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Review Article

Review of New Aspects of Mycorrhiza

Abdullah Msaad Al Falih*

Department of Botany and Microbiology, College of Science, King Saud University, Saudi Arabia

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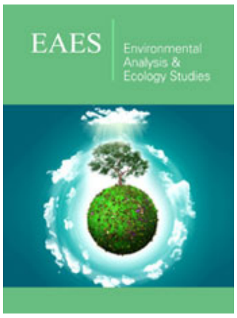

***Corresponding author:** Abdullah Msaad Al Falih, Department of Botany and Microbiology, College of Science, King Saud University, Saudi Arabia

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Abstract

Mycorrhiza, a symbiotic association between fungi and plant roots, has been extensively studied for its ecological and agricultural significance. Recent advancements in molecular biology, climate change studies, and biotechnology have expanded our understanding of mycorrhizal functions. This review explores the latest discoveries in mycorrhizal research, including signaling mechanisms, biotechnological applications, interactions with pathogens, and their role in carbon sequestration. The evolving landscape of mycorrhizal research underscores the complexity and significance of plant-fungal interactions in natural ecosystems and human-modified environments. The recent discoveries of new species, the elucidation of molecular signaling pathways, and the understanding of their role in mitigating climate change highlight the importance of these fungi in both ecological and applied contexts. The continued exploration of mycorrhizal fungi offers the potential for groundbreaking advances in sustainable agriculture, environmental conservation, and climate change mitigation. Through deeper insights into their biology, diversity, and functionality, mycorrhizal fungi hold the key to unlocking more sustainable and resilient systems for the future.

Keywords: Mycorrhiza; Symbiotic; Biotechnology; Pathogens and plant immunity

Introduction

Mycorrhizae play a crucial role in plant nutrition, soil ecology, and ecosystem stability. Traditional studies have focused on nutrient exchange and plant growth promotion, but recent research highlights new roles in plant immunity, stress tolerance, and global carbon cycles. With the emergence of new molecular tools and environmental challenges, understanding mycorrhizal interactions at a deeper level has become a priority. This review summarizes these novel aspects and provides insights into future applications. Mycorrhizal fungi are essential symbiotic organisms that form intimate associations with plant roots, facilitating the exchange of nutrients and contributing to the overall health and growth of plants. The relationship between fungi and plants has long been understood to play a crucial role in enhancing nutrient uptake, especially phosphorus, nitrogen, and other essential minerals. However, in recent years, research has illuminated the more complex nature of this relationship, revealing that mycorrhizal fungi are involved in far more than simple nutrient exchange. This review delves into five key areas of recent advancements in mycorrhizal research, including molecular mechanisms and signaling pathways, the role of mycorrhizal fungi in climate change and carbon sequestration, their agricultural applications, their interactions with pathogens and plant immunity, and the discovery of newly classified species [1].

The molecular mechanisms that underpin the establishment and functioning of mycorrhizal symbiosis have become a significant focus of modern plant-fungal interaction research. Recent work has shown that the establishment of this symbiosis involves a complex exchange of molecular signals between the plant and fungal partners. Plants release signals, such as strigolactones, that attract mycorrhizal fungi, while fungi reciprocate with signaling molecules such as myc factors, which help the plant recognize the fungal presence and establish a connection [2]. At the molecular level, mycorrhizal fungi and their host plants engage in a sophisticated signaling network involving hormones, receptors, and transcription factors. For instance, plant hormones like auxins, cytokinins, and abscisic acid play a crucial role in regulating the development of mycorrhizal structures, including arbuscules (tree-like structures formed inside plant root cells by arbuscular mycorrhizal fungi) and hyphal networks. The regulation of these molecular pathways is critical for maintaining symbiotic relationships, and recent breakthroughs have shed light on how the plant can modulate it signaling pathways to accommodate fungal partners while ensuring that it receives the necessary nutrients [3].

One of the most fascinating recent findings is the identification of specific genes and proteins in both plants and fungi that facilitate this mutualistic exchange. Studies involving genomic sequencing of both fungal and plant genomes have revealed key players involved in these signaling networks, offering new opportunities for manipulating these pathways to enhance mycorrhizal efficiency in agricultural settings [4]. As concerns about climate change and its global impacts intensify, the role of mycorrhizal fungi in carbon cycling has gained significant attention. Mycorrhizal fungi play a central role in the carbon sequestration process, an essential function that can help mitigate the effects of climate change. Arbuscular Mycorrhizal (AM) fungi contribute to the stabilization of carbon in soils by transferring carbon from plants into the soil in the form of organic compounds, such as glomalin-a glycoprotein that helps to bind soil particles together.

Studies have shown that the presence of mycorrhizal fungi increases the amount of carbon stored in the soil, both by enhancing plant growth (and thus photosynthesis) and by increasing the longevity of carbon compounds in the soil [5]. These fungi facilitate nutrient uptake, particularly of phosphorus and nitrogen, which allows plants to grow more robustly and sequester more carbon. Additionally, the fungal hyphal networks create a physical structure in the soil that improves soil aggregation, reduces soil erosion and enhances the long-term storage of carbon. The increasing recognition of mycorrhizal fungi's role in carbon sequestration is particularly relevant in the context of global carbon cycle models. Researchers are exploring how changes in mycorrhizal communities, driven by climate change or soil disturbances, could affect carbon fluxes in ecosystems. A decline in mycorrhizal populations could lead to reduced carbon storage, exacerbating global warming [6].

