Role of Soil Fungi in Sustainable Brown Biofarming: Enhancing Drought Tolerance, Soil Health and Crop Productivity

Ashwini Chandrakant Patil[1], Dr. Vijayalaxami Shelke Sarode[2], Dr. Mahesh Prakash Patil[3]

[1]Department of Biotechnology, R.C. Patel Arts, Commerce and Science College, Shirpur, Tal. Shirpur, Dist. Dhule, 425405 (Maharashtra)
[2]Department of Botany, R.C. Patel Arts, Commerce and Science College, Shirpur, Tal. Shirpur, Dist. Dhule, 425405 (Maharashtra)
[3]Department of Microbiology, R.C. Patel Arts, Commerce and Science College, Shirpur, Tal. Shirpur, Dist. Dhule, 425405 (Maharashtra)

ABSTRACT
Brown Biofarming is a concept that deals with sustainable agricultural practices in arid and semi-arid regions where water scarcity, soil degradation, and climate variability have been continuously reducing crop productivity. Soil fungi are one of the most significant components of the soil microbiome and they contribute in many ways to nutrient cycling, soil aggregation, plant growth promotion, and mitigation of various abiotic stresses. This review summarizes the present knowledge about the role of beneficial soil fungi in improving drought tolerance, maintaining soil health, and enhancing crop productivity under water-limited field conditions. Particular attention is given to arbuscular mycorrhizal fungi (AMF), Trichoderma spp., endophytic fungi, and other plant growth-promoting fungal communities. The mechanisms through which fungi improve water uptake, nutrient acquisition, antioxidant defense systems, and soil physical structure have been discussed in detail. Recent advances in the development of fungal biofertilizers and their potential role in building climate-resilient agricultural systems have also been highlighted. Finally, existing research gaps and future perspectives for integrating fungal biotechnology into sustainable Brown Biofarming systems have been presented, keeping in view the practical challenges of field-level application.

Keywords: Brown Biofarming, Soil Fungi, Drought Tolerance, Arbuscular Mycorrhizal Fungi, Soil Health, Sustainable Agriculture, Biofertilizers, Climate Resilience

1. Introduction

Agriculture is the backbone of food security for billions of people across the world, particularly in developing nations where a large proportion of the population depends directly on farming for their daily livelihood. However, over the past few decades, the combined pressure of climate change, overuse of chemical inputs, and poor land management has led to serious problems of soil health deterioration, water scarcity, and loss of crop productivity. Arid and semi-arid zones, which together cover nearly 40% of the Earth's land surface, are particularly vulnerable to these problems because they face chronic water deficit and poor soil fertility conditions throughout the year.

In this context, Brown Biofarming has emerged as a promising and practically relevant approach to sustainable agriculture. It refers to the use of biologically derived and ecologically sound methods to manage dryland agricultural systems in a productive and sustainable manner. Unlike conventional farming which depends heavily on synthetic fertilizers and irrigation, Brown Biofarming relies on enhancing natural biological processes in soil, with particular emphasis on soil microorganisms, organic matter management, and adaptive crop systems.

Among soil microorganisms, fungi occupy a very important and often underappreciated position. Soil fungi are extraordinarily diverse in their ecological roles and they participate in nearly every important process that determines soil fertility and plant health. They act as decomposers of organic matter, mutualistic symbionts of plant roots, producers of plant growth-promoting substances, and suppressors of soil-borne pathogens. Most importantly, several groups of soil fungi have the remarkable ability to help plants survive and grow even under conditions of severe drought stress, which makes them exceptionally valuable for dryland farming systems.

Arbuscular mycorrhizal fungi (AMF) are perhaps the most widely studied group in this regard. Their symbiotic association with plant roots is known to enhance nutrient and water uptake, improve soil structure through glomalin production, and trigger drought tolerance mechanisms at both physiological and molecular levels. Trichoderma species, on the other hand, are well known for their biocontrol abilities and they have also demonstrated significant potential in promoting plant growth and inducing systemic tolerance to drought stress. Endophytic fungi, which live within plant tissues without causing any visible harm, have recently gained attention for their ability to confer tolerance to various abiotic stresses including drought and high temperature.

The present review has been written with the objective of bringing together current knowledge about these different groups of beneficial soil fungi and presenting a comprehensive picture of how they contribute to sustainable Brown Biofarming. Special attention has been paid to the mechanisms through which fungi improve drought tolerance, the role of fungi in maintaining and improving soil health, and their impact on crop productivity in water-limited environments. The review also discusses the current status of fungal biofertilizer technology and what needs to be done in future research to fully realize the potential of soil fungi in climate-resilient agricultural systems.

2. Concept of Brown Biofarming and Dryland Agriculture

2.1 Definition and Scope

Brown Biofarming is a relatively new term in agricultural science that integrates principles from dryland farming, biological agriculture, and soil ecology. The word "brown" in this context refers to the characteristic dry and often brownish appearance of arid and semi-arid landscapes, where agriculture must deal with limited water availability and degraded soil conditions. The concept goes beyond simple organic farming or conventional dryland agriculture by specifically emphasizing the biological components of the soil-plant system, particularly the role of soil microorganisms in maintaining productivity without relying on large external inputs of water or synthetic chemicals.

The scope of Brown Biofarming is quite wide. It includes practices like the use of microbial inoculants including fungal biofertilizers, promotion of soil organic matter through crop residue management, adoption of drought-tolerant crop varieties with enhanced microbial compatibility, minimal tillage to protect soil fungal networks, and integration of cover crops to maintain biological activity during dry seasons. The fundamental philosophy is that a biologically active soil is inherently more resilient to climate variability, and that investing in soil biology is a far more cost-effective and environmentally sustainable strategy than relying entirely on irrigation or chemical inputs.

2.2 Global Importance

The global importance of Brown Biofarming cannot be overstated given current trends in climate change and population growth. According to estimates from the United Nations Food and Agriculture Organization, approximately 2.5 billion people worldwide depend on dryland agriculture for their food and income. These regions, which include large parts of Sub-Saharan Africa, South Asia, the Middle East, and Mediterranean Europe, are expected to face even more severe water stress in coming decades due to changing precipitation patterns and rising temperatures.

India, in particular, has a very large proportion of its agricultural land under dryland conditions. States like Rajasthan, Gujarat, Maharashtra, Karnataka, and Andhra Pradesh have vast tracts of rain-fed agriculture where farmers regularly face crop failure due to drought. The development and adoption of Brown Biofarming practices in these regions could make a transformative difference to food security and farmer incomes. Similar situations exist across many parts of Africa and Latin America where smallholder farmers have limited access to irrigation infrastructure but urgently need solutions to improve their crop yields under rainfall uncertainty.

Brown Biofarming therefore represents not just an agricultural innovation but a food security strategy of global significance, particularly for the economically vulnerable communities living in dryland regions who have the least capacity to adapt to climate change.

