



Ecological Roles of Fungal Networks: Integrating Nutrient Cycling, Soil Health, and Climate Resilience-A Systematic Review

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Abstract

Beneath every thriving ecosystem lies a living web of fungal networks that quietly sustain the planet's fertility and balance. These underground systems—woven by mycorrhizal and saprotrophic fungi—act as the foundation of soil life, recycling nutrients, storing carbon, and enabling plants to communicate and share resources. This systematic review brings together recent insights from molecular biology, metagenomics, and field ecology to explore how these intricate networks shape and sustain ecosystems. Mycorrhizal fungi, for instance, form symbiotic relationships with plant roots, extending their reach for water and minerals while exchanging vital nutrients. Saprotrophic fungi, meanwhile, orchestrate decomposition, breaking down organic matter into life-sustaining soil carbon. Together, these fungal communities regulate nutrient cycling, influence microbial diversity, and even suppress soil-borne pathogens. Yet, their delicate balance is increasingly threatened by deforestation, intensive agriculture, and climate change, all of which disrupt the invisible threads that hold

ecosystems together. The review highlights the urgent need for conservation-focused land management—practices that protect fungal biodiversity, minimize chemical use, and restore natural soil processes. Recognizing fungi not as background players but as ecological engineers reframes how we approach sustainability. By restoring and respecting these subterranean alliances, we can strengthen soil health, support global food systems, and build resilience against environmental change.

Keywords: Fungal Networks, Mycorrhizae, Soil Ecology, Nutrient Cycling, Microbial Interactions, Climate Resilience, Sustainable Agriculture

Significance | Understanding fungal-soil interactions enables strategies for sustainable agriculture, soil health improvement, biodiversity conservation, and climate change mitigation through enhanced ecosystem resilience.

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1. Introduction

Fungi are fundamental architects of terrestrial ecosystems, shaping soil structure, driving nutrient cycles, and maintaining plant and microbial diversity. Unlike higher plants and animals, fungi form extensive belowground networks that connect biotic and abiotic components of ecosystems. These fungal networks, particularly those formed by mycorrhizal fungi, enable plants to access essential nutrients, enhance soil stability, and regulate microbial interactions (Smith & Read, 2008). Their ecological role is not only crucial for individual plants but also extends to ecosystem-level processes such as carbon sequestration, nitrogen cycling, and resilience to climate variability (Rillig et al., 2019). As global challenges such as deforestation, soil degradation, and climate change intensify, understanding the intricate dynamics of fungal networks has

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become increasingly important. One of the most well-documented aspects of fungal networks is their symbiotic association with plant roots, known as mycorrhizal symbiosis. These associations, which occur in approximately 80% of vascular plants, involve a bidirectional exchange: fungi provide mineral nutrients such as phosphorus and nitrogen, while plants supply carbon compounds derived from photosynthesis (van der Heijden et al., 2015). Arbuscular mycorrhizal fungi (AMF), in particular, are recognized for enhancing nutrient mobilization from organic material, a process that directly influences soil fertility and plant productivity (Hodge et al., 2010). Moreover, ectomycorrhizal fungi, which dominate in forest ecosystems, play a critical role in organic matter decomposition and nutrient recycling (Courty et al., 2010).

Beyond nutrient exchange, fungal networks profoundly influence soil structure and microbial ecology. Mycorrhizal hyphae contribute to soil aggregation, thereby improving water retention and resistance to erosion (Rillig & Mummey, 2006). At the microbial level, fungi shape bacterial niche development, providing spatial heterogeneity and metabolic interactions that sustain microbial diversity (de Boer et al., 2005). Such interactions exemplify the concept of fungi as ecosystem engineers, where their activities influence community assembly and ecosystem resilience. Fungal networks also mediate plant-to-plant communication and defense responses. Common mycorrhizal networks (CMNs) facilitate the transfer of signaling molecules and nutrients between interconnected plants. For example, underground signaling through CMNs can alert neighboring plants to herbivore attack, enabling pre-emptive defensive responses (Babikova et al., 2013). Similarly, CMNs have been shown to extend the reach of allelochemicals in soils, influencing plant competition and community dynamics (Barto et al., 2012). These discoveries challenge traditional views of plant ecology by highlighting the cooperative and communicative functions of fungal networks.