Mycorrhizal fungi have been recognized as potential tools for improving agricultural productivity and sustainability. Agricultural scientists have been exploring the use of mycorrhizal inoculants-fungal spores and hyphal fragments that can be added to soil to promote beneficial plant-fungal symbioses [7]. These inoculants are being used to enhance plant growth, especially in nutrient-poor soils, and to reduce reliance on chemical fertilizers. Mycorrhizal fungi play a key role in enhancing plant nutrient uptake, particularly phosphorus, nitrogen, and micronutrients (Table 1). They are also involved in improving water retention in soils, promoting drought tolerance, and increasing resistance to soil-borne diseases. The use of mycorrhizal fungi in agriculture has the potential to revolutionize farming by improving soil health, enhancing crop yield, and reducing the need for chemical inputs, which are costly and harmful to the environment [7].

Table 1: Types of mycorrhizal associations and their key feature.

Mycorrhizal Type	Host Plants	Key Fungal Phyla	Main Characteristics	Example Species
Arbuscular Mycorrhiza (AM)	80% of land plants (e.g., cereals, legumes)	Glomeromycota	Arbuscules, vesicles, intracellular hyphae	Rhizophagus irregularis
Ectomycorrhiza (ECM)	Trees (e.g., pines, oaks)	Basidiomycota, Ascomycota	Hartig net, fungal mantle, extracellular hyphae	Pisolithus tinctorius
Ericoid Mycorrhiza (ERM)	Ericaceae (e.g., blueberries)	Ascomycota	Intracellular hyphae	Oidiodendron maius
Orchids Mycorrhiza (ORM)	Orchids	Basidiomycota	Nutrient supply from fungi to seedling	Tulasnella calospora

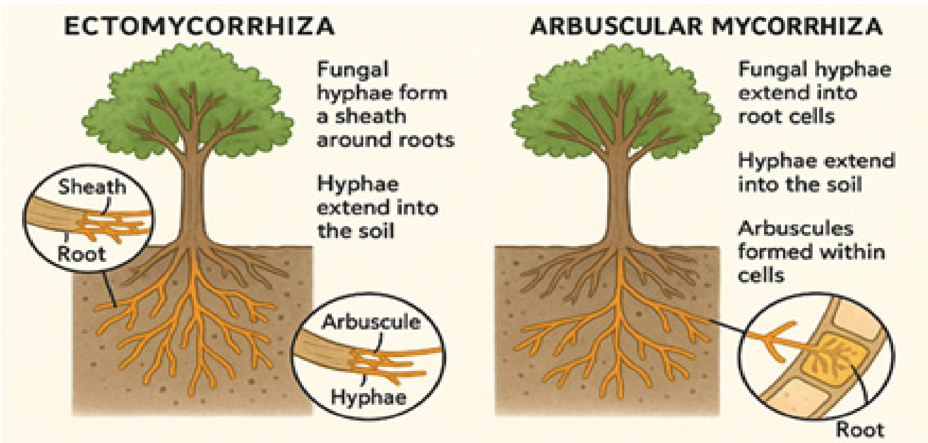

Figure 1: Types of mycorrhizal associations and their key features.

In biotechnology, the manipulation of mycorrhizal fungi at the genetic level holds promises for creating fungi with enhanced performance. For example, biotechnologists are investigating how to engineer mycorrhizal fungi that are more resilient to environmental stressors, such as drought or salinity, or that can establish beneficial relationships with a wider range of plant species. Such innovations could lead to the development of more resilient crops and more sustainable agricultural practices, providing solutions to the growing challenges of food security and climate change [8]. One of the more intriguing aspects of mycorrhizal fungi is their ability to influence plant immunity and provide protection against pathogens. Research has shown that plants in mycorrhizal symbiosis exhibit enhanced resistance to a range of pathogens, including bacteria, fungi, and nematodes. This protective effect is largely mediated by the signaling pathways activated by the presence of mycorrhizal fungi [9] as shown in detail (Figure 1).

Mycorrhizal fungi activate plant immune responses through the production of signaling molecules that trigger the plant's defense mechanisms. For example, the mycorrhizal fungus Rhizophagus irregularis has been shown to enhance systemic resistance in plants to pathogenic fungi like Fusarium species. These fungi also help plants better withstand biotic stressors by inducing the production of antimicrobial compounds in plant tissues [10]. The interaction between mycorrhizal fungi and the plant immune system is an area of intense research, with studies showing that plants can differentiate between beneficial fungi and harmful pathogens, modulating their immune responses accordingly [11]. This ability to trigger specific immune responses also suggests that mycorrhizal fungi could be used as biocontrol agents, offering an eco-friendly alternative to chemical pesticides in agriculture.

The discovery of new mycorrhizal species and the reevaluation of existing classifications continue to reshape our understanding of fungal diversity and plant-fungal interactions. New species of both mycorrhizal fungi and mycoheterotrophic plants (those that rely entirely on fungi for nutrition) are being discovered regularly, especially in biodiversity hotspots such as tropical rainforests, temperate forests, and high-altitude ecosystems. These findings often reveal novel interactions and adaptations that challenge existing taxonomic and ecological paradigms [12]. For instance, mycoheterotrophic plants like Thismia malayana and Thismia villosa have been recently described. These plants form parasitic relationships with mycorrhizal fungi and rely on them for nutrition, instead of engaging in photosynthesis [13]. These plants are important both ecologically and evolutionarily, as they provide insights into the complexity of plant-fungal interactions and the potential evolutionary pathways that mycorrhizal relationships might follow.

In addition to new plant species, novel fungal taxa have been identified in unexplored ecosystems. Advances in molecular techniques, such as DNA sequencing and metagenomics, have greatly enhanced our ability to uncover hidden fungal diversity in soil and plant roots. As a result, the classification of mycorrhizal fungi has become more refined, with new genera and species being added to the growing list of known mycorrhizal organisms [14].