2.3 Challenges in Arid and Semi-Arid Ecosystems

Dryland agricultural ecosystems present a unique and complex set of challenges that are quite different from those faced in well-irrigated farming systems. The most obvious challenge is of course the low and unpredictable rainfall, which creates conditions of chronic soil moisture deficit that severely limits plant growth and crop yield. But beyond just water shortage, arid soils tend to suffer from a range of interconnected problems that make farming even more difficult.

Arid soils are typically low in organic matter content because the dry conditions slow down the decomposition of plant residues and limit the growth of soil organisms. This leads to poor soil structure, which in turn reduces water infiltration and increases runoff and erosion. The reduced biological activity also means that nutrient cycling is slow, leading to nutrient deficiencies that further limit plant growth. High temperature and low humidity cause rapid evaporation, meaning that even whatever little water is available gets lost quickly before plants can make use of it.

Soil salinity is another common problem in dryland areas, particularly in regions where irrigation is practised without adequate drainage. Salt accumulation in the root zone creates osmotic stress that is in many ways similar to drought stress from the plant's perspective. Wind erosion is also a serious problem in bare arid soils, leading to loss of the topsoil layer that contains most of the soil's biological activity and organic matter.

In addition to all these physical and chemical challenges, dryland farmers also face socioeconomic constraints such as limited access to quality seeds, fertilizers, credit, and technical knowledge, which further reduces their ability to adapt to difficult growing conditions. It is in this complex context that soil fungi offer a genuinely practical and affordable solution, because they are naturally adapted to dryland conditions and can be applied as bioinoculants at relatively low cost.

3. Soil Fungi: Diversity and Ecological Functions

3.1 Major Functional Groups of Soil Fungi

Soil fungi are an extraordinarily diverse group of organisms and they perform a wide range of ecological functions that are essential for the health and productivity of terrestrial ecosystems. Based on their ecological role and mode of interaction with plants and other soil organisms, soil fungi can be broadly classified into several major functional groups, each of which has distinct characteristics and contributions to soil health.

Mycorrhizal fungi form symbiotic associations with the roots of the majority of land plants. Within this broad category, arbuscular mycorrhizal fungi (AMF) are the most widespread and agriculturally important group, forming associations with

roughly 80% of all plant species including most major food crops. Ectomycorrhizal fungi are important in forest ecosystems and some agroforestry systems. Ericoid and orchid mycorrhizal fungi are more specialized in their host range.
Saprotrophic or decomposer fungi play a critical role in breaking down dead organic matter and making its nutrients available for plant uptake. This group includes many common species of Aspergillus, Penicillium, Chaetomium, and Fusarium that are frequently found in agricultural soils. Endophytic fungi, including dark septate endophytes (DSE) and mutualistic endophytes like Piriformospora indica, live within plant tissues without causing disease and often provide significant benefits to the host plant in terms of stress tolerance and nutrient acquisition. Plant growth-promoting fungi like phosphate solubilizing fungi and hormone producing species also form an important part of the soil fungal community.
Table 1 below provides a summary of the major groups of soil fungi and their agricultural functions.

Table 1. Major Soil Fungi and Their Agricultural Functions

Fungal Group	Key Genera/Species	Primary Agricultural Functions	Remarks
Arbuscular Mycorrhizal Fungi (AMF)	Glomus, Rhizophagus, Funneliformis	Nutrient uptake, drought tolerance, soil aggregation	Most widely studied in dryland agri.
Trichoderma spp.	T. harzianum, T. viride, T. asperellum	Plant growth promotion, biocontrol, stress tolerance	Widely used as commercial biocontrol
Endophytic Fungi	Piriformospora indica, Sebacinales	Colonize plant tissue, drought resistance, yield boost	Emerging importance in stress biology
Saprophytic Fungi	Aspergillus, Penicillium, Mortierella	Organic matter decomposition, phosphate solubilization	Key role in nutrient cycling
Ectomycorrhizal Fungi	Pisolithus, Suillus, Laccaria	Tree root symbiosis, water & mineral acquisition	Important in forest & agroforestry systems
Dark Septate Endophytes (DSE)	Phialocephala, Periconia	Drought resistance, phosphorus acquisition in arid soils	Tolerant to low rainfall environments
Phosphate Solubilizing Fungi	Aspergillus niger, Penicillium citrinum	Convert insoluble phosphate to plant-available forms	Critical in P-deficient soils
Free-living Saprophytes	Chaetomium, Fusarium (beneficial strains)	Cellulose degradation, humus formation	Improve soil organic matter content

3.2 Fungal Biodiversity in Dryland Soils

The diversity of soil fungal communities in dryland and arid ecosystems is often underestimated by researchers who tend to focus more on temperate or tropical forest soils that are perceived as more biologically rich. However, dryland soils support a unique and surprisingly diverse fungal community that has evolved specialized adaptations to survive and function under conditions of low water availability, high temperature, and poor soil fertility.
Studies using modern molecular techniques like metagenomics and amplicon sequencing have revealed that dryland soils can harbour hundreds of fungal species from diverse taxonomic groups. Ascomycetes are typically the most abundant group in arid soils, followed by Basidiomycetes and Zygomycetes. Interestingly, dark septate endophytes (DSE) are particularly well-represented in dryland soils compared to more mesic environments, suggesting that they may have a specific adaptive advantage in low-water conditions [20].
AMF diversity in dryland soils is often lower than in more humid environments, but the species that do persist in arid soils tend to have greater colonization efficiency and drought tolerance than their humid-adapted counterparts. Genera like Glomus, Funneliformis, and Rhizophagus are most commonly found in dryland agricultural soils, while Scutellospora and Gigaspora are more commonly associated with natural semi-arid ecosystems. Soil fungal diversity is influenced by many factors in dryland systems including soil texture, pH, salinity, organic matter content, plant cover, and management history.
Conventional tillage practices, excessive use of fungicides, and removal of crop residues all tend to reduce soil fungal diversity in dryland systems. Conservation agricultural practices like minimum tillage, retention of crop stubble, and use of cover crops

help to maintain and even enhance fungal biodiversity, which in turn improves the overall biological functioning of the dryland soil ecosystem.