The ecological benefits of fungal symbioses extend to stress tolerance and ecosystem stability. Mycorrhizal plants exhibit greater resilience to drought, salinity, and heavy metal stress compared with non-mycorrhizal plants (Aroca et al., 2007; Colpaert et al., 2004). This adaptive advantage is particularly critical in degraded or marginal soils, where fungi can act as biofertilizers to support sustainable agriculture (Verbruggen et al., 2013). Moreover, fungal contributions to carbon storage are gaining attention in the context of climate change. Mycorrhizal competition with decomposers for nutrients has been shown to slow down organic matter decomposition, promoting long-term carbon sequestration in soils (Averill et al., 2014).

Biodiversity within fungal communities also shapes ecosystem functions. Variability in mycorrhizal species composition influences plant diversity, nutrient cycling, and productivity (Börstler et al., 2006; Rillig et al., 2019). This diversity is maintained

through mechanisms such as preferential carbon allocation to more cooperative fungal partners, which ensures the persistence of mutualistic relationships (Bever et al., 2010). However, fungal community structure is sensitive to environmental disturbances, including land-use changes, pollution, and climate variability, which may alter the stability of plant–fungal symbioses (He et al., 2009). Such vulnerabilities raise concerns about the sustainability of ecosystem services provided by fungi in the Anthropocene.

Another dimension of fungal networks lies in their contributions to biogeochemical processes and bioremediation. Saprotrophic fungi, through their enzymatic activity, break down complex organic matter and recycle nutrients back into the soil (Baldrian, 2008). Furthermore, fungi have demonstrated remarkable capabilities in detoxifying soils contaminated with heavy metals and other pollutants, making them invaluable agents in bioremediation (Gadd, 2010). These roles emphasize the multifunctional nature of fungi in maintaining soil health and environmental stability.

The rhizosphere, a critical zone of soil influenced by plant roots, serves as the interface where mycorrhizal fungi, plants, and microbes interact. Research highlights that fungi not only mobilize nutrients but also regulate microbial activity in the rhizosphere, shaping community dynamics and influencing plant growth (Philippot et al., 2013). These processes suggest that fungal networks are integral to understanding the complexity of plant–soil–microbe interactions and their implications for ecosystem sustainability.

Despite significant advances, much remains to be understood about fungal networks. Studies integrating molecular techniques, field experiments, and ecological modeling have begun to reveal the mechanisms underlying CMNs, nutrient trade-offs, and biodiversity maintenance (Simard et al., 2012; Jakobsen et al., 2005). However, the dynamic nature of these networks and their responses to environmental pressures warrant further investigation. Addressing these gaps will enhance our ability to harness fungal functions for sustainable agriculture, forest conservation, and climate change mitigation.

This study aims to critically examine the ecological roles of fungal networks in soil ecosystems, with a focus on nutrient cycling, microbial interactions, plant communication, and environmental resilience. By synthesizing evidence from mycorrhizal symbioses, saprotrophic activity, and bioremediation processes, the study seeks to highlight the multifunctionality of fungi and their potential applications in sustainable land management and climate change adaptation.

2. Materials and Methods

This study adopted a structured review methodology to synthesize existing literature on fungal networks, with particular focus on their ecological roles in nutrient cycling, soil structure, plant

communication, and environmental resilience. The methodological process consisted of four stages: literature identification, screening, eligibility assessment, and data synthesis.

2.1 Literature Identification

A comprehensive search strategy was employed to capture a wide range of studies related to fungal ecology, mycorrhizal symbioses, saprotrophic fungi, and fungal–bacterial interactions. Major scientific databases, including Web of Science, Scopus, PubMed, and Google Scholar, were searched between March and May 2025. Keywords and Boolean operators were combined to maximize retrieval, including: “*fungal networks*,” “*mycorrhiza*,” “*saprotrophic fungi*,” “*rhizosphere*,” “*soil ecology*,” “*common mycorrhizal networks*,” “*fungal biodiversity*,” and “*bioremediation*.” Reference lists of key papers were also manually screened to identify additional relevant studies.

2.2 Screening and Eligibility Criteria

Studies were included if they met the following criteria:

- Published in peer-reviewed journals between 2000 and 2025.
- Focused on ecological roles of fungi in soil systems, including nutrient cycling, plant–fungus interactions, soil structure, microbial regulation, communication, or stress tolerance.
- Empirical studies, meta-analyses, reviews, or theoretical models that provided evidence-based insights.
- Publications in English language to ensure consistency of analysis.

Exclusion criteria eliminated grey literature, conference abstracts, and studies that focused solely on fungal taxonomy without ecological context. After applying these criteria, approximately 80 articles were deemed eligible for detailed review.