Molecular Mechanisms and Signaling Pathways

Mycorrhizal recognition and signal exchange

The initial step in mycorrhizal formation involves intricate signaling mechanisms between fungi and plant roots. Recent studies reveal that plant-derived strigolactones serve as crucial signaling molecules stimulating fungal spore germination and hyphal branching. In response, fungi release lipochitooligosaccharides (Myc factors) that facilitate host compatibility by activating plant symbiosis-related genes [12]. The discovery of these molecular dialogues has paved the way for engineering to improve plant-microbe interactions (Table 2).

Table 2: Key signaling molecules in mycorrhizal symbiosis.

Molecule	Function	Mycorrhizal Type	Plant/Fungal Source
Strigolactones	Fungal attraction, hyphal branching	AM	Plant
Myc Factors	Fungal recognition by plant	AM	Fungus
LysM Receptors	Perception of Myc factors	AM	Plant
DMI1/DMI2/DMI3	Ca^{2+} spiking and symbiosis	AM	Plant
SYMRK	Symbiosis receptor kinase	AM	Plant
CCaMK	Ca^{2+}-dependent kinase	AM	Plant
PT4 Transporter	Phosphate uptake	AM	Plant
Lipids & Sugars	Carbon transfer to fungi	AM, ECM	Plant

Strigolactones and fungal perception: Strigolactones are carotenoid-derived plant hormones secreted into the rhizosphere, where they act as key signaling molecules in mycorrhizal recognition. These compounds stimulate fungal spore germination and directional hyphal growth toward the root [15]. The regulation of strigolactone biosynthesis is influenced by environmental factors such as phosphorus availability, which suggests an adaptive response in plants to attract mycorrhizal fungi under nutrient-deficient conditions (Figure 2).

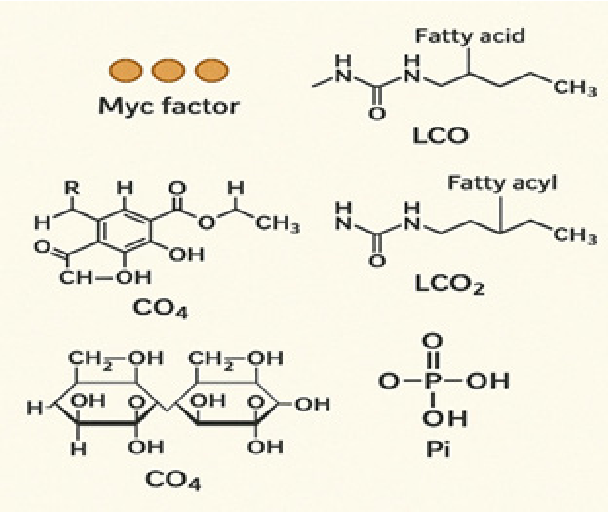

Figure 2: Signaling molecules formula in mycorrhizal symbiosis.

Myc factors and plant receptor activation: Mycorrhizal fungi release lipochitooligosaccharides (LCOs), known as Myc factors, which are structurally similar to rhizobial Nod factors. These Myc factors bind to LysM receptor-like kinases on the plant root surface, triggering a cascade of symbiotic signaling events [4]. The activation of these receptors initiates downstream responses that facilitate fungal colonization, including cytoskeletal rearrangements and changes in gene expression related to symbiosis.

Calcium signaling and nuclear responses: One of the earliest intracellular responses to Myc factor perception is calcium spiking in plant root cells. This oscillatory calcium signaling, known as calcium signatures, is decoded by calcium/calmodulin-dependent protein kinases (CCaMK), which subsequently activate transcription factors required for symbiosis [11]. Mutations in CCaMK or downstream signaling components disrupt mycorrhizal colonization, highlighting the essential role of calcium signaling in symbiotic establishment (Figure 3).

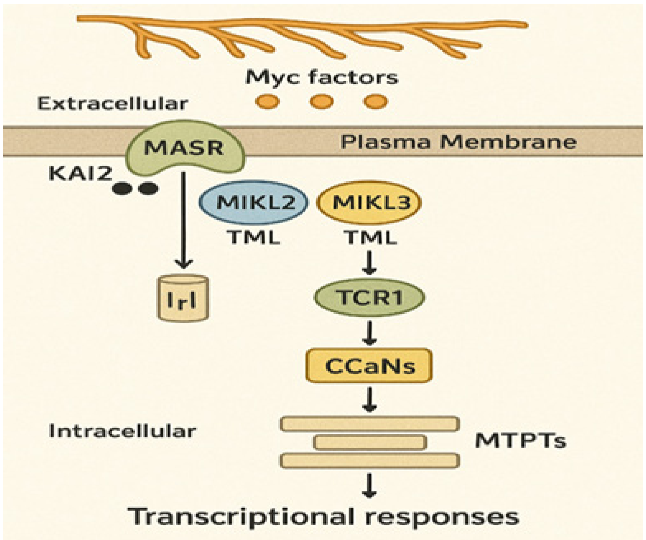

Figure 3: Mycorrhizal molecular mechanisms and signaling pathways.

Hormonal crosstalk in mycorrhizal recognition: Phytohormones such as auxins, cytokinins, and gibberellins interact with mycorrhizal signaling pathways to regulate fungal colonization. Auxins promote root hair elongation and infection site formation, while gibberellins modulate DELLA proteins, which act as negative regulators of symbiosis [16]. Additionally, cytokinins play a dual role in balancing fungal colonization and plant immune responses, ensuring optimal symbiotic interactions.

Fungal perception of plant-derived signals: Mycorrhizal fungi possess receptor-like proteins that detect plant-released strigolactones and other secondary metabolites. This perception triggers fungal morphological changes, including enhanced hyphal branching and increased secretion of Myc factors. Genetic studies have identified fungal genes involved in this perception, such as those encoding G-protein-coupled receptors and MAP kinase signaling components [17]. Understanding fungal responses to plant signals provides new insights into engineering beneficial plant-fungal associations.