3.3 Soil-Plant-Fungi Interactions

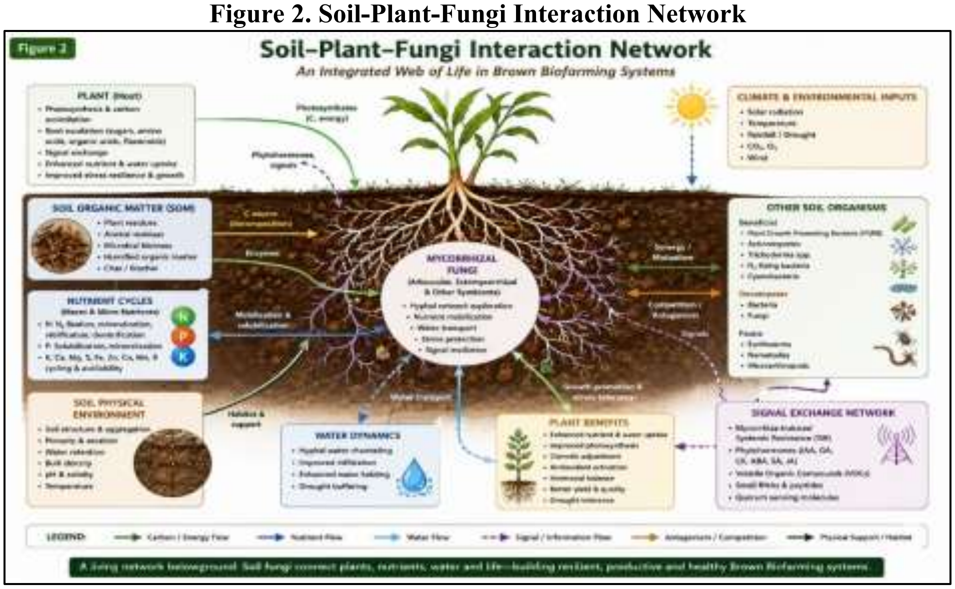
The relationship between soil fungi, plants, and the broader soil environment is a complex and dynamic network of interactions that operates at multiple spatial and temporal scales. At the most basic level, plants provide fungi with carbohydrates derived from photosynthesis, while fungi provide plants with nutrients, water, and protection from stress and pathogens. This fundamental exchange underpins the mycorrhizal symbiosis and has been central to the evolutionary success of land plants.

But beyond this simple mutualism, soil-plant-fungal interactions involve many more layers of complexity. The plant root exudes a range of chemical compounds into the surrounding soil, collectively called the rhizosphere, which attract specific groups of fungi and bacteria and create a zone of intense biological activity around the roots [12]. Mycorrhizal fungi in turn produce hyphae that extend far beyond the root zone and form connections with other plants in the community, creating what is sometimes called the "wood wide web" or common mycorrhizal network [19]. Through these networks, carbon, nutrients, and even signaling molecules can be transferred between connected plants.

Soil fungi also interact with the mineral soil matrix, producing organic acids and enzymes that weather minerals and release nutrients, contributing to the formation of soil aggregates that improve water retention and aeration. The mycelium of dead fungi adds organic matter to the soil and contributes to the formation of stable humus. All these interactions make soil fungi not just passive inhabitants of the soil but active engineers of the soil environment that shape its physical, chemical, and biological properties in ways that have profound consequences for plant growth and agricultural productivity.

Figure 2 conceptually illustrates the complex network of interactions between soil, plants, and fungi in a dryland agricultural system, showing how these interactions collectively support crop productivity and soil health.

Figure 2. Soil-Plant-Fungi Interaction Network



4. Mechanisms of Fungal-Mediated Drought Tolerance

Soil fungi, particularly mycorrhizal and endophytic species, have evolved a remarkable array of mechanisms through which they help their plant hosts survive and maintain productivity under drought conditions. These mechanisms operate at multiple levels, from the physical and structural level of root and soil systems all the way down to the molecular and genetic level within plant cells. Understanding these mechanisms in detail is essential for developing effective strategies to use fungi in dryland agricultural systems.

4.1 Enhanced Water Uptake

One of the most direct ways in which mycorrhizal fungi improve plant drought tolerance is by physically extending the water-absorbing capacity of the root system. The fungal hyphae of AMF are typically very thin, with diameters of 2 to 7 micrometres, which allows them to penetrate very fine soil pores that are inaccessible to plant root hairs [1]. Since soil moisture tends to be retained longest in the finest pores during dry periods, this hyphal access to fine pores gives mycorrhizal plants a significant advantage in extracting water from partially dry soils.

The extraradical mycelium of a single mycorrhizal plant can extend many centimetres beyond the root surface and can explore a volume of soil several times larger than would be possible with roots alone. Research has demonstrated that the length of AMF hyphae in agricultural soils can reach tens of metres per gram of soil, representing an enormous surface area for water absorption. At the molecular level, fungal colonization has been found to upregulate the expression of aquaporin genes in both plant roots and fungal hyphae. Aquaporins are protein channels that facilitate the rapid movement of water across cell membranes, and their increased activity in mycorrhizal plants is associated with faster water transport from soil to shoot.

4.2 Osmotic Adjustment

When plants experience water deficit, they must maintain cell turgor pressure to continue metabolic activities. One important way they do this is through osmotic adjustment, which involves accumulating small molecular weight compounds inside cells that lower the osmotic potential and thus draw water in by osmosis even under conditions of low soil water potential. Mycorrhizal and endophytic fungi significantly enhance this process in their host plants.

Colonization by AMF has been shown to increase the accumulation of compatible solutes such as proline, glycine betaine, trehalose, mannitol, and sugar alcohols in plant tissues [5,23]. These compounds not only reduce osmotic potential but also protect cellular proteins and membranes from denaturation caused by water stress. Trichoderma species produce their own osmolytes and also stimulate proline accumulation in colonized plants. Endophytic fungi including Piriformospora indica have been shown to significantly increase proline content in drought-stressed host plants, which is consistently correlated with improved survival and growth under water-limited conditions.

4.3 Antioxidant Defense Systems

Drought stress inevitably leads to the accumulation of reactive oxygen species (ROS) in plant cells, including superoxide radicals, hydrogen peroxide, and hydroxyl radicals. These highly reactive molecules damage cellular membranes, proteins, DNA, and photosynthetic pigments, and their unchecked accumulation is one of the main reasons why severe drought leads to irreversible cell damage and crop loss. Beneficial soil fungi significantly enhance the antioxidant defense capacity of their host plants, providing protection against ROS damage.

The main antioxidant enzymes involved in this defense are superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), and glutathione peroxidase (GPX). Research has consistently shown that plants colonized by AMF, Trichoderma, or Piriformospora indica maintain significantly higher activities of these enzymes under drought stress compared to non-colonized control plants [9,21]. This allows colonized plants to neutralize ROS more effectively and protect their cellular machinery from oxidative damage. Additionally, non-enzymatic antioxidants like ascorbic acid, glutathione, tocopherols, and carotenoids are also enhanced in fungi-colonized plants under drought conditions.

4.4 Regulation of Stress-Responsive Genes

Beyond the biochemical level, soil fungi also influence drought tolerance at the molecular genetic level by modulating the expression of stress-responsive genes in their host plants. This is one of the most exciting areas of current research in plant-microbe interactions and it reveals the depth and sophistication of the fungal-plant communication system.

AMF colonization has been shown to upregulate the expression of drought-responsive transcription factors like DREB (dehydration responsive element binding proteins) and ABRE-binding proteins in host plants. These transcription factors in turn activate a cascade of downstream genes that produce dehydrins, late embryogenesis abundant (LEA) proteins, and other stress protective compounds. The abscisic acid (ABA) signaling pathway, which is the central hormonal signaling route for drought response in plants, is also modulated by mycorrhizal colonization, generally leading to a more efficient and responsive activation of drought defense when water stress is encountered [21].