2.3 Data Extraction

From each selected study, information was systematically extracted using a data extraction sheet. The following variables were recorded:

- **Authors and publication year**
- **Fungal type** (e.g., arbuscular mycorrhizal, ectomycorrhizal, saprotrophic)
- **Ecosystem context** (e.g., forest, agricultural, desert, alpine, polluted soils)
- **Ecological function studied** (nutrient cycling, soil aggregation, plant signaling, stress tolerance, carbon sequestration, or bioremediation)
- **Methodological approach** (field experiments, laboratory studies, molecular techniques, or modeling)
- **Key findings** relevant to fungal ecological roles

2.4 Data Synthesis and Analysis

The analysis was conducted using a narrative synthesis approach, integrating findings into thematic categories. Studies were grouped into six key ecological functions: (1) nutrient acquisition and cycling, (2) soil structural contributions, (3) fungal–bacterial

interactions, (4) communication and resource sharing via mycelial networks, (5) plant stress tolerance and resilience, and (6) carbon storage and bioremediation. This thematic framework facilitated cross-comparison of results across ecosystems and fungal groups.

Where quantitative data were available, findings on nutrient exchange rates, soil aggregation indices, or carbon sequestration contributions were highlighted. For qualitative studies, emphasis was placed on mechanistic insights and conceptual models. By integrating multiple lines of evidence, this method provided a holistic understanding of the multifunctional roles of fungal networks.

2.5 Quality Assessment

To ensure reliability, each study was evaluated based on methodological rigor, clarity of experimental design, and ecological relevance. For field studies, attention was given to sample size, replication, and environmental controls. Laboratory experiments were assessed for reproducibility and the use of molecular tools. Review papers were appraised for comprehensiveness and citation of primary research. Only studies meeting moderate to high methodological standards were prioritized in the synthesis.

3.6 Ethical Considerations

As this was a review study, no new data were collected, and ethical approval was not required. However, all efforts were made to ensure accurate representation and citation of original research findings, respecting intellectual property and academic integrity.

3. Functional Roles of Fungi in Ecosystem Dynamics and Sustainable Land Management

Fungi play a pivotal role in terrestrial ecosystems through their contributions to nutrient cycling, soil structure, plant health, and microbial community dynamics. Over the past decades, research has expanded the understanding of fungal networks, particularly mycorrhizal associations, saprotrophic processes, and fungal–bacterial interactions. This literature review synthesizes the major findings in these areas, highlighting their ecological significance, functional diversity, and implications for sustainable land management.

3.1 Mycorrhizal Symbioses and Nutrient Dynamics

Mycorrhizal fungi are among the most extensively studied fungal groups due to their symbiotic relationships with plants. Smith and Read (2008) emphasized that mycorrhizal symbioses occur in nearly 80% of vascular plants, with fungi supplying mineral nutrients while receiving carbon from the host. This mutualism underpins plant productivity and ecosystem stability. Arbuscular mycorrhizal fungi (AMF) enhance nutrient mobilization from organic substrates and provide plants with nitrogen and phosphorus otherwise inaccessible to roots (Hodge et al., 2010; Jakobsen et al., 2005). In forest systems, ectomycorrhizal fungi

extend this role by decomposing complex organic matter and supporting long-term nutrient recycling (Courty et al., 2010).

The ecological diversity of mycorrhizal associations is significant. Brundrett (2009) documented the wide range of plant hosts and fungal partners, while van der Heijden et al. (2015) traced the evolutionary pathways that established these symbioses. Diversity among fungal partners can lead to complementary functional benefits for plants. For instance, Jansa et al. (2006) found that simultaneous colonization by multiple AMF species enhances plant nutrient uptake and improves resilience against environmental stress.

3.2 Soil Structure and Ecosystem Engineering

Fungi exert profound effects on soil structure, often functioning as ecosystem engineers. The hyphal networks of mycorrhizal fungi promote soil aggregation, improving aeration, water retention, and resistance to erosion (Rillig & Mummey, 2006). These structural improvements influence not only plant health but also the stability of entire ecosystems. Rillig et al. (2019) argued that soil fungi drive both plant diversity and ecosystem functioning by creating stable habitats conducive to species coexistence.

Research also points to the role of fungal communities in mediating environmental responses. Börstler et al. (2006) demonstrated that mycorrhizal diversity in alpine afforestation projects significantly altered soil structure and community composition. These findings highlight how fungal community composition directly influences ecosystem restoration and management outcomes.