Evolutionary perspectives on mycorrhizal recognition: Comparative genomic studies suggest that mycorrhizal signaling pathways share common elements with rhizobial nitrogen-fixing symbioses. The presence of conserved symbiotic genes across land plants indicates an ancient evolutionary origin for mycorrhizal recognition mechanisms [2]. Exploring these conserved pathways can help in identifying novel genes that enhance symbiotic efficiency in different plant species.

Genetic regulation of symbiosis

Transcriptomic and genomic studies have identified several regulatory genes involved in mycorrhizal symbiosis. For example, RAM1, a key transcription factor, regulates arbuscule development within root cortical cells. Other genes, such as NSP1 and NSP2, contribute to symbiotic signaling pathways, facilitating fungal colonization [18]. CRISPR-Cas9 technology has enabled precise gene modifications, providing new insights into mycorrhizal genetic regulation.

The establishment and maintenance of mycorrhizal symbiosis involve complex genetic regulation in both host plants and fungi. Several key genes, transcription factors, and signaling pathways play crucial roles in facilitating this mutualistic interaction. Recent genomic and transcriptomic studies have provided insights into the molecular mechanisms underlying mycorrhizal symbiosis, shedding light on genes involved in fungal recognition, signaling, and nutrient exchange.

Plant genes involved in mycorrhizal symbiosis: Several plant genes have been identified as essential for mycorrhizal formation and function. Among them, genes related to the Common Symbiosis Signaling Pathway (CSSP) play a pivotal role in establishing both arbuscular mycorrhizal (AM) and rhizobial symbioses. These genes include:

A. DMI1, DMI2, and DMI3 (Doesn't Make Infections): These genes encode proteins required for calcium spiking, an essential early signaling event in mycorrhizal colonization.

B. SYMRK (Symbiosis Receptor-like Kinase): A key receptor that perceives fungal signals and triggers intracellular signaling cascades.

C. CCaMK (Calcium/Calmodulin-Dependent Protein Kinase): Acts as a downstream regulator of calcium signaling, essential for arbuscule formation.

D. RAM1 (Required for Arbuscular Mycorrhization 1): A transcription factor involved in fungal accommodation within plant roots.

E. STR and STR2 (Stunted Arbuscule genes): Transporters that regulate lipid transfer between plant cells and fungal structures, critical for maintaining the mutualistic relationship.

These genes work in a coordinated manner to perceive fungal signals, activate symbiosis-related pathways, and ensure proper colonization and nutrient exchange.

Fungal genes regulating symbiosis: On the fungal side, several genes are required for successful host colonization and nutrient exchange. These genes contribute to fungal hyphal growth, root penetration, and the formation of specialized structures such as arbuscules and Hartig nets. Key fungal genes include:

a. Myc Factors: Small signaling molecules released by mycorrhizal fungi to initiate symbiosis. These factors induce plant gene expression changes necessary for fungal accommodation.

b. SP7 (Secreted Protein 7): A key effector protein secreted by AM fungi to modulate plant immune responses and promote colonization.

c. Fungal Transporter Genes: Including phosphate transporters such as GintPT (in Glomus species), which facilitate the movement of nutrients from fungi to plant roots.

d. Ectomycorrhizal Symbiosis-Associated Genes: Such as Laccase genes, which play a role in modifying plant root surfaces for colonization.

Transcriptional regulation of symbiosis: The establishment of mycorrhizal symbiosis requires precise regulation of gene expression. Various transcription factors control the activation of symbiosis-related genes in plants, including:

a) GRAS Family Transcription Factors: Such as RAM1 and NSP1, which regulate arbuscule formation and fungal accommodation.

b) MYB Transcription Factors: Involved in lipid metabolism and nutrient exchange, ensuring a balanced symbiotic relationship.

c) WRKY Transcription Factors: Regulate plant immunity and help suppress defense responses against beneficial mycorrhizal fungi.

On the fungal side, transcription factors such as STE12 regulate hyphal development and host interaction, ensuring effective colonization.

Epigenetic regulation in mycorrhizal symbiosis: Recent studies suggest that epigenetic modifications, such as DNA methylation and histone modifications, play a role in regulating symbiosis-related genes. DNA methylation patterns in host plants have been shown to change upon fungal colonization, leading to stable gene expression changes that favor mutualistic interactions. Additionally, small RNAs and microRNAs contribute to fine-tuning gene expression during mycorrhizal interactions, further highlighting the complexity of genetic regulation in symbiosis.

Future perspectives and applications: Understanding the genetic regulation of mycorrhizal symbiosis opens new avenues for agricultural and ecological applications. Genetic engineering approaches could be used to enhance plant-mycorrhizal interactions, improving nutrient uptake and stress tolerance in crops. Additionally, manipulating fungal genes to enhance symbiotic efficiency may provide novel strategies for restoring degraded soils and promoting sustainable agriculture. Further research into the interplay between genetic, epigenetic, and environmental factors will be crucial in harnessing mycorrhizal symbiosis for future applications.

A. Key plant genes involved in signaling and arbuscule formation (e.g., DMI1-3, SYMRK, CCaMK, RAM1).

B. Important fungal genes like SP7 (modulating plant immunity) and GintPT (phosphate transport).

C. Roles of transcription factors such as GRAS, MYB, WRKY (in plants), and STE12 (in fungi).

D. An overview of epigenetic regulation, including DNA methylation and small RNAs, as mechanisms that fine-tune gene expression during symbiosis.

Mycorrhiza in Climate Change and Carbon Sequestration

Mycorrhizal fungi play a significant role in carbon sequestration by increasing root biomass and contributing to stable carbon compounds like glomalin, a glycoprotein responsible for soil aggregation [19]. This carbon storage potential has important implications for mitigating climate change effects by enhancing soil organic matter stability. Climate change affects mycorrhizal communities by altering fungal diversity and functionality. Studies indicate that Arbuscular Mycorrhizal Fungi (AMF) exhibit temperature-dependent activity, influencing plant stress responses and carbon exchange processes [20]. Understanding these adaptations can help predict ecosystem responses to climate change and develop resilient agricultural practices.