Endophytic fungi like Colletotrichum tropicale have been found to alter the transcriptome of their host plants in ways that prepare them for stress conditions even before any stress is actually experienced, a phenomenon that has been called "priming" for stress tolerance [16]. This represents a particularly valuable property for dryland agriculture where farmers cannot always predict when drought will occur during the growing season.

4.5 Improvement of Root Architecture

The physical structure of the root system is critically important for drought tolerance because a deeper and more extensively branched root system can access soil moisture from greater depths and explore a larger soil volume. Beneficial soil fungi, particularly AMF and Trichoderma species, significantly modify root architecture in ways that improve drought tolerance.

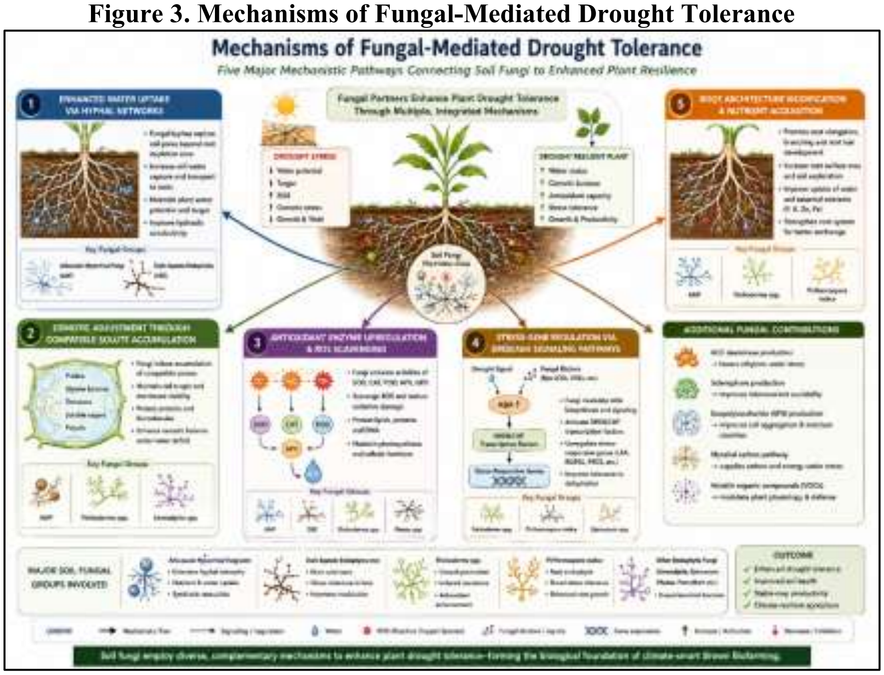
Trichoderma species produce plant growth regulators including indole acetic acid (IAA), ethylene modifying enzymes, and cytokinins that stimulate lateral root formation, increase root branching density, and promote overall root elongation [11]. AMF colonization also affects root architecture by producing signaling molecules that interact with the plant's hormonal network. Plants with mycorrhizal associations typically have more extensive root systems with greater surface area per unit shoot weight, making them more efficient at capturing soil resources including water under drought conditions. This combination of biochemical signaling effects on root architecture with the direct hyphal extension of the water-absorbing zone represents a powerful dual mechanism for improving drought tolerance.

Table 2. Mechanisms of Drought Stress Mitigation by Soil Fungi

Mechanism	Fungal Species Involved	Biochemical/Molecular Basis	Agronomic Outcome
Enhanced Water Uptake	AMF, DSE	Hyphal networks extend beyond root zone, accessing soil pores inaccessible to roots; aquaporin gene upregulation	Increases leaf relative water content; reduces wilting under drought

Osmotic Adjustment	AMF, Trichoderma, Endophytes	Accumulation of compatible solutes: proline, glycine betaine, trehalose, mannitol in colonized plants	Maintains turgor pressure; protects cellular membranes under low water potential
Antioxidant Defense	AMF, Trichoderma, Piriformospora	Upregulation of SOD, CAT, APX, GPX enzymes; reduced ROS accumulation in plant tissues	Minimizes oxidative stress; prevents chlorophyll breakdown; protects photosystems
Root Architecture Improvement	AMF, Trichoderma spp.	Indole acetic acid (IAA) and cytokinin production; increased root length, surface area, branching	Deeper and wider root systems improve access to subsoil moisture
Stress-Gene Regulation	AMF, Endophytes	Activation of DREB, ABRE, LEA, dehydrin genes; modulation of ABA signaling pathways	Prepares plant for water deficit; improves long-term drought memory
Soil Water Retention	AMF, Saprophytes	Glomalin-related soil proteins (GRSP) improve soil aggregation; organic matter addition retains moisture	Reduces evaporation loss; increases plant available water in soil profile
Stomatal Regulation	AMF, Trichoderma	Modulation of ABA-mediated stomatal closure; improved water use efficiency (WUE)	Reduces transpirational water loss without significantly reducing photosynthesis
Nutrient Acquisition Under Stress	AMF, Phosphate Solubilizers	Phosphorus and micronutrient uptake maintained through fungal hyphae even under water-limited conditions	Adequate P and Zn improves plant drought response via membrane integrity

Figure 3. Mechanisms of Fungal-Mediated Drought Tolerance



5. Arbuscular Mycorrhizal Fungi (AMF) in Brown Biofarming

5.1 Biology of AMF

Arbuscular mycorrhizal fungi belong to the phylum Glomeromycota, a group that has been forming symbiotic associations with plant roots for approximately 450 to 460 million years, making this one of the oldest and most evolutionarily significant partnerships in the living world [4,25]. The name "arbuscular" comes from the characteristic tree-like branched structures called arbuscules that the fungi form within root cortical cells. These arbuscules are the primary sites of nutrient and carbon exchange between the plant and the fungus and represent the intimate contact point where the two organisms interact most directly [3].

AMF are obligate biotrophs, meaning they cannot complete their life cycle in the absence of a living plant host [28]. They produce asexual spores in the soil, which germinate when stimulated by root exudates from a compatible host plant. The germinating hyphae grow towards the root, penetrate the root cortex, and eventually form arbuscules within cortical cells and in some species also produce vesicles which serve as storage organs. The extraradical mycelium that extends outside the root is the main structure responsible for soil exploration and nutrient and water uptake on behalf of the plant.

The global community of AMF contains approximately 300 to 400 described species, though molecular studies suggest that actual diversity may be considerably higher. All identified AMF species belong to a relatively small number of genera including Glomus, Rhizophagus, Funneliformis, Claroideoglomus, Gigaspora, Scutellospora, Acaulospora, and Diversispora. Different species vary considerably in their host preference, colonization characteristics, effectiveness in nutrient transfer, and tolerance to soil environmental conditions including drought.

5.2 Nutrient Acquisition

The most well-established benefit of AMF symbiosis for crop plants is the improvement of nutrient acquisition, particularly phosphorus. Phosphorus is one of the most important macronutrients for plant growth but it is relatively immobile in the soil and tends to become depleted in the immediate vicinity of roots. AMF hyphae extend far beyond the phosphorus-depleted zone around roots and access soil zones with higher phosphorus availability. The fungi take up phosphorus through specific phosphate transporter proteins in the hyphal membrane and transport it back to the root where it is transferred to plant cells at the arbuscule interface in exchange for carbon compounds from the plant.

