizal fungi are also master "ecosystem engineers" that physically modify their soil environment.[30]

- **Water Uptake:** The fine hyphae can explore soil *micropores* that are physically inaccessible to plant roots, tapping into water reserves that would otherwise be lost.[29] They also improve the soil's hydraulic conductivity by *bridging macropores* (air gaps).[29] This enhanced access to soil water directly confers plant tolerance to drought and salinity.[19]
- **Soil Structure (AMF):** AMF play a crucial role in soil aggregation.[27] The hyphal network itself physically binds soil particles.[4] More importantly, AMF exude a unique, sticky glycoprotein called **glomalin**.[28] Glomalin acts as a potent and stable "glue" that binds soil microparticles together to form stable macroaggregates, or "crumbs".[28] This aggregation is the hallmark of healthy soil structure, improving porosity, aeration, and water infiltration while reducing soil crusting and erosion.[28]
- **Rhizosphere Management:** The influence of AMF extends beyond just the plant-fungus connection. They are active "managers" of the rhizosphere. Not only do they physically build their habitat via glomalin, but they also modulate plant signaling to "coordinate soil bacterial communities".[38] This creates a three-way, synergistic relationship where the AMF-colonized plant directs specific *bacterial* populations to mobilize other nutrients, such as phosphate and sulfur, further enhancing the entire system's efficiency.[38]

3. Endophytic Fungi: Internal Mechanisms for Growth and Defense

3.1 Definition: The "Internal Microbiome" of Plants

Endophytic fungi are microorganisms that colonize the *internal* tissues of plants—including roots, stems, and leaves—without causing any visible symptoms of disease.[8] This ancient and ubiquitous relationship is found in most, if not all, plant species, forming a critical part of the plant's "microbiome".[8] They are transmitted both horizontally (e.g., from the soil or airborne spores) and vertically (from the parent plant via seed).[40]

3.2 Function: Direct Plant Growth Promotion (PGPF)

Many endophytes are classified as Plant Growth-Promoting Fungi (PGPF) due to their direct, positive effects on host physiology.[6] They achieve this through two primary mechanisms:

1. **Phytohormone Production:** Endophytes synthesize and secrete a range of potent plant-growth-regulating hormones. These include **Auxins (IAA)**, which stimulate root development [40], and **Gibberellins (GA)** (e.g., GA3, GA4, GA7), which promote stem elongation and germination.[40]
2. **Nutrient Acquisition:** Endophytes provide direct nutrient benefits to their host.[8] They possess a "better ability over bacteria" to mobilize nutrients like phosphorus, particularly in the harsh, acidic soil conditions where bacteria often struggle.[40] They also produce **siderophores**, which are low-molecular-weight compounds that chelate iron (Fe^{3+}) from the soil, making this essential micronutrient available to the plant.[8]

3.3 Function: Conferring Abiotic Stress Tolerance

One of the most valuable functions of endophytic fungi is their ability to enhance plant resilience to major abiotic stresses, including drought, salinity, and temperature extremes.[6] For instance, endophyte-conferred tolerance has been shown to *reduce water consumption* by 20-30% in commercial rice varieties, all while increasing biomass and yield.[49]

This profound stress mitigation is achieved through several sophisticated internal mechanisms:

- **Hormonal Regulation:** Endophytes modulate the plant's own stress hormone signaling, such as by balancing Abscisic Acid (ABA) and Gibberellin (GA) levels, to mount a more effective response.[47]
- **Osmotic Adjustment:** Under drought or salt stress, endophytes help the host plant accumulate organic solutes (osmolytes), which helps maintain cellular turgor pressure and prevent wilting.[45]
- **Antioxidant System Management:** Abiotic stress creates a flood of damaging Reactive Oxygen Species (ROS) within plant cells. Endophytes protect the plant by both scavenging these ROS directly and, more importantly, by upregulating the plant's native antioxidant enzyme systems, such as Catalase (CAT), Superoxide Dismutase (SOD), and

Peroxidase (POD).[45]

3.4 Function: Mediating Biotic Stress Resistance (Pests & Pathogens)

Endophytes act as "bodyguards" [51] by providing systemic protection against herbivores (insects) and pathogens.[10] This defense is multi-layered:

1. **Induced Systemic Resistance (ISR):** This is an *indirect* mechanism.[8] The mere presence of the "friendly" endophyte acts as a "vaccination," priming the plant's own systemic defense pathways (ISR/ASR).[41] When a *real* pathogen or pest attacks, the plant's defenses are activated faster and more robustly. This is often triggered when the plant's receptors recognize fungal MAMPs (Microbial-Associated Molecular Patterns) like chitin from the endophyte cell wall.[44]
2. **Direct Antagonism (Antibiosis):** This is a *direct* mechanism.[44] The endophytes themselves produce a "wide range of bioactive metabolites" [46] that are antifungal, antibacterial, or toxic/deterrent to insect herbivores.[8]
3. **Competition:** Endophytes colonize the plant's internal tissues, "competing for space and nutrients".[42] This physical occupation effectively prevents incoming pathogens from gaining a foothold.[41]

The relationship between a plant and its endophytic community can be understood as the plant "outsourcing" critical physiological functions. The endophytes function as an *outsourced endocrine system* by producing growth hormones [40], an *outsourced stress response system* by managing ROS and stress hormones [47], and an *outsourced immune system* by providing ISR and producing defensive antibiotics.[44] The resulting "holobiont" (the plant + its microbes) is far more resilient and efficient than a sterile, endophyte-free plant.