Mycorrhizal fungi play a crucial role in mitigating climate change by influencing carbon cycling, enhancing soil carbon storage, and improving plant resilience to environmental stressors. These fungi form vast underground networks that contribute to soil structure, organic matter accumulation, and carbon sequestration, making them a key component in global carbon dynamics.

Role in soil carbon storage

Mycorrhizal fungi contribute significantly to soil carbon storage through multiple mechanisms. By forming extensive hyphal networks, they promote soil aggregation and stability, reducing carbon loss from soil erosion. A major contributor to long-term carbon sequestration is glomalin, a glycoprotein produced by Arbuscular Mycorrhizal Fungi (AMF), which binds to soil particles and enhances organic matter retention [19]. Additionally, mycorrhizae facilitate the transfer of photosynthetically fixed carbon from plants into the soil, where it is stored in fungal biomass and converted into stable carbon forms.

For instance, a long-term study on tallgrass prairie restoration in the U.S. Midwest found that soil organic carbon increased by 10-25% over a decade, largely due to enhanced AMF activity and glomalin production. In subtropical China, reforestation with mycorrhizal tree species led to soil organic carbon accumulation rates of up to 1.5Mg C ha^{-1} $year^{-1}$, with glomalin levels positively correlated with carbon stabilization. Furthermore, ectomycorrhizal fungi have been shown to reduce organic matter decomposition rates by competing with saprotrophic microbes for nutrients, indirectly slowing carbon turnover in forest ecosystems. For example, boreal forests in Sweden dominated by ectomycorrhizal fungi exhibited soil carbon stocks 70% higher than those associated with AMF, primarily due to slower decomposition and deeper carbon storage.

Influence on plant biomass and photosynthesis

Mycorrhizal fungi improve plant biomass production by enhancing nutrients and water uptake. Increased root biomass directly translates to greater carbon inputs into soil systems. Moreover, symbiosis influences plant photosynthetic rates by optimizing nutrient acquisition, particularly nitrogen and phosphorus, which are essential for chlorophyll synthesis and energy metabolism. Enhanced plant productivity results in greater atmospheric CO_2 sequestration through photosynthesis, indirectly contributing to climate change mitigation [3].

Recent findings indicate that mycorrhizal fungi not only enhance nutrient absorption but also regulate hormonal pathways that control plant growth and development. Studies have identified that AMF modulates cytokinin and auxin signaling, leading to increased root and shoot biomass. This enhanced plant vigor not only increases carbon fixation but also improves stress tolerance under climate-induced environmental fluctuations. Empirical data from Indian agroecosystems show that AMF inoculation led to a 30% increase in root biomass and a 15% rise in soil carbon over three cropping seasons, particularly under low-phosphorus conditions. These results highlight the direct contribution of mycorrhizal-induced plant growth to carbon input in soils.

Response to global warming and environmental stress

Climate change influences mycorrhizal communities by altering fungal diversity, distribution, and functionality. Studies suggest that arbuscular mycorrhizal fungi exhibit temperature-dependent activity, with shifts in fungal composition affecting plant stress responses and carbon exchange processes. Under elevated temperatures, certain mycorrhizal associations enhance drought resilience by modulating root hydraulic properties and promoting water retention. However, extreme temperature fluctuations and prolonged heat stress can reduce fungal colonization rates, potentially weakening plant-fungal interactions in some ecosystems [21].

Additionally, the resilience of mycorrhizal symbioses under elevated CO_2 levels has been a major focus of research. Some studies suggest that AMF colonization rates increase under high CO_2 conditions, promoting faster plant growth and carbon sequestration. Greenhouse studies simulating climate change have shown that AMF colonization increased by up to 45% under elevated CO_2, resulting in a 20% rise in plant-derived carbon translocated to soil. However, this effect is dependent on soil nutrient availability, as low phosphorus conditions can limit the benefits of enhanced fungal associations.

Mycorrhiza and soil microbiome interactions

Beyond their direct role in carbon sequestration, mycorrhizal fungi interact with other soil microbes to influence organic matter decomposition and nutrient cycling. These interactions regulate microbial respiration rates, affecting carbon turnover. Some mycorrhizal fungi suppress microbial decomposers that accelerate organic matter breakdown, effectively slowing carbon release into the atmosphere. Others facilitate the formation of microbial consortia that enhance carbon stabilization, supporting long-term soil fertility and resilience to environmental change [2].

Recent metagenomic studies have revealed that mycorrhizal fungi can alter the composition of rhizosphere bacterial communities, selectively enriching microbial groups that contribute to soil carbon storage. These indirect effects of mycorrhizal symbioses highlight the complex interactions between fungal networks and microbial ecosystems, further influencing global carbon dynamics.

Potential for carbon sequestration in agricultural and forest systems

Agricultural practices that enhance mycorrhizal associations, such as reduced tillage, cover cropping, and organic amendments, can improve soil carbon sequestration. Similarly, in forest ecosystems, mycorrhizal fungi contribute to carbon storage by increasing tree biomass and promoting soil organic matter accumulation. Recent studies highlight the importance of mycorrhizal diversity in determining forest carbon dynamics, with ectomycorrhizal fungi playing a particularly significant role in temperate and boreal forests by slowing organic matter decomposition and enhancing deep soil carbon storage [22].