Research has shown that AMF can supply between 20% and 80% of a plant's total phosphorus requirement, depending on the soil phosphorus status and the efficiency of the particular fungal species involved [15]. In addition to phosphorus, AMF also improve the uptake of zinc, copper, iron, and various other micronutrients that are often deficient in arid soils with high pH [14]. Nitrogen uptake is also enhanced by some AMF species that maintain associations with nitrogen-fixing bacteria in the soil [15]. These nutrient acquisition benefits are particularly important in dryland soils where chemical fertilizer use is often limited by cost or availability.

5.3 Soil Aggregation and Carbon Sequestration

Beyond their direct benefits to the plant, AMF also play a critical role in improving the physical structure of the soil, which has profound effects on water retention, aeration, and resistance to erosion. The primary mechanism through which AMF improve soil structure is the production of a glycoprotein called glomalin, which is also referred to as glomalin-related soil protein (GRSP). Glomalin is produced abundantly by AMF hyphae and it coats soil particles and helps bind them together into stable aggregates.

Stable soil aggregates create a porous soil structure that allows water to infiltrate quickly during rain events while also retaining water in the fine pores between and within aggregates for plant use during dry periods. This is an especially valuable property in dryland soils which are often prone to surface crusting that prevents water infiltration and leads to runoff and erosion. The improved aggregate stability also provides physical protection of soil organic matter, slowing its decomposition and contributing to long-term carbon sequestration in agricultural soils.

Studies have demonstrated strong positive correlations between AMF hyphal length and density, glomalin content, and soil aggregate stability across diverse soil types and climatic conditions [20]. The contribution of AMF to soil carbon sequestration is now recognized as an important component of the global terrestrial carbon budget, adding another dimension to the ecological value of these fungi beyond their direct agricultural benefits.

5.4 Drought Stress Alleviation

The role of AMF in alleviating drought stress in agricultural crops has been studied extensively and the evidence is now very strong that AMF colonization consistently improves plant performance under water-limited conditions. In greenhouse and field experiments with drought-stressed crops, AMF-colonized plants have shown higher leaf relative water content, lower leaf temperature (indicating better stomatal function), higher chlorophyll content, greater photosynthetic rate, higher proline content, and ultimately higher grain or biomass yield compared to non-colonized controls [5,18,2].

Wheat, maize, rice, chickpea, sorghum, sunflower, and tomato are among the many crops for which significant AMF-mediated drought tolerance improvements have been documented. The benefits appear to be particularly pronounced in soils that are naturally low in phosphorus, which is characteristic of many dryland soils, presumably because the nutrient acquisition benefits compound the direct water-related benefits under these conditions. Interestingly, studies have also shown that plants pre-inoculated with AMF before being subjected to drought stress show better tolerance than plants inoculated after stress onset, suggesting that establishing the mycorrhizal association early in the crop's life gives maximum benefit.

6. Trichoderma and Other Beneficial Fungi

6.1 Plant Growth Promotion

Trichoderma species are among the most extensively studied and commercially successful beneficial fungi in agricultural science. Originally known primarily as biocontrol agents against soil-borne plant pathogens, they have in recent years received increasing attention for their remarkable plant growth promotion abilities that are independent of their biocontrol effects. Trichoderma species promote plant growth through multiple mechanisms including the production of phytohormones, solubilization of mineral nutrients, and improvement of root system development.

Species like Trichoderma harzianum, T. asperellum, T. atroviride, and T. viride produce significant quantities of indole acetic acid (IAA), gibberellins, and cytokinin-like compounds that directly stimulate root elongation, lateral root formation, and shoot growth. They also produce glucanases, cellulases, and phosphatases that break down organic matter and release phosphorus and other nutrients from unavailable forms, functioning effectively as biological fertilizers. In greenhouse and field trials across different crops and soil types, Trichoderma inoculation has consistently resulted in shoot and root biomass increases of 20% to 60% compared to uninoculated controls even in the absence of any pathogen pressure [11].

6.2 Disease Suppression

The biocontrol abilities of Trichoderma represent one of its most commercially valuable properties and have been extensively exploited in agriculture for many decades. Trichoderma suppresses plant pathogens through several distinct mechanisms including direct mycoparasitism in which Trichoderma hyphae physically attach to and penetrate the hyphae of pathogenic fungi like Rhizoctonia, Pythium, Fusarium, and Sclerotinia and degrade them using lytic enzymes. Antibiosis is another mechanism where Trichoderma produces a range of volatile and non-volatile secondary metabolites including peptaibols, gliotoxin, and harzianic acid that inhibit the growth and activity of pathogens [11,10].

Perhaps equally important is the ability of Trichoderma to induce systemic resistance in host plants, a phenomenon where fungal colonization of the root triggers a general state of increased defensive readiness throughout the entire plant including above-ground tissues. This induced systemic resistance involves priming of the plant's natural immune system and provides non-specific protection against a broad range of pathogens, both fungal and bacterial. In dryland farming systems where farmers have limited access to fungicide inputs, the biocontrol properties of Trichoderma represent a particularly valuable disease management tool.

6.3 Abiotic Stress Tolerance

The role of Trichoderma in helping plants cope with abiotic stresses including drought, salt, and heat stress is an area of more recent but rapidly growing research interest. Multiple studies have now demonstrated that Trichoderma-colonized plants show significantly improved performance under drought stress conditions, and the mechanisms involved appear to overlap considerably with those described for AMF, including enhanced antioxidant enzyme activity, greater accumulation of osmolytes like proline and glycine betaine, modulation of stress-responsive gene expression, and improved root system architecture.

Trichoderma asperellum and T. harzianum have been particularly well studied in this context. In experiments with drought-stressed wheat, inoculation with T. harzianum improved grain yield by 25% to 40% compared to uninoculated drought-stressed controls [30]. Similar improvements have been reported for maize, tomato, and chickpea under both controlled drought stress and variable rainfall field conditions. The combination of biocontrol, nutrient enhancement, and drought tolerance abilities makes Trichoderma an extremely versatile and valuable organism for inclusion in Brown Biofarming systems where multiple stresses often occur simultaneously.

Phosphate solubilizing fungi, particularly Aspergillus niger, Aspergillus awamori, and Penicillium bilaiae, represent another important group of beneficial fungi in dryland systems. These organisms produce organic acids including citric, oxalic, and gluconic acid that dissolve insoluble calcium and iron phosphates in the soil, converting them to forms that plant roots can absorb. In phosphorus-deficient dryland soils, this can make a dramatic difference to plant nutrition and productivity. Research has also shown that phosphate solubilizing fungi often interact synergistically with AMF, with the phosphate solubilizers increasing the pool of available phosphorus in the soil that AMF then transport more efficiently to the plant, a pattern of synergistic action also documented between plant growth-promoting rhizobacteria and beneficial fungi in the rhizosphere [22,29].