4. Fungal Biocontrol Agents (BCAs): Specialized Applications for Plant Protection

4.1 Introduction to Fungal BCAs

This functional group includes fungi that are applied specifically as "natural enemies" [53] or "microbial pesticides" [6] to manage agricultural pests and diseases. Their use is a cornerstone of Integrated Pest Management (IPM) programs, offering an eco-friendly alternative to synthetic chemical pesticides.[51]

4.2 Entomopathogenic Fungi (EPF): The Insect Killers

Entomopathogenic fungi (EPFs) are organisms that naturally infect and parasitize arthropod pests.[12]

- **Key Species:** The most widely commercialized EPFs in agriculture are *Beauveria bassiana* [12] and the *Metarhizium anisopliae* species complex.[12] Other important genera include *Cordyceps* (formerly *Isaria*) and *Akanthomyces*.[12]
- **Mode of Action (Direct Infection):** Unlike bacterial pesticides that must be ingested, EPFs are contact killers.
  1. Spores adhere to the insect's outer body (the cuticle).[12]
  2. The fungus germinates, releasing enzymes and using mechanical pressure to *penetrate* the cuticle.[12]
  3. Once inside the insect's body cavity (the hemolymph), the fungus multiplies, attacks vital organs, and often releases toxins, leading to host death.[12]
  4. The fungus then emerges from the host cadaver, producing a characteristic "muscardine"—a white moldy growth for *Beauveria* (white muscardine disease) or a green-spored mold for *Metarhizium* (green muscardine disease)—which releases new spores into the environment.[12]
- **Target Pests:** EPFs are effective against a broad spectrum of pests, including aphids, whiteflies, thrips, mealybugs, psyllids, stem borers, weevils, grasshoppers, ticks, and mites.[12]

A critical development in EPF research is the discovery of their "dual role".[13] The traditional application method is a foliar spray [51], which acts as a short-lived *contact pesticide* vulnerable to UV radiation and desiccation. However, modern research confirms that *B. bassiana* and *M. anisopliae* can also be applied to the soil or as a seed treatment, where they will colonize the plant *endophytically*.[10] When living as an endophyte, the fungus provides *systemic* biological control [53], protecting the plant from within by deterring insect feeding and even antagonizing fungal pathogens.[13] Thus, the application method (foliar spray vs. soil drench) fundamentally changes the fungus's function from a temporary contact pesticide to a persistent, systemic bodyguard.

4.3 Mycoparasitic Fungi: The Fungal Pathogen Killers

Mycoparasitic fungi are those that parasitize and kill other fungi, particularly plant pathogens.

- **Key Species:** This category is dominated by the genus *Trichoderma*, with species like *T. harzianum*, *T. virens*, and *T. asperellum*.[14] *Trichoderma*-based products account for an estimated 60% of the global fungal biocontrol market.[14]
- **Target Pathogens:** They are highly effective against a wide range of devastating soil-borne pathogens, including *Pythium*, *Rhizoctonia*, *Fusarium*, and *Sclerotinia*.[12]
- **Mechanisms of Action:** *Trichoderma* employs a multi-pronged attack strategy:
    1. **Mycoparasitism:** The *Trichoderma* hyphae directly attack the pathogen, coiling around its hyphae, penetrating its cell wall, and "feeding" on its contents.[14]
    2. **Antibiosis:** *Trichoderma* secretes a powerful cocktail of lytic enzymes (e.g., chitinases and glucanases) that degrade the pathogen's cell wall, along with secondary metabolites and antibiotics (e.g., trichodermin, viridin) that inhibit its growth.[14]
    3. **Competition:** *Trichoderma* is an extremely fast-growing and aggressive colonizer of the rhizosphere (the root zone).[15] It simply outcompetes pathogens for space and essential nutrients, "starving" them out.[14]
    4. **Endophytic Function:** As noted previously, *Trichoderma* also colonizes plant roots *endophytically*, where it promotes plant growth (PGPF) and activates the plant's Induced Systemic Resistance (ISR).[16]

4.4 Nematicidal Fungi: The Nematode Killers

Nematicidal fungi are specialized fungi that prey on or parasitize plant-parasitic nematodes (PPNs), which are microscopic roundworms that cause significant crop damage.[61] These fungi employ several ingenious mechanisms [11]:

1. **Nematode-Trapping (Predatory):** Fungi such as *Arthrobotrys* are "carnivorous," forming physical traps in the soil. These traps can be adhesive "nets" or "knobs" that stick to the nematode, or constricting "rings" that snap shut on the nematode when it passes through.[11]
2. **Ovicidal (Egg Parasites):** This is the most common commercial strategy. Fungi parasitize the nematode eggs, digesting their contents. The key commercial species in this group is *Purpureocillium lilacinum* (formerly *Paecilomyces*).[12]

3. **Endoparasitic:** Fungal spores attach to the nematode's cuticle or are ingested, germinating inside the host and killing it from within.
4. **Toxin-Producing:** Some fungi, such as the common edible oyster mushroom (*Pleurotus ostreatus*), produce toxins that immobilize nematodes, which the fungus then penetrates and digests.[64]
5. **Multi-Guild Action:** *Trichoderma* species also exhibit strong nematicidal activity, capable of parasitizing nematode eggs and affecting juvenile viability.[61]