The application of AMF inoculants in degraded Indian farmlands has demonstrated a capacity to significantly enhance root biomass and carbon sequestration, even under nutrient-poor conditions. Similarly, prairie restoration in North America using mycorrhizal-supportive techniques yielded substantial improvements in soil carbon stocks within a decade. Moreover, the introduction of mycorrhizal inoculants into degraded lands has shown promising results in restoring soil fertility and increasing carbon sequestration rates. By establishing functional fungal networks, these inoculants facilitate plant growth, accelerate organic matter accumulation, and contribute to ecosystem recovery.

Future directions in climate mitigation strategies

Understanding mycorrhizal contributions to carbon sequestration has significant implications for climate change mitigation. Strategies such as inoculating crops with efficient mycorrhizal species, promoting mycorrhizal conservation in degraded landscapes, and integrating fungal networks into carbon offset programs are being explored as potential solutions. Further research into mycorrhizal adaptation to climate change, including their ability to maintain symbiotic efficiency under altered environmental conditions, will be critical for developing resilient agroecosystems and natural carbon sinks. By enhancing carbon sequestration and promoting plant health under changing climatic conditions, mycorrhizal fungi represent a promising tool for mitigating global warming effects. Future interdisciplinary research integrating mycorrhizal biology, soil science, and climate modeling will be essential in harnessing their full potential for sustainable environmental management.

Agricultural Applications and Biotechnology of Mycorrhiza

Enhancing crop yield and nutrient uptake

Mycorrhizal fungi play a significant role in improving agricultural productivity by enhancing nutrient uptake, particularly phosphorus and nitrogen. The extensive fungal hyphal network extends beyond the root zone, increasing nutrient absorption efficiency. This natural nutrient acquisition process reduces dependency on chemical fertilizers, lowering production costs and minimizing environmental impact [23].

Concrete examples support these benefits. In maize cultivation in sub-Saharan Africa, AMF inoculation led to a 60% increase in phosphorus uptake and a 25% yield boost. Similarly, wheat fields in Australia inoculated with AMF showed a 15-20% increase in grain yield, while fertilizer inputs were reduced by up to 30%. In India, inoculation of chickpea with AMF resulted in a 20% yield increase and reduced phosphorus fertilizer use by 40%, demonstrating significant cost savings and environmental benefits.

Stress tolerance and disease resistance

Mycorrhizal fungi help plants tolerate abiotic stresses such as drought, salinity, and heavy metal toxicity by improving water retention, regulating ion balance, and modulating stress-related gene expression. They also enhance plant resistance to pathogens by inducing systemic resistance and competing with harmful soil microbes, reducing the need for chemical pesticides. For example, tomato crops in saline soils of Iran treated with AMF showed increased biomass and fruit yield by 35% compared to non-inoculated controls. In Spain, AMF inoculation in lettuce under water-stressed conditions led to a 40% improvement in water-use efficiency and a 25% increase in yield. These results highlight mycorrhizae's practical role in improving stress tolerance in challenging environments.

Soil health and sustainable agriculture

Incorporating mycorrhizal fungi into agricultural practices improves soil structure, enhances microbial diversity, and increases soil organic matter. These benefits contribute to long-term soil fertility, making mycorrhizae essential for sustainable farming systems. Field trials in France demonstrated that long-term use of mycorrhizal inoculants in vineyards improved soil aggregation and microbial biomass by over 30%, while enhancing grapevine resilience to drought. In Brazilian soybean systems, mycorrhizal application improved soil organic carbon by 18% and sustained yields over multiple growing seasons.

Biotechnological innovations

Advancements in biotechnology have enabled the large-scale production of mycorrhizal inoculants for commercial use. Genetic engineering approaches are being explored to enhance fungal efficiency, optimize plant-fungal compatibility, and develop biofertilizers tailored for specific crops and soil conditions. Commercial success stories include the development of crop-specific AMF formulations used in Californian almond orchards, where inoculated trees exhibited a 20% increase in nut yield and improved nutrient density. Biotech firms are also exploring AMF strains with higher stress tolerance for use in arid regions. Genetic regulation of mycorrhizal symbiosis is a growing focus of biotechnology. Key plant genes such as DMI1, DMI2, DMI3, SYMRK, CCaMK, and RAM1 have been identified as critical to the establishment and functioning of arbuscular mycorrhizal relationships. These genes regulate early signaling, calcium spiking, and arbuscule development, allowing plants to effectively host and benefit from symbiotic fungi. On the fungal side, genes such as SP7 and GintPT facilitate plant immune modulation and phosphate transport, respectively.

Transcription factors like the GRAS, MYB, and WRKY families regulate symbiotic gene expression in plants, while fungal transcription factors such as STE12 govern hyphal development and host interactions. Emerging research also indicates that epigenetic mechanisms-such as DNA methylation and small RNAs—modulate symbiosis-related gene expression, offering potential biotechnological targets for improving the efficacy and stability of mycorrhizal associations in agricultural settings.

Future prospects

Future research should focus on optimizing mycorrhizal applications through precision agriculture, genetic engineering, and microbiome management. Integrating mycorrhizal biotechnology with other sustainable practices, such as organic farming and regenerative agriculture, will be key to ensuring food security and environmental sustainability. The role of mycorrhizal fungi in plant ecology and nutrient cycling is vast, and recent research has revealed even more complexity regarding their species, interactions, and classifications. I'll break it down into more detailed sections, covering newly discovered species, classifications, and the importance of mycorrhizal relationships.

Newly Discovered Mycorrhizal Species and Relationships

A. Mycoheterotrophic plants

Mycoheterotrophic plants are a fascinating subset of plant species that do not perform photosynthesis and instead depend entirely on fungal associations for nutrients. These plants parasitize fungi, which are in turn mycorrhizal with other plants. This has raised the profile of certain species in mycorrhizal studies. Here are a few key findings [24]:

a) Thismia malayana (2024) This species was newly described in Malaysia and has drawn attention due to its complete reliance on mycorrhizal fungi for survival. Unlike typical plants, which form mutualistic relationships with fungi, Thismia malayana has evolved to parasitize the fungal network for sustenance, extracting nutrients that the fungi themselves acquire from the soil. These kinds of plants are often rare and are a source of intrigue for understanding evolutionary adaptations in plant-fungal interactions [25].