7. Endophytic Fungi and Climate Resilience

7.1 Plant-Fungus Symbiosis

Endophytic fungi are organisms that live within the tissues of healthy plants, residing in the intercellular spaces or sometimes within cells, without causing any visible symptoms of disease. This lifestyle is distinct from that of mycorrhizal fungi which colonize roots from the outside and remain primarily in the soil-root interface zone, as well as from plant pathogens which cause disease symptoms. Endophytic associations are extraordinarily widespread in the plant kingdom, and virtually every plant species that has been examined for endophytic fungi has been found to harbour at least some, often several dozen different species.

The relationship between endophytic fungi and their host plants ranges from strictly neutral commensalism to active mutualism in which the fungus provides significant benefits to the host. The most celebrated example of an endophytic mutualist in agriculture is Piriformospora indica, which belongs to the order Sebacinales [26] and has a remarkably broad host range covering hundreds of plant species. P. indica colonizes plant roots and can be cultivated in pure culture without a plant host, making it much easier to study and produce commercially than obligate symbionts like AMF. Studies with P. indica have revealed an impressive array of benefits conferred to host plants including enhanced nutrient uptake, improved resistance to pathogens, and significantly improved tolerance to drought, salt, and other abiotic stresses [31].

7.2 Role in Drought Adaptation

The role of endophytic fungi in promoting drought adaptation of their host plants has received increasing research attention over the past decade, and the findings are compelling enough to suggest that endophytes may be underutilized tools for improving crop performance in water-limited environments. The mechanisms through which endophytic fungi confer drought tolerance overlap considerably with those described for AMF and Trichoderma, but also include some unique features.

Colletotrichum species, which include both endophytic and pathogenic strains, have been found to enhance drought tolerance in their host plants by modifying root architecture and improving osmotic adjustment [16]. Curvularia protuberata, an endophyte originally isolated from a thermotolerant grass growing in geothermal soils in Yellowstone National Park, has been shown to confer heat and drought tolerance to host plants through mechanisms that involve the production of specific secondary metabolites [33]. Neotyphodium endophytes in grass species produce alkaloids that deter insect herbivores and also contribute to improved drought tolerance, though some of these alkaloids are toxic to livestock which limits their use in forage grasses.

Dark septate endophytes (DSE), which are among the most abundant fungal endophytes in dryland soils, have recently emerged as particularly important contributors to drought adaptation in arid agricultural systems. Unlike AMF, DSE are not restricted in their host range and they can colonize a wide variety of crop plants including cereals, legumes, and vegetables. Studies have shown that DSE colonization improves plant growth under drought by enhancing phosphorus and nitrogen acquisition, improving water uptake, and modulating antioxidant responses, making them potentially very useful for dryland agriculture applications [17].

7.3 Agricultural Applications

Despite their great promise, endophytic fungi have so far seen limited direct agricultural application compared to AMF and Trichoderma. The main reason for this is the practical challenge of producing and delivering endophytic fungi in forms that can be efficiently applied to field crops. Unlike Trichoderma which grows readily on a wide range of substrates and can be formulated as dry spore products, many endophytic fungi are less amenable to mass production, and their establishment in field-grown crops from external inoculation can be inconsistent.

However, progress is being made on several fronts. P. indica can be produced in liquid fermentation and formulated as a liquid bioinoculant. Research groups in India, Germany, and China have developed methods for producing P. indica at scale and have demonstrated its effectiveness as a seed treatment or root dip inoculation in cereal crops under controlled conditions [6]. As the commercial interest in endophytic inoculants grows and more investment flows into this area, it is expected that practical production and delivery systems for endophytic fungi will be developed within the next decade. The potential market for endophytic bioinoculants in drought-prone regions like the Indo-Gangetic plains, the Sahel, and the Mediterranean basin is considerable.

8. Fungal Biofertilizers and Commercial Applications

8.1 Current Products

The commercial development of fungal biofertilizers has made significant progress over the past two decades, moving from largely research-based laboratory demonstrations to commercially available products that are being used by farmers in many parts of the world. The most established category of commercial fungal biofertilizers is based on AMF, particularly species of the genus Glomus and Rhizophagus. Several companies in Europe, North America, and India now offer AMF-based inoculant products in various formulations including granular, powder, gel, and liquid forms. Trichoderma-based biocontrol and biofertilizer products represent another large and well-established segment of the commercial fungal bioproducts market [13].

In India specifically, the market for fungal biofertilizers has grown considerably in response to government promotion of organic farming and reduced chemical input subsidies. Products combining Trichoderma viride, phosphate solubilizing fungi, and AMF are available from dozens of companies and are registered for use on a wide range of crops. The performance of these products in farmers' fields has been variable, largely due to issues of quality control and appropriate application conditions, but when used correctly they have demonstrated meaningful benefits in terms of crop growth and yield, particularly in rain-fed farming systems [32].

Table 3 presents an overview of some commercially available fungal biofertilizer products and their characteristics.

Table 3. Commercial Fungal Biofertilizers Used in Agriculture

Product Name	Active Fungal Component	Manufacturer/ Country	Target Crops	Key Benefits
Mycorrhiza Plus	Glomus intraradices + G. mosseae	IFFCO-Tokio, India	Wheat, Maize, Pulses	Drought tolerance, P uptake, root growth
Trichoderma Viride WP	Trichoderma viride (2x10^6 CFU/g)	Biofit Agro, India	Vegetables, Cereals, Cotton	Soil-borne disease suppression, growth promotion

BioRhiz AMF	Rhizophagus irregularis	Symborg, Spain	Grapevine, Olive, Tomato	Water use efficiency, soil health, yield
Rootgrow	Mixed AMF consortium (7 species)	PlantWorks UK	Ornamentals, Vegetables	Transplant success, drought survival
Piriformospora indica Culture	Piriformospora indica	NRCPB, India (Research stage)	Barley, Tobacco, Maize	Nutrient acquisition, systemic stress tolerance
Trianum-P	Trichoderma harzianum T22	Koppert Biologicals, Netherlands	Tomato, Pepper, Cucumber	Root growth stimulation, Pythium suppression
Phospho-Fungi	Aspergillus awamori + Penicillium sp.	Agri Life, India	Rice, Sugarcane, Groundnut	Phosphate solubilization, soil fertility improvement
MYCO-T	Glomus aggregatum + Trichoderma asperellum	Lallemand Plant Care, France	Cereals, Legumes, Oilseeds	Combined drought tolerance and biocontrol

8.2 Challenges in Field Application

Despite the considerable promise of fungal biofertilizers and the growing commercial market for these products, there are several significant challenges that currently limit their widespread adoption and consistent performance in farmer fields, particularly in dryland agriculture systems. Understanding these challenges is essential for developing more effective products and application strategies.