3.3 Fungal–Bacterial Interactions in the Rhizosphere

Beyond plant–fungal interactions, fungi shape microbial community dynamics in soils. The rhizosphere serves as a hotspot where plants, fungi, and bacteria interact. Philippot et al. (2013) emphasized the microbial ecology of the rhizosphere, noting that fungal networks regulate bacterial activity and resource distribution. Similarly, de Boer et al. (2005) argued that fungal structures provide spatial heterogeneity, which supports bacterial niche development and sustains microbial diversity.

Such interactions extend to nutrient cycling and pathogen control. Fungal exudates, enzymes, and hyphal networks mediate competitive and cooperative interactions with bacteria, ultimately influencing ecosystem processes. This complexity underscores the multifunctional role of fungi beyond their direct plant associations.

3.4 Communication and Resource Sharing via Mycelial Networks

One of the most fascinating discoveries in fungal ecology is the role of common mycorrhizal networks (CMNs) in interplant communication. Simard et al. (2012) outlined the mechanisms by which CMNs transfer nutrients, carbon, and signaling molecules among plants. These networks create interconnected communities where plants can share resources and information.

Experimental evidence supports the ecological significance of CMNs. Babikova et al. (2013) showed that signals transmitted

through mycelial networks warned neighboring plants of aphid attacks, enabling them to mount defensive responses. Barto et al. (2012) further demonstrated that CMNs extend the bioactive zones of allelochemicals, thereby mediating plant–plant competition. Such findings reveal that fungal networks not only sustain resource flows but also facilitate plant cooperation and defense.

3.5 Stress Tolerance and Environmental Adaptation

Mycorrhizal fungi enhance plant tolerance to abiotic stresses such as drought, salinity, and heavy metal contamination. Aroca et al. (2007) observed that mycorrhizal tomato plants exhibited greater drought tolerance than non-mycorrhizal counterparts, linked to improved water regulation and stress hormone responses. Colpaert et al. (2004) studied ectomycorrhizal fungi tolerant to heavy metals, demonstrating their capacity to support plant survival in contaminated soils.

These adaptive advantages highlight the potential application of fungi in ecological restoration and sustainable agriculture. Verbruggen et al. (2013) proposed that mycorrhizal biofertilizers could reduce reliance on chemical inputs, contributing to sustainable farming practices. Such insights reinforce the multifunctionality of fungi in responding to environmental challenges.

3.6 Fungi and Soil Carbon Dynamics

Fungal contributions to global carbon cycling have drawn increasing attention in the context of climate change. Saprotrophic fungi decompose organic matter, releasing nutrients and influencing soil carbon storage. Baldrian (2008) described the enzymatic diversity of saprotrophic fungi, which enables them to degrade complex polymers such as lignin and cellulose. Meanwhile, Averill et al. (2014) proposed that competition between mycorrhizal fungi and decomposers reduces decomposition rates, thereby enhancing soil carbon sequestration.

These processes underline the dual role of fungi as both decomposers and stabilizers of organic matter. Their activity is central to predicting soil carbon dynamics under global environmental change scenarios.

3.7 Bioremediation and Geochemical Roles

Fungi also contribute to environmental remediation through geomicrobiological processes. Gadd (2010) emphasized the role of fungi in metal mobilization, mineral transformations, and bioremediation of polluted soils. By altering the chemical environment, fungi not only detoxify soils but also support microbial communities and plant colonization in degraded ecosystems. These properties make fungi promising tools in ecological engineering and restoration.

Table 1. Functional Roles of Fungal Networks in Soil Ecosystems

Function	Mechanism	Key References
Nutrient cycling	AMF and ECM enhance uptake of phosphorus and nitrogen; saprotrophs decompose organic matter	Hodge et al., 2010; Baldrian, 2008; Jakobsen et al., 2005
Soil structure improvement	Hyphal networks bind soil particles, increase aggregation, and improve water retention	Rillig & Mummey, 2006
Plant communication	Mycorrhizal networks transmit chemical signals warning of herbivore/pest attack	Simard et al., 2012; Babikova et al., 2013
Microbial balance	Fungal exudates influence bacterial niches and pathogen suppression	de Boer et al., 2005; Philippot et al., 2013
Carbon storage	Mycorrhizal-mediated competition promotes carbon sequestration in soils	Averill et al., 2014