4.5 Table 2: Comparative Analysis of Fungal Biocontrol Mechanisms

BCA Type	Key Genera	Primary Target	Primary Mechanism (Direct Action)	Secondary Mechanism (Indirect/Endophytic)
Entomopathogenic	*Beauveria*, *Metarhizium*	Sucking/chewing insects (e.g., Aphids, Thrips, Weevils) [12]	Direct cuticle penetration; toxin production in hemolymph.[12]	Endophytic colonization; systemic defense; herbivore deterrence.[13, 53]
Mycoparasitic	*Trichoderma*	Fungal pathogens (e.g., *Fusarium*, *Rhizoctonia*) [12]	Mycoparasitism (direct attack); antibiosis (enzymes/metabolites); competition.[14, 15, 16]	Endophytic PGP; Induced Systemic Resistance (ISR).[16]
Nematicidal (Ovicidal)	*Purpureocillium*	Plant-Parasitic Nematode eggs [12]	Direct parasitism and digestion of egg contents.[62]	Toxin production; enzyme secretion.[64]

Nematicidal (Predatory)	*Arthrobotrys*	Nematode juveniles/adults [62]	Physical trapping with adhesive nets or constricting rings.[11]	(N/A)

5. Saprotrophic Fungi: The Foundation of Soil Fertility and Nutrient Cycling

5.1 The Ecological Role of Decomposition

Saprotrophic fungi are the ecosystem's "primary recyclers".[4] They are defined by their ability to acquire nutrients from *dead* organic matter. In terrestrial ecosystems, they are the "key regulators of nutrient cycling" [67] and the *primary* agents responsible for the decomposition of plant litter.[11] This decomposition function is what replenishes the soil with organic matter and liberates mineral nutrients for plant use.[4]

5.2 The Mechanism: Enzymatic Breakdown of Recalcitrant Matter

Saprotrophs function by secreting a powerful cocktail of *extracellular enzymes* into their environment (e.g., soil, leaf litter, compost).[11] While soil bacteria are efficient at degrading simple sugars and proteins, fungi are the unique specialists required to break down the most complex and recalcitrant plant polymers.[11]

Their primary targets are:

- **Cellulose:** The main structural component of plant cell walls.[70]
- **Lignin:** The tough, complex, "woody" compound that binds cellulose fibers together. Lignin is notoriously difficult to degrade and is handled almost exclusively by fungi (e.g., white-rot fungi).[11]

By breaking down these complex molecules, saprotrophs convert locked-up organic nutrients into simpler, mineralized forms that can be absorbed by plant roots and mycorrhizal fungi.

5.3 Application in Composting and Soil Building

Saprotrophic fungi are the biological engines of the composting process.[69] A compost pile undergoes a "fungal succession" as it matures:

1. **Initial/Mesophilic Phase:** Mesophilic fungi (and bacteria) rapidly consume the most soluble, easily degradable compounds. Yeasts such as *Candida* and *Dipodascus* may be dominant during this initial stage.[71]
2. **Thermophilic Phase:** As decomposition generates heat, compost temperatures rise above 40°C.[71] Heat-loving *thermophilic* fungi take over, specializing in the breakdown of complex polymers like cellulose and hemicellulose.[71] Non-thermophilic fungi are restricted to the cooler, outer 10-15 cm of the pile.[71]
3. **Maturation/Curing Phase:** As the most energetic compounds are exhausted, the pile cools. Mesophilic fungi and actinomycetes (filamentous bacteria) re-colonize to decompose the most resistant compounds remaining, primarily lignin, forming the stable, nutrient-rich organic end-product: humus.[71]

A key horticultural product derived from this process is **Spent Mushroom Compost (SMC)**. SMC is the recycled substrate (e.g., composted straw and manure) *after* saprotrophic fungi like *Agaricus bisporus* (button mushroom) have been cultivated on it. This "spent" material is an exceptional soil amendment, rich in organic carbon, nutrients, and a diverse community of beneficial microbes that can enhance soil quality.[79]

5.4 Contribution to Soil Structure and Water Dynamics

Like mycorrhizae, saprotrophic fungi are critical "soil engineers." Their extensive mycelial networks (the thread-like body of the fungus) grow through the soil and physically bind loose particles together, creating water-stable aggregates.[80] Furthermore, their hyphae can perform "hydraulic redistribution," acting as a "fast connection" to transport water from wet soil patches to dry ones. This process facilitates decomposition by keeping the soil micro-environment moist, even during periods of drought.[82]

These fungi are the foundational guild of the soil food web. They are the "architects" that build the physical soil structure (aggregates) [80] and the "chefs" that "cook" the raw, complex ingredients (lignin, cellulose).[11] This "cooking" process (decomposition) *mineralizes* nutrients, effectively "stocking the pantry" for the entire soil ecosystem. This saprotrophic activity is what enables the other guilds to thrive; for example, the application of compost (the product of saprotrophs) is known to *increase* the functional populations of *both* saprophytic fungi and AMF in the soil.[69]

6. Commercialization and Application in Modern Agriculture

6.1 Commercial Formulations: From Lab to Field

The beneficial fungi discussed are commercially available to growers in a variety of formulations.[84] These products are broadly grouped into two classes:

1. **Biofertilizers / Biostimulants:** These products contain live microbes intended to promote plant growth, nutrient uptake, and stress tolerance.[7] They typically contain **AMF** (e.g., *Glomus intraradices*) or **PGPF** (e.g., *Trichoderma* spp.). Commercial examples include MycoApply [88], Mykos [89], and various other AMF-based inoculants.[7]
2. **Biopesticides (or Mycopesticides):** These are products containing fungal Biocontrol Agents (BCAs) registered for the management of pests and diseases.[6]
   - **Mycoinsecticides:** Contain **EPFs** such as *Beauveria bassiana* (e.g., BotaniGard 22WP, Mycotrol) or *Metarhizium anisopliae* (e.g., Met52).[12]
   - **Mycofungicides / Myconematicides:** Contain **mycoparasites** like *Trichoderma harzianum* (e.g., RootShield WP) or **nematicides** like *Purpureocillium lilacinum* (e.g., BioAct WG).[12]

These fungal products are sold in various formats, including wettable powders (WP), granules, and liquids. The active fungal spores or hyphae are typically mixed with inert "carriers" (e.g., peat, vermiculite, talc, or oil) to ensure viability and ease of application.[84]

6.2 Inoculation and Delivery Systems: A Comparative Analysis

The method of application is critical for establishing the fungus and ensuring its intended function.[92]

- **Seed Inoculation:** A highly cost-effective, precise, and practical method that places the inoculant exactly where it is needed at the moment of germination.[92]
  - *Seed Coating/Dressing:* Applying microbes in a thin polymer layer to the seed surface.[91] This is an ideal delivery system for AMF and *Trichoderma*, as it ensures the fungus is present when the first roots emerge.[95]
  - *Seed Priming/Soaking:* Soaking seeds in a liquid suspension of microbes before planting.[91]
- **Soil Inoculation:** Applying the inoculant directly to the soil or growing media.[84]
  - *Liquid In-Furrow:* Spraying a liquid formulation directly into the planting furrow with the seed.[91]
  - *Soil Drench:* Applying a liquid suspension to the soil surface or root zone after planting.[84]
  - *Granular Application:* Incorporating dry granules into the soil or potting mix.[92]
- **Plant/Root Inoculation:** Applying directly to the plant, primarily used for transplants or established crops.[92]
  - *Root Dipping:* Immersing the roots of bare-root transplants (e.g., orchard trees, grapevines) into a fungal gel or slurry before planting. This is a common method for EMF.[92]
  - *Foliar Spray:* Spraying a liquid suspension onto the plant's leaves.[92] This is the primary method for EPFs when used as a *contact* pesticide.[51]

6.3 Practical Challenges and Incompatibilities

Fungal inoculants are not "silver bullets"; they are living organisms and their success is subject to biological and environmental constraints.

- **Efficacy and Competition:** Commercial inoculants must compete with the diverse, complex, and already-established native soil microbiome. In some field conditions, laboratory-raised inoculants may struggle to establish, making field results less reproducible than greenhouse trials.[84]
- **Environmental Sensitivity:** The efficacy of biopesticides, particularly EPFs applied as foliar sprays, is highly dependent on environmental conditions. They are sensitive to *UV radiation* (sunlight), *low humidity*, and *extreme temperatures*, which can rapidly reduce spore viability and persistence.[51]
- **Chemical Incompatibility:** This is the most critical management challenge for growers.
  - **Fungicides:** Most chemical fungicides are broad-spectrum and *will kill* beneficial

fungal inoculants, rendering them useless.[4]

  - **Fertilizers:** The mycorrhizal symbiosis is suppressed by high levels of available soil phosphorus. If a plant can get P easily from chemical fertilizers, it *will not* expend the carbon (sugars) needed to form the fungal partnership.[4]
- **Ecological Risk:** There is an emerging scientific concern regarding the "microbial invasion" of non-native, commercially aggressive fungal strains, which could potentially outcompete and reduce the diversity of beneficial *native* fungal communities that are locally adapted to the environment.[26]

6.4 Table 3: Practical Application Guide for Fungal Inoculants

Fungal Category	Product Type	Primary Application Method(s)	Target Crops	Key Function	Critical Incompatibility
Arbuscular Mycorrhizae (AMF)	Biofertilizer / Soil Inoculant (e.g., *Glomus intraradices*)	Seed Coating, In-Furrow, Soil Drench, Root Dip [91, 92, 95]	Vegetables, Row Crops, Grasses [11]	P-Uptake, Drought Tolerance, Soil Structure [29, 30, 35]	**High-P Fertilizers**, Fungicides [4]
Ectomycorrhizae (EMF)	Biofertilizer / Soil Inoculant (e.g., *Pisolithus*)	Root Dip (transplants), Soil Drench [92, 96]	Woody Plants (Orchards: Pecan, Hazelnut) [19]	N/P Uptake (from organic matter) [32]	Fungicides
***Trichoderma* spp.**	Mycofungicide / Biostimulant (e.g., *T. harzianum*) [12]	Seed Coating, Soil Drench, In-Furrow [12, 92]	All (field, greenhouse, nursery) [12]	Suppress *Pythium*, *Fusarium*; Plant Growth Promotion [12, 14, 16]	Fungicides, some pesticides [53]

EPF (Contact Pesticide) (*Beauveria*, *Metarhizium*) [12]	Mycoinsecticide (e.g., BotaniGard) [12]	Foliar Spray [51, 97]	All (for foliar pests)	Kills aphids, whiteflies, thrips on contact [12]	**UV light**, **Low humidity**, Fungicides [51]
EPF (Systemic Endophyte) (*Beauveria*, *Metarhizium*)	Mycoinsecticide / Inoculant	Soil Drench, Seed Coating, In-Furrow [10, 17]	All	Systemic, internal defense against herbivores [13, 53]	Soil fungicides