The most fundamental challenge is the issue of product quality and consistency. The effectiveness of a fungal biofertilizer depends entirely on the viability and activity of the fungal organisms it contains, and maintaining adequate live fungal populations through the manufacturing, storage, and transport chain is technically demanding, and field efficacy of a given microbial strain can vary considerably depending on the local soil type and resident microbial community [24]. Many commercial products on the market, particularly in developing countries, contain fewer viable spores or propagules than indicated on the label, which leads to disappointing field results that undermine farmer confidence in the technology. Regulatory standards for biofertilizer quality are increasingly being developed in countries like India and Brazil but enforcement remains a challenge.

Another major challenge is the specificity of fungal-plant interactions and the influence of soil conditions. AMF effectiveness in particular is strongly influenced by the existing soil AMF community, the soil phosphorus level, the crop variety being grown, and various soil chemical and physical parameters. A product that performs well in one soil type or region may give poor results in a different context, making it difficult to develop universal recommendations [8]. The presence of high soil phosphorus levels, which suppresses mycorrhizal colonization, is a particular problem in intensively fertilized soils.

For dryland farming systems specifically, the challenge of ensuring adequate soil moisture during the critical establishment period of the fungal-plant association is also a limiting factor. If the soil is too dry immediately after inoculation, the fungal propagules may not survive long enough to establish a productive association with plant roots. Formulation technology improvements, including encapsulation of fungal propagules in moisture-retaining materials, are being developed to address this problem.

8.3 Future Market Potential

Despite the current challenges, the future market potential for fungal biofertilizers is very substantial. The global biofertilizer market is currently valued at several billion US dollars and is growing at a compound annual growth rate of around 10% to 12%, driven by increasing consumer demand for organic food products, regulatory pressure on synthetic chemical inputs, and growing awareness among farmers of the long-term costs of chemical-intensive agriculture. Fungal products represent an important and growing segment of this market.

The development of precision fermentation technologies, better encapsulation and formulation science, and improved strain selection through genomics-assisted breeding programs is expected to significantly improve product quality and performance in coming years. The integration of fungal biofertilizer technology with precision agriculture tools including drone-based inoculant application, soil microbiome mapping, and AI-powered crop management platforms represents an exciting emerging frontier that could dramatically improve the targeting and effectiveness of biofertilizer inputs. For dryland agriculture systems in countries like India, where the government has strong policy incentives for reducing chemical fertilizer use while maintaining food production, the conditions for rapid expansion of the fungal biofertilizer market are increasingly favorable.

9. Impact of Soil Fungi on Crop Productivity

The collective impact of soil fungi on agricultural crop productivity in dryland systems, when all their contributions are considered together, is very substantial. Numerous field trials and meta-analyses have now quantified the productivity benefits of fungal inoculants across a wide range of crops, soil types, and climatic conditions, and the results consistently show significant positive effects particularly under water-limited or nutrient-deficient conditions.

A comprehensive meta-analysis of AMF inoculation trials published in recent years examined data from several hundred field and greenhouse studies and found that AMF inoculation improved crop yield by an average of 26% under drought stress conditions and by 18% under non-stressed conditions [2]. The benefits were more pronounced in soils with naturally low mycorrhizal populations and in crops with low root hair density. Wheat, chickpea, maize, and sorghum showed particularly consistent yield benefits from AMF inoculation in dryland environments [18].

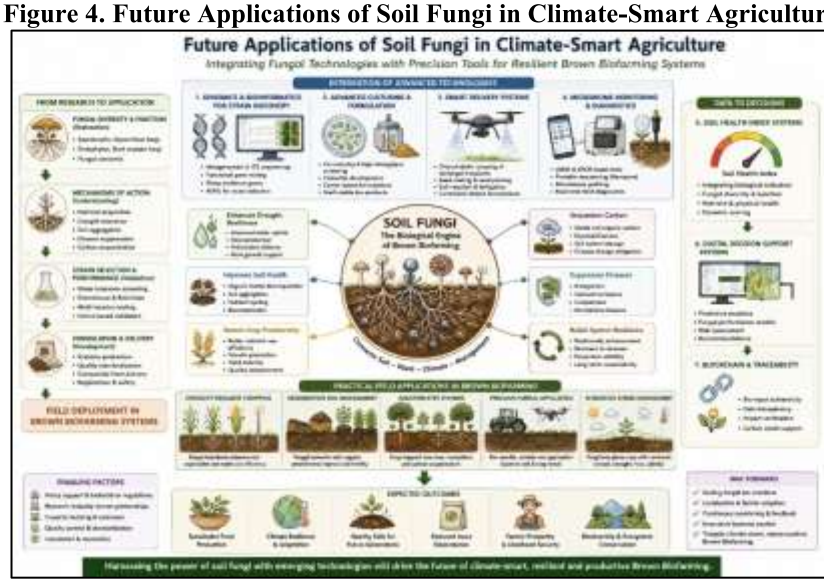
For Trichoderma inoculants, a similar pattern of significant yield benefits has been documented. Trials in India, Pakistan, and Mediterranean countries have shown 15% to 35% yield improvements in rain-fed wheat and chickpea following Trichoderma inoculation, associated with both disease suppression and direct growth promotion effects [11]. Combined inoculants containing both AMF and Trichoderma species have in several studies produced synergistic effects greater than either organism alone, suggesting that the two groups complement each other's mechanisms of action [8].

Beyond yield, soil fungi also improve the quality of crop produce. Mycorrhizal colonization has been shown to improve the nutritional content of crop grains, particularly zinc and iron content, which are important for addressing micronutrient deficiencies that affect large proportions of the population in developing countries [14]. The production of essential oils and secondary metabolites in medicinal and aromatic crops is also enhanced by AMF colonization, increasing the commercial value of the produce.

Looking at the broader picture of soil productivity over multiple growing seasons, the contributions of soil fungi to long-term soil health through organic matter building, aggregate stability maintenance, and nutrient cycling mean that their benefits compound over time. Fields with diverse and active fungal communities tend to become progressively more productive over years of conservation management, while those subjected to fungicidal treatments and intensive tillage show declining biological activity and productivity. This long-term soil health dimension of fungal contributions is perhaps their most important benefit from the perspective of sustainable Brown Biofarming.

Figure 4 illustrates the future applications of soil fungi in climate-smart agriculture, showing how current research directions are expected to translate into practical tools for dryland farming systems in the coming years.

Figure 4. Future Applications of Soil Fungi in Climate-Smart Agriculture



10. Research Gaps and Future Perspectives

While the existing body of research on soil fungi and their role in sustainable dryland agriculture is already substantial, there remain many important knowledge gaps that need to be addressed before the full potential of these organisms can be realized in practical Brown Biofarming systems. Identifying these gaps clearly is important for guiding future research investment and ensuring that scientific progress translates efficiently into practical agricultural impact.

One of the most significant gaps concerns the ecology of soil fungal communities in Indian and South Asian dryland agricultural systems. While extensive research on AMF and other beneficial fungi has been conducted in Europe and North America, relatively fewer systematic studies have characterized the native soil fungal communities in the specific dryland agroecosystems of Rajasthan, the Deccan Plateau, the Indo-Gangetic plains, or the dryland areas of Maharashtra and Karnataka. Understanding which fungal species are naturally abundant and ecologically effective in these specific environments is a prerequisite for selecting the most appropriate native strains for biofertilizer development, as locally adapted strains are likely to outperform exotic strains introduced from other geographic regions.