B. Novel fungal species

In recent years, scientists have identified and classified novel species of mycorrhizal fungi that contribute to better nutrient uptake, especially in challenging environments like deserts and high-altitude forests. For example, researchers have discovered unique species that form symbiotic relationships with plants in nutrient-poor soils, like those found in tropical rainforests or arid regions [26].

1) Boletopsis nothofagi (2012) This is a specific example of a fungus identified in New Zealand, which forms ectomycorrhizal relationships with the red beech tree (Nothofagus fusca). Unlike other mycorrhizal fungi, it forms dense clusters of fruiting bodies and plays a key role in nutrient cycling within its ecosystem [27]. This discovery adds to our understanding of fungi's roles in forest dynamics and plant health, particularly in terms of how fungi may adapt to specific plant hosts in restricted ecological zones.

C. Ectomycorrhizal fungi in tropical regions

Mycorrhizal fungi are most studied in temperate forests, but recent studies have expanded to tropical ecosystems. New species of ectomycorrhizal fungi, capable of associating with a broader range of plant species than previously thought, have been discovered. These species help plants in tropical forests acquire nutrients such as phosphorus and nitrogen, which are essential for growth [28].

New classifications in mycorrhizal fungi

Mycorrhizal fungi are classified based on the way they interact with plant roots and the structure of their mycelium. In the past decade, scientists have refined these classifications due to new insights into fungal genetics and interactions with plants [29]. These classifications are often more dynamic than previously thought, with emerging groups like ericoid mycorrhizal fungi becoming recognized as a distinct category [30].

Main classifications of mycorrhizal associations (Table 3):

Table 3: The comparative of AM vs ECM signaling pathways.

Feature	Arbuscular Mycorrhiza (AM)	Ectomycorrhiza (ECM)
Signal Molecule	Strigolactones, Myc factors	Unknown ECM factors
Primary Receptor	LysM Receptors	Unknown
Calcium Oscillations	Essential	Not essential
Intracellular Structures	Arbuscules	No intracellular entry
Carbon Exchange	Sugars, lipids	Mainly sugars
Nutrient Transfer	Phosphorus	Nitrogen, phosphorus

Arbuscular Mycorrhiza (AM):

a. Fungal Characteristics: AM fungi (mainly in the phylum Glomeromycota) penetrate root cells, forming structures like arbuscules (branched structures) and vesicles (storage organs). The fungus absorbs phosphorus, nitrogen, and other nutrients from the soil and exchanges them with the plant for sugars. The diversity of this group is vast, with over 200 species identified across numerous plant families.

b. Symbiosis Significance: AM fungi being critical for improving nutrient acquisition in plants, particularly in phosphorus-limited soils. Recent studies have shown that AM fungi can also affect plant disease resistance, water stress tolerance, and even soil microbial communities.

c. Emerging Insights: Studies are now focusing on understanding how AM fungi interact with plant microbiome. These interactions could improve crop yield in poor soil conditions and lead to more sustainable agricultural practices.

Ectomycorrhiza (ECM):

1. Fungal Characteristics: Unlike AM fungi, ECM fungi (belonging to several fungal families like Boletaceae and Russulaceae) do not penetrate root cells. Instead, they form a dense network around the roots. The most notable feature is the formation of the Hartig net-a structure that facilitates nutrient exchange between the plant and fungus.

2. Symbiosis Significance: ECM fungi are particularly important for trees and shrubs in temperate and boreal forests. They improve the uptake of nitrogen, phosphorus, and other essential nutrients. These fungi also help in buffering plants against environmental stresses such as drought or extreme temperatures.

3. Evolutionary Understanding: ECM fungi are thought to have evolved with their plant hosts in temperate climates, with significant diversification observed in regions such as the northern hemisphere.

Ericoid Mycorrhiza (ERM):

a. Fungal Characteristics: ERM fungi (which belong to the family Sebacinales and the phylum Basidiomycota) are particularly associated with plants in the family Ericaceae, such as blueberries, rhododendrons, and heathers. These fungi are essential for plants growing in acidic, nutrient-poor soils, as they enhance nutrient uptake, especially nitrogen.

b. Symbiosis Significance: These relationships are crucial in maintaining biodiversity in heathlands, bogs, and other specialized ecosystems. ERM fungi plays a key role in ecosystem stability by improving plant health and soil nutrient cycling.

Mycorrhizal relationships also play additional roles in plant defense and secondary metabolism. These fungi can be found within plant tissues without causing disease, and recent discoveries are focusing on how these interactions affect plant growth and stress resistance [31].

The world of mycorrhizal fungi is far from fully understood, with continuous discoveries reshaping how scientists view plant-fungal relationships. From newly discovered mycoheterotrophic plants to novel fungal species with specialized ecological roles, mycorrhizal research continues to have profound implications for environmental conservation, agriculture, and ecological studies [32]. With the latest advancements in fungal genetics and ecological research, these relationships are becoming more crucial than ever for understanding biodiversity, ecosystem services, and sustainable agricultural practices (Figure 4).