7. Concluding Analysis: The Fungal Network as a Cornerstone of Sustainable Production

7.1 Synthesis: The Synergistic Fungal Network

The true power of beneficial fungi in agriculture lies not in any single category, but in the synergistic and holistic function of the entire fungal network. These guilds do not work in isolation; they are deeply interconnected, with each group enabling the success of the others. A fully functional, sustainable agricultural soil relies on this multi-guild synergy:

1. **Foundation (The "Chefs"):** The **Saprotrophic Fungi** are the foundational guild. They initiate the process by decomposing complex crop residues and compost, building soil structure, and "cooking" raw organic matter (lignin, cellulose) to *mineralize* nutrients, stocking the soil's pantry.[11]
2. **Transport (The "Logistics"):** The **Mycorrhizal Fungi (AMF)** then act as the transport network. Their extensive hyphae access the nutrients liberated by the saprotrophs and efficiently *deliver* them to the plant root in exchange for carbon.[22]
3. **Internal Optimization (The "Managers"):** The **Endophytic Fungi** work *inside* the plant. They receive the nutrients and water delivered by the AMF and, through phytohormone production, *optimize* the plant's internal physiology to use those resources for maximum

growth and stress resilience.[40]
4. **Defense (The "Bodyguards"):** Finally, the **Biocontrol Fungi** (like *Trichoderma* and *Beauveria*, often *also* acting as endophytes) *protect* this high-functioning, nutrient-rich plant from attack by insect pests and fungal pathogens.[13]

This holistic system—where saprotrophs build fertility, mycorrhizae enhance uptake, endophytes optimize growth, and biocontrol agents provide protection—creates a resilient, self-sustaining agricultural ecosystem. This multi-guild approach [5] is the biological foundation that can significantly reduce the required inputs of *both* chemical fertilizers and chemical pesticides.[7]

7.2 Future Outlook and Research Directions

The clear trend in modern agriculture is a shift away from single-action chemical inputs and toward complex, multi-functional biological solutions.[6] Fungi are at the forefront of this transition. Future progress will depend on several key areas of research:

- **Understanding Competition:** More field research is needed to understand the complex interactions between commercial inoculants and robust, locally-adapted native microbial communities.[26]
- **Developing Native Inoculants:** A promising strategy involves isolating and developing *native* fungal strains from local high-performing ecosystems, which may be better adapted and more effective than generic commercial products.[7]
- **Improving Formulations:** Significant research is focused on developing new formulations (e.g., encapsulation, oil dispersions) that improve the shelf-life and environmental persistence of fungal biopesticides, particularly protecting them from UV radiation and desiccation.[51]

Ultimately, harnessing the power of these diverse fungal guilds is no longer a niche practice but a fundamental component of productive, resilient, and sustainable food production for the 21st century.

Works cited

1. Current Insights in Fungal Importance—A Comprehensive Review - PMC - PubMed Central, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10304223/
2. Benefits of Fungi for the Environment and Humans - UN Decade on Ecosystem Restoration, accessed November 1, 2025, https://www.decadeonrestoration.org/stories/benefits-fungi-environment-and-h

umans
3. accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10304223/#:~:text=In%20agriculture%2C%20fungi%20play%20a,area%20of%20the%20root%20system.
4. Beneficial Fungi in the Landscape - Oklahoma State University Extension, accessed November 1, 2025, https://extension.okstate.edu/programs/gardening/grow-gardening-columns/grow-columns-2020/june-21-2020-beneficial-fungi.html
5. Fungal Biodiversity and Their Role in Soil Health - Frontiers, accessed November 1, 2025, https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2018.00707/full
6. Fungi in Horticultural Crops: Promotion, Pathogenicity and Monitoring, accessed November 1, 2025, https://www.mdpi.com/2073-4395/15/7/1699
7. Soil Fungi in Sustainable Agriculture - PMC - NIH, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10819681/
8. Endophytic fungi: a tool for plant growth promotion and sustainable agriculture - PMC - NIH, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC8856089/
9. Fungi in Horticultural Crops: Promotion, Pathogenicity and Monitoring - ResearchGate, accessed November 1, 2025, https://www.researchgate.net/publication/393672421_Fungi_in_Horticultural_Crops_Promotion_Pathogenicity_and_Monitoring
10. Entomopathogenic fungal endophytes - UNL Digital Commons - University of Nebraska–Lincoln, accessed November 1, 2025, https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1390&context=usdaarsfacpub
11. Role of Soil Fungus | Ohioline, accessed November 1, 2025, https://ohioline.osu.edu/factsheet/anr-37
12. Fungi Used for Pest Management in Crop Production | Oklahoma ..., accessed November 1, 2025, https://extension.okstate.edu/fact-sheets/fungi-used-for-pest-management-in-crop-production.html
13. Entomopathogenic Fungi as Dual Control Agents against Two Phytopathogens and the Lepidopteran Pest Rachiplusia nu in Soybean (Glycine max (L.) Merr) - MDPI, accessed November 1, 2025, https://www.mdpi.com/2309-608X/10/2/93
14. Trichoderma Species: Our Best Fungal Allies in the Biocontrol of ..., accessed November 1, 2025, https://www.mdpi.com/2223-7747/12/3/432
15. Molecular interaction between plants and Trichoderma species against soil-borne plant pathogens - Frontiers, accessed November 1, 2025, https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2023.1145715/full
16. Harnessing Trichoderma Mycoparasitism as a Tool in the Management of Soil Dwelling Plant Pathogens - PMC - NIH, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11663191/