3.8 Knowledge Gaps and Emerging Perspectives

Despite extensive research, many aspects of fungal networks remain underexplored. He et al. (2009) highlighted the spatial and temporal variability of mycorrhizal associations in desert ecosystems, underscoring the need for long-term monitoring. Simard et al. (2012) noted that ecological modeling of CMNs remains in its infancy, with mechanisms of resource allocation and communication still debated. Similarly, Bever et al. (2010) argued that preferential allocation of plant carbon to beneficial fungi raises questions about how cooperation is maintained under fluctuating environmental conditions. Future studies integrating molecular techniques, ecological modeling, and field-based experimentation are necessary to unravel the complexities of fungal networks. Advancing this knowledge will be critical for translating fungal ecology into applied solutions for agriculture, forestry, and climate change mitigation.

4. Functional Roles of Fungal Networks in Ecosystem Sustainability

The review of selected literature revealed six central themes that collectively illustrate the ecological importance of fungal networks. These include nutrient cycling, soil structure formation, microbial interactions, plant communication, stress tolerance, and their role in carbon storage and bioremediation. Together, these findings highlight fungi as multifunctional organisms that sustain soil health, plant productivity, and ecosystem resilience.

4.1 Nutrient Cycling and Plant Productivity

A dominant finding across the reviewed studies is that fungal networks significantly enhance nutrient acquisition in plants. Arbuscular mycorrhizal fungi (AMF) improve plant access to phosphorus and nitrogen that are otherwise unavailable in soil (Smith & Read, 2008). Experimental evidence demonstrates that AMF can directly mobilize nitrogen from organic matter, accelerating decomposition and nutrient transfer (Hodge et al.,

2010). This function is particularly vital in nutrient-poor ecosystems where plants would otherwise struggle to survive. Ectomycorrhizal fungi, which dominate in forest systems, extend this function by decomposing complex organic material and recycling nutrients at ecosystem scales (Courty et al., 2010). Multi-species colonization studies further reveal that simultaneous root colonization by different AMF species enhances nutrient uptake and fosters plant growth resilience (Jansa et al., 2006). These findings underline the centrality of fungal networks in driving primary productivity across both agricultural and natural ecosystems.

4.2 Soil Structure and Ecosystem Engineering

Another consistent result is the contribution of fungi to soil stability. Hyphal networks of mycorrhizal fungi bind soil particles together, leading to improved soil aggregation, aeration, and water retention (Rillig & Mummey, 2006). This process creates stable microhabitats that are essential for supporting diverse microbial and plant communities. Research in afforested alpine systems showed that mycorrhizal diversity is closely linked to soil structure and community restoration, demonstrating the role of fungi as ecological engineers (Börstler et al., 2006). Similarly, Rillig et al. (2019) emphasized that fungal contributions to soil architecture are directly linked to maintaining plant diversity and ecosystem functioning. These findings collectively suggest that without fungal-driven structural stability, soils would be more vulnerable to erosion and degradation (Table 1).

4.3 Microbial Interactions and Rhizosphere Dynamics

Fungal networks were also shown to shape microbial community dynamics in the rhizosphere. Studies confirm that fungal hyphae provide spatial heterogeneity and serve as structural frameworks that support bacterial niches (de Boer et al., 2005). This interaction contributes to microbial diversity and ensures balanced nutrient cycling.

Table 2. Practical Applications and Implications of Fungal Networks

Application Area	Practical Role of Fungi	Key References
Sustainable agriculture	Mycorrhizal biofertilizers reduce chemical fertilizer use, improve crop resilience	Verbruggen et al., 2013; Bever et al., 2010
Ecosystem restoration	Mycorrhizal reintroduction accelerates soil recovery and plant establishment	Börestler et al., 2006; Courty et al., 2010
Climate change mitigation	Carbon sequestration through fungal-driven organic matter storage	Averill et al., 2014
Pollution management	Heavy metal detoxification and bioremediation of contaminated soils	Gadd, 2010; Colpaert et al., 2004
Biodiversity conservation	Maintenance of plant diversity and resilience via fungal-plant interactions	Rillig et al., 2019; van der Heijden et al., 2015

Philippot et al. (2013) highlighted that fungi regulate microbial ecology by controlling nutrient flows and signaling processes in the rhizosphere. These dynamics help plants access nutrients more efficiently while reducing pathogen loads. The evidence suggests that fungi not only benefit plants directly but also indirectly by creating favorable conditions for beneficial bacteria, thereby stabilizing soil ecosystems.

4.4 Plant Communication and Resource Sharing