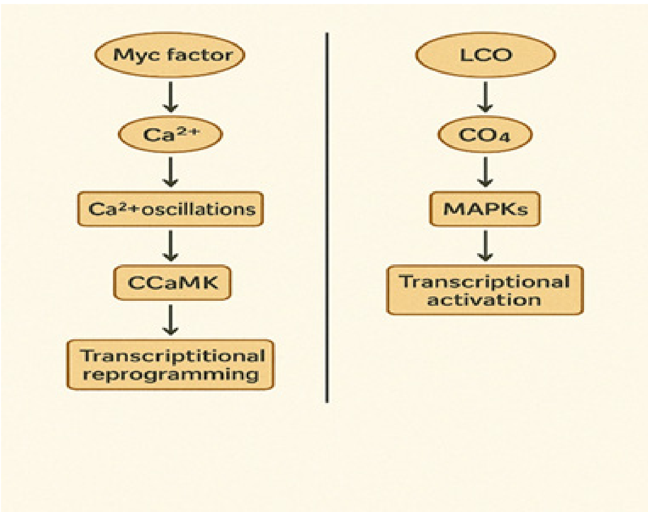

Figure 4: Overview of AM vs ECM signaling pathways.

Mycorrhiza Interaction with Pathogens and Plant Immunity

Mycorrhiza-Induced Resistance (MIR)

Mycorrhizal fungi contribute to plant defense through Mycorrhiza-Induced Resistance (MIR), a phenomenon where colonization by mycorrhizae enhances the plant's systemic resistance to pathogens. This resistance involves [33]:

a. Priming of defense genes: Mycorrhizae stimulates the expression of plant defense-related genes, enabling a faster and stronger response to pathogen attack.

b. Increased production of antimicrobial compounds: Mycorrhizal plants often exhibit higher levels of phytoalexins, phenolics, and other antimicrobial metabolites.

c. Activation of hormonal pathways: Mycorrhizae modulate key hormonal pathways, particularly those involving Jasmonic Acid (JA) and Salicylic Acid (SA), both critical for plant immune responses.

Competition and antagonism with pathogens

Mycorrhizal fungi can directly suppress plant pathogens by competing for space and nutrients, reducing the ability of harmful fungi and bacteria to establish infections. Some mechanisms include [34]:

1) Competition for root colonization sites: Mycorrhizal fungi occupy root tissues, limiting the available space for pathogen attachment.

2) Nutrient competition: By efficiently absorbing essential nutrients such as phosphorus and nitrogen, mycorrhizal fungi reduce the resources available for pathogens.

3) Production of antifungal compounds: Certain mycorrhizal fungi release antifungal secondary metabolites that inhibit pathogen growth.

Enhancement of physical barriers

Mycorrhizae enhance plant cell wall strength, making it more difficult for pathogens to penetrate plant tissues. This occurs through:

a) Increased deposition of callose and lignin: These compounds reinforce plant cell walls, providing structural resistance against pathogen invasion.

b) Stimulation of root exudates: Mycorrhizal plants secrete specific compounds that deter pathogenic microbes from colonizing root surfaces.

Role in indirect defense mechanisms

Mycorrhizal fungi also contribute to plant defense by influencing interactions with beneficial soil microbes and plant-associated organisms:

A. Attracting Beneficial Microbes: Mycorrhizal roots create favorable conditions for the proliferation of plant-friendly bacteria and fungi that suppress pathogens.

B. Inducing Systemic Resistance (ISR): Mycorrhizae can trigger plant-wide immune responses that protect distant tissues from infection.

Potential applications in agriculture

Harnessing the protective effects of mycorrhizae against pathogens presents opportunities for sustainable crop protection strategies [35]:

a) Use of mycorrhizal inoculants: Integrating mycorrhizal fungi into agricultural systems can enhance plant immunity, reducing dependency on chemical pesticides.

b) Breeding for mycorrhizal responsiveness: Selecting and engineering crops with enhanced mycorrhizal interactions can improve pathogen resistance.

c) Integration with biological control agents: Combining mycorrhizae with beneficial biocontrol microbes can create a more resilient and disease-resistant crop production system.

Future research directions

Further research is needed to explore the molecular mechanisms underlying mycorrhiza-induced resistance and to optimize mycorrhizal applications in different agricultural systems. Key areas of study include [36]:

1. Genetic Modifications for Enhanced MIR: Identifying and modifying plant genes that improve mycorrhizal-mediated defense responses.

2. Microbiome Engineering: Designing soil microbial communities that work synergistically with mycorrhizae to enhance plant health.

3. Impact of Climate Change on Mycorrhizal-Pathogen Interactions: Understanding how environmental factors influence the balance between mycorrhizae, pathogens, and plant immunity.

By leveraging these advancements, mycorrhizal fungi can play an increasingly critical role in promoting plant health and sustainable agriculture. The integration of mycorrhizal biotechnology in modern farming practices can lead to reduced reliance on chemical fertilizers and pesticides, fostering an eco-friendly and cost-effective approach to crop production [37]. Furthermore, ongoing research into mycorrhizal genetics and their interactions with plant immune systems may unlock new strategies for breeding more resilient crops. Enhanced understanding of the soil microbiome and its synergistic relationship with mycorrhizal fungi also presents an opportunity for optimizing soil health, improving carbon sequestration, and mitigating the effects of climate change [38]. The continued exploration of mycorrhizal fungi in precision agriculture, bioengineering, and microbial consortia development will further solidify their role as essential agents of sustainable food production and ecosystem resilience.

Conclusion

Recent advancements of Mycorrhiza in molecular biology, climate change studies, and biotechnology have expanded our understanding of mycorrhizal functions. This review explores the latest discoveries in mycorrhizal research, including signaling mechanisms, biotechnological applications, interactions with pathogens and their role in carbon sequestration. The recent discoveries of new species, the elucidation of molecular signaling pathways, and the understanding of their role in mitigating climate change highlight the importance of these mycorrhiza in both ecological and applied contexts. The continued exploration of mycorrhizal fungi offers the potential for groundbreaking advances in sustainable agriculture, environmental conservation and climate change mitigation. Overview mycorrhizal fungi hold the key to unlocking more sustainable and resilient systems for the future of agriculture and biotechnology.

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