17. Fungal Endophytes: Beyond Herbivore Management - Frontiers, accessed November 1, 2025, https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2018.00544/full
18. Use and impact of endophytic entomopathogenic fungi: Their potential in the context of agricultural sustainability - Redalyc, accessed November 1, 2025, https://www.redalyc.org/journal/6729/672978747049/html/
19. Mycorrhizal Fungi | Oklahoma State University, accessed November 1, 2025, https://extension.okstate.edu/fact-sheets/mycorrhizal-fungi.html
20. Question: Is mycorrhizae a "process of symbiosis" or an actual class of fungi? How foes it compare to humic acid for root growth? : r/botany - Reddit, accessed November 1, 2025, https://www.reddit.com/r/botany/comments/10luk43/question_is_mycorrhizae_a_process_of_symbiosis_or/
21. Mycorrhizae, accessed November 1, 2025, https://www2.nau.edu/gaud/bio300/mycorrhizae.htm
22. Fungi Fertilize the Future | Crop and Soil Sciences, accessed November 1, 2025, https://cals.ncsu.edu/crop-and-soil-sciences/news/fungi-fertilize-the-future/
23. Mycorrhizae - Wisconsin Horticulture, accessed November 1, 2025, https://hort.extension.wisc.edu/articles/mycorrhizae/
24. The power of fungi | Agency of Agriculture Food and Markets, accessed November 1, 2025, https://agriculture.vermont.gov/power-fungi
25. Mycorrhizal Relationships - Muir Woods National Monument (U.S. National Park Service), accessed November 1, 2025, https://www.nps.gov/muwo/learn/nature/mycorrhizal-relationships.htm
26. Does Commercial Inoculation Promote Arbuscular Mycorrhizal Fungi Invasion? - PMC - NIH, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC8879836/
27. Arbuscular Mycorrhizal Fungi in Sustainable Agriculture - MDPI, accessed November 1, 2025, https://www.mdpi.com/2071-1050/14/19/12250
28. Mycorrhizal Fungi: Beneficial Microbes for Increased Plant Health, accessed November 1, 2025, https://rvpadmin.cce.cornell.edu/pdf/veg_edge/pdf5_pdf.pdf
29. Mycorrhizal Fungi – The Powerhouse Of The Soil » Green Cover, accessed November 1, 2025, https://greencover.com/mycorrhizal-fungi-powerhouse/
30. Role of Arbuscular Mycorrhizal Fungi in Regulating Growth ..., accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10489935/
31. The Importance and Conservation of Ectomycorrhizal Fungal Diversity in Forest Ecosystems: Lessons From Europe and the Pacific Northwest, accessed November 1, 2025, https://www.fs.usda.gov/pnw/pubs/pnw_gtr431.pdf
32. Insights into the Biotic Factors Shaping Ectomycorrhizal Associations - MDPI, accessed November 1, 2025, https://www.mdpi.com/2079-7737/13/12/1044
33. Decomposition of soil organic matter by ectomycorrhizal fungi: Mechanisms and consequences for organic nitrogen uptake and soil carbon stabilization - Frontiers, accessed November 1, 2025, https://www.frontiersin.org/journals/forests-and-global-change/articles/10.3389/ff

gc.2022.934409/full
34. accessed November 1, 2025, https://www2.nau.edu/gaud/bio300/mycorrhizae.htm#:~:text=The%20roots%20provide%20essential%20nutrients,obtain%20from%20the%20surrounding%20soil.
35. Arbuscular Mycorrhizal Fungi Contribute to Phosphorous Uptake and Allocation Strategies of Solidago canadensis in a Phosphorous-Deficient Environment - Frontiers, accessed November 1, 2025, https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2022.831654/full
36. Arbuscular Mycorrhizal Fungi Contribute to Phosphorous Uptake and Allocation Strategies of Solidago canadensis in a Phosphorous-Deficient Environment - NIH, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC8987128/
37. Roles of Arbuscular Mycorrhizal Fungi on Soil Fertility: Contribution in the Improvement of Physical, Chemical, and Biological Properties of the Soil - Frontiers, accessed November 1, 2025, https://www.frontiersin.org/journals/fungal-biology/articles/10.3389/ffunb.2022.723892/full
38. Arbuscular mycorrhizal fungi enhance phosphate uptake and alter bacterial communities in maize rhizosphere soil - Frontiers, accessed November 1, 2025, https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2023.1206870/full
39. Nutrient transfer to plants by phylogenetically diverse fungi suggests convergent evolutionary strategies in rhizospheric symbionts - NIH, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC3689567/
40. Beneficial fungal communities from different habitats and their roles in plant growth promotion and soil health - Microbial Biosystems, accessed November 1, 2025, https://mb.journals.ekb.eg/article_99231_4f436f8d598cb9c02f1c8590492bae94.pdf
41. Fungi That Promote Plant Growth in the Rhizosphere Boost Crop Growth - PMC - NIH, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC9966197/
42. Full article: Endophytic fungi: a tool for plant growth promotion and sustainable agriculture, accessed November 1, 2025, https://www.tandfonline.com/doi/full/10.1080/21501203.2021.1945699
43. Elucidating Mechanisms of Endophytes Used in Plant Protection and Other Bioactivities With Multifunctional Prospects - PMC - NIH, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC7242734/
44. Uniting the Role of Endophytic Fungi against Plant Pathogens and ..., accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC9860820/
45. Fungal Endophytes to Combat Biotic and Abiotic Stresses ... - Frontiers, accessed November 1, 2025, https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2022.953836/full