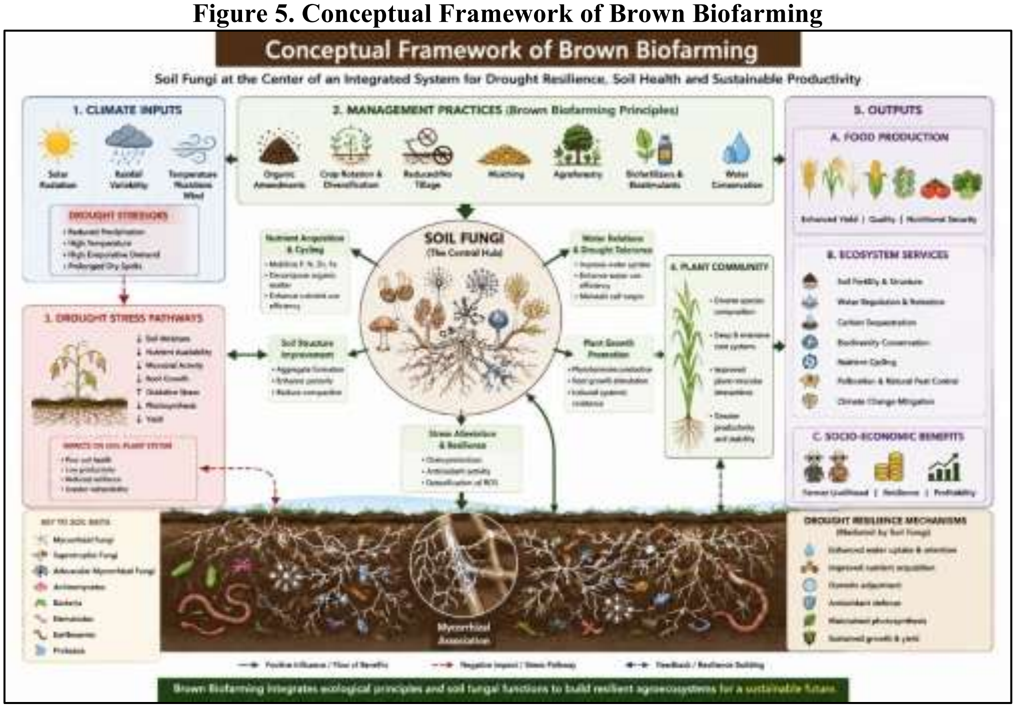
The molecular mechanisms through which fungi communicate with plant roots during the drought stress response are still incompletely understood. While significant progress has been made in characterizing the signaling molecules involved in mycorrhizal establishment, the specific molecular dialogues that occur between fungi and plants during stress conditions, and how these lead to the observed transcriptomic and physiological changes in plants, remain areas of active investigation. A better mechanistic understanding would allow researchers to identify the most important molecular targets for strain improvement and to design smarter inoculation strategies.

The interaction between soil fungal communities and other components of the soil microbiome, including bacteria, archaea, and protists, is another area where understanding remains limited. It is increasingly recognized that the beneficial effects of fungi often depend on positive interactions with specific groups of bacteria, and that the composition of the broader microbial community strongly influences how effectively introduced fungal inoculants establish and function [27,26]. Developing holistic microbiome management strategies rather than single-organism inoculants may produce more consistent and durable benefits in field applications.

Climate change itself introduces additional complexities that need more research attention. How will the composition and ecological functions of soil fungal communities change as temperatures rise and rainfall patterns shift over the coming decades? Which fungal species and functional groups will be winners and which will be losers as climate envelopes shift? How will the mutualistic associations between plants and fungi be affected by elevated atmospheric CO_2 concentrations, which are known to alter plant carbon allocation patterns including the carbon supplied to mycorrhizal symbionts [7]? These are questions of fundamental ecological importance that also have direct practical relevance for the long-term viability of fungi-based Brown Biofarming strategies.

Finally, there is a need for more rigorous, multi-year, multi-location field trials of fungal biofertilizer products under realistic dryland farming conditions, particularly in developing countries where much of the need lies but where research infrastructure is most limited. Many existing studies have been conducted under controlled greenhouse or laboratory conditions that do not fully capture the variability and complexity of actual farmer fields. Building a more robust evidence base from field trials that include farmer participatory research components would greatly accelerate the adoption of fungal biotechnology in dryland agricultural systems.

Figure 5. Conceptual Framework of Brown Biofarming



11. Conclusions

Soil fungi represent one of the most important and yet still underutilized biological resources available to sustainable agriculture in arid and semi-arid regions. As this review has attempted to show, the contributions of beneficial soil fungi to plant drought tolerance, soil health maintenance, and crop productivity are diverse, multi-mechanistic, and consistently demonstrated across a wide range of crops, soil types, and climatic conditions.

Arbuscular mycorrhizal fungi, through their combined contributions to water and nutrient uptake, glomalin-mediated soil aggregation, and drought-responsive gene regulation, provide the most comprehensively documented set of benefits for dryland crops. Trichoderma species add complementary benefits through biocontrol of pathogens, direct plant growth promotion, and induced abiotic stress tolerance. Endophytic fungi, particularly dark septate endophytes and Piriformospora indica, represent an emerging frontier with substantial unrealized potential for dryland agricultural applications. Together, these groups of fungi form the biological foundation of a Brown Biofarming system that can be genuinely productive and sustainable without relying on large inputs of synthetic chemicals or irrigation water.

The translation of this scientific knowledge into practical tools for farmers, however, requires continued progress on several fronts. Improvement in the quality, consistency, and shelf life of commercial biofertilizer products is essential. Better understanding of how to match specific fungal strains to specific soil and crop contexts will improve the reliability of field performance. The development of integrated microbiome management approaches that optimize the entire soil biological community rather than just targeting individual organisms will likely produce more durable and consistent benefits in the complex, variable conditions of real farmer fields.

Perhaps most importantly, the integration of soil fungal biotechnology into Brown Biofarming must be approached as a long-term investment in soil health rather than as a quick-fix input. The real power of soil fungi lies in their ability to restore and maintain the biological processes that make soil inherently fertile and resilient over time. Farming systems that nurture their soil fungal communities through conservation tillage, organic matter management, diverse crop rotations, and reduced pesticide use will progressively build the biological capital that underpins sustainable productivity in dryland environments. This biological capital, once established, represents a form of natural insurance against the increasingly unpredictable climate variability that threatens food security in arid regions around the world.

In conclusion, investing in the science and practice of soil fungal management is not merely an agronomic option but an ecological imperative for the long-term sustainability of food production in dryland ecosystems globally. Future research and policy should strongly support the development and deployment of fungal biotechnology as a core component of climate-resilient Brown Biofarming systems, particularly in the food-insecure dryland regions of South Asia, Sub-Saharan Africa, and the Mediterranean basin where the need is most urgent.

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