46. Fungal Endophytes as Mitigators against Biotic and Abiotic Stresses in Crop Plants - MDPI, accessed November 1, 2025, https://www.mdpi.com/2309-608X/10/2/116
47. Full article: A review on plant endophytes in response to abiotic stress, accessed November 1, 2025, https://www.tandfonline.com/doi/full/10.1080/26395940.2024.2323123
48. Endophytic Fungi for Crops Adaptation to Abiotic Stresses - PMC - NIH, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11279104/
49. Fungal endophytes for sustainable crop production | FEMS Microbiology Ecology | Oxford Academic, accessed November 1, 2025, https://academic.oup.com/femsec/article/92/12/fiw194/2570446
50. Fungal Endophytes and Their Role in Agricultural Plant Protection against Pests and Pathogens - MDPI, accessed November 1, 2025, https://www.mdpi.com/2223-7747/11/3/384
51. Model Application of Entomopathogenic Fungi as Alternatives to Chemical Pesticides: Prospects, Challenges, and Insights for Next-Generation Sustainable Agriculture - Frontiers, accessed November 1, 2025, https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2021.741804/full
52. Advances in the beneficial endophytic fungi for the growth and health of woody plants - PMC, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11524292/
53. Endophytic Entomopathogenic Fungi: Their Role in Enhancing Plant Resistance, Managing Insect Pests, and Synergy with Management Routines - NIH, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11677045/
54. General Limitations to Endophytic Entomopathogenic Fungi Use as Plant Growth Promoters, Pests and Pathogens Biocontrol Agents - MDPI, accessed November 1, 2025, https://www.mdpi.com/2223-7747/10/10/2119
55. Management of Plant Beneficial Fungal Endophytes to Improve the Performance of Agroecological Practices - PMC, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC9604847/
56. Entomopathogen-based biopesticides: insights into unraveling their potential in insect pest management - PubMed Central, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10411202/
57. Beauveria bassiana and Metarhizium anisopliae endophytically colonize cassava roots following soil drench in - USDA ARS, accessed November 1, 2025, https://www.ars.usda.gov/arsuserfiles/5818/Greenfield%20et%20al%20-%20B%20bassiana%20and%20M%20anisopliae%20endophytically%20colonize%20cassava%20roots%20-%20Biological%20Control%202016%20.pdf
58. Tropical Occurrence and Agricultural Importance of Beauveria bassiana and Metarhizium anisopliae - Frontiers, accessed November 1, 2025, https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2020.00006/full
59. Field Applications of Entomopathogenic Fungi Beauveria bassiana and Metarhizium anisopliae F52 (Hypocreales: Clavicipitaceae) for the Control of Ixodes scapularis (Acari: Ixodidae) - Oxford Academic, accessed November 1,

2025, https://academic.oup.com/jme/article/47/6/1107/994317
60. Trichoderma and its role in biological control of plant fungal and nematode disease - PMC, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10189891/
61. Biocontrol Strategies Against Plant-Parasitic Nematodes Using Trichoderma spp.: Mechanisms, Applications, and Management Perspectives - MDPI, accessed November 1, 2025, https://www.mdpi.com/2309-608X/11/7/517
62. ENY-058/NG047: Nematode Management in Organic Agriculture - UF/IFAS EDIS, accessed November 1, 2025, https://edis.ifas.ufl.edu/publication/NG047
63. Insights into Biocontrol through Antagonistic ... - USDA ARS, accessed November 1, 2025, https://www.ars.usda.gov/ARSUserFiles/2279/Bhat%20et%20al%202023.%20Micr.pdf
64. Biocontrol of plant parasitic nematodes by bacteria and fungi: a multi-omics approach for the exploration of novel nematicides in sustainable agriculture - PMC - NIH, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11316259/
65. Strategy of Nematophagous Fungi in Determining the Activity of Plant Parasitic Nematodes and Their Prospective Role in Sustainable Agriculture - NIH, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10512347/
66. Saprotrophic fungi / RHS Gardening, accessed November 1, 2025, https://www.rhs.org.uk/biodiversity/saprotrophic-fungi
67. Functional and ecological consequences of saprotrophic fungus–grazer interactions - PMC, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC3475375/
68. accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC3475375/#:~:text=Saprotrophic%20fungi%20are%20key%20regulators,which%20nutrients%20are%20readily%20distributed.
69. Microbial Community in the Composting Process and Its Positive Impact on the Soil Biota in Sustainable Agriculture - MDPI, accessed November 1, 2025, https://www.mdpi.com/2073-4395/13/2/542
70. accessed November 1, 2025, https://www.rhs.org.uk/biodiversity/saprotrophic-fungi#:~:text=Saprotrophic%20fungi%20produce%20enzymes%20that,fungi%20can%20also%20decompose%20lignin.
71. Compost Microorganisms - CORNELL Composting, accessed November 1, 2025, https://compost.css.cornell.edu/microorg.html
72. Microbes in the Compost Pile - Mansfield, CT, accessed November 1, 2025, http://www.mansfieldct.org/mms-compost/microbes.htm
73. Saprotrophic nutrition - Wikipedia, accessed November 1, 2025, https://en.wikipedia.org/wiki/Saprotrophic_nutrition
74. What Is the Role of Fungi in Compost? → Question - Lifestyle → Sustainability Directory, accessed November 1, 2025, https://lifestyle.sustainability-directory.com/question/what-is-the-role-of-fungi-in

-compost/
75. Relative Contribution of Fungal Communities to Carbon Loss and Humification Process in Algal Sludge Aerobic Composting - MDPI, accessed November 1, 2025, https://www.mdpi.com/2073-4441/16/8/1084
76. Fungal and bacterial successions in the process of co-composting of organic wastes as revealed by 454 pyrosequencing | PLOS One - Research journals, accessed November 1, 2025, https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0186051
77. Core fungal species strengthen microbial cooperation in a food-waste composting process - PMC - NIH, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC9500350/
78. Chapter 1, The Decomposition Process - Earth-Kind® Landscaping Earth-Kind® Landscaping - Aggie Horticulture, accessed November 1, 2025, https://aggie-horticulture.tamu.edu/earthkind/landscape/dont-bag-it/chapter-1-the-decomposition-process/
79. Agro-Based Spent Mushroom Compost Substrates Improve Soil ..., accessed November 1, 2025, https://www.mdpi.com/2073-4395/13/9/2291
80. Systematic Review on the Role of Microbial Activities on Nutrient Cycling and Transformation Implication for Soil Fertility and Crop Productivity | bioRxiv, accessed November 1, 2025, https://www.biorxiv.org/content/10.1101/2024.09.02.610905v1.full-text
81. Stimulated saprotrophic fungi in arable soil extend their activity to the rhizosphere and root microbiomes of crop seedlings, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC8596668/
82. Redistribution of soil water by a saprotrophic fungus enhances carbon mineralization | PNAS, accessed November 1, 2025, https://www.pnas.org/doi/10.1073/pnas.1514435112
83. Redistribution of soil water by a saprotrophic fungus enhances carbon mineralization - PMC, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC4664368/
84. Soil Microbial Inoculants: Biology and Commercial Use ..., accessed November 1, 2025, https://gpnmag.com/article/soil-microbial-inoculants-biology-and-commercial-use/
85. A comprehensive overview of eco-friendly bio-fertilizers extracted from living organisms, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10663222/
86. Recent advances in the commercial formulation of arbuscular mycorrhizal inoculants, accessed November 1, 2025, https://www.frontiersin.org/journals/industrial-microbiology/articles/10.3389/finmi.2025.1553472/full
87. Can mycorrhizal fungi fix farming? Benefits and limitations of applying them to agroecosystems | The Biochemist | Portland Press, accessed November 1, 2025, https://portlandpress.com/biochemist/article/45/3/2/233130/Can-mycorrhizal-fungi-fix-farming-Benefits-and

88. Mycorrhizae Biostimulants for Plants | Horticulture Soil & Garden Mycorrhizal Products, accessed November 1, 2025, https://mycorrhizae.com/
89. Mycorrhizal Fungi Inoculant | Mycorrhizae for Sale - Grow Organic, accessed November 1, 2025, https://www.groworganic.com/collections/mycorrhizal-inoculants
90. Commercial Mycorrhizal Fungi | Reforestation Technologies International | Gilroy, accessed November 1, 2025, https://www.reforest.com/
91. Biological Seed Treatments: A Comprehensive Guide for Farmers, Distributors & Retailers, accessed November 1, 2025, https://locusag.com/blog/biological-seed-treatments/
92. Microbial seed coating: An attractive tool for sustainable agriculture ..., accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC9841043/
93. Seed Coating: A Tool for Delivering Beneficial Microbes to Agricultural Crops - PMC - NIH, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC6852281/
94. Seed Treatment: Types, Methods & Benefits - Verdesian Life Sciences, accessed November 1, 2025, https://vlsci.com/blog/seed-treatment-guide/
95. Seed Coating with Arbuscular Mycorrhizal Fungi for Improved Field Production of Chickpea, accessed November 1, 2025, https://www.mdpi.com/2073-4395/9/8/471
96. Complete Guide to Mycorrhizal Fungi | BBC Gardeners World Magazine, accessed November 1, 2025, https://www.gardenersworld.com/how-to/maintain-the-garden/mycorrhizal-fungi/
97. Materials Engineering to Help Pest Control: A Narrative Overview of Biopolymer-Based Entomopathogenic Fungi Formulations - NIH, accessed November 1, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10532551/
98. Soil Inoculants | CAES Field Report - UGA, accessed November 1, 2025, https://fieldreport.caes.uga.edu/publications/C990/soil-inoculants/
99. Integrated Pest Management Program The Use of Entomopathogenic Fungi in the Greenhouse - University of Connecticut, accessed November 1, 2025, https://ipm-cahnr.media.uconn.edu/wp-content/uploads/sites/3216/2023/02/2023entomopathogenicfungghsfactsheetfinal.pdf
100. 9 Ways To Help The Beneficial Fungi In Your Soil - Smiling Gardener, accessed November 1, 2025, https://www.smilinggardener.com/garden-planning/beneficial-fungi/
101. Arbuscular Mycorrhizae Contribute to Growth, Nutrient Uptake, and Ornamental Characteristics of Statice (Limonium sinuatum [L.] Mill.) Subject to Appropriate Inoculum and Optimal Phosphorus - MDPI, accessed November 1, 2025, https://www.mdpi.com/2311-7524/9/5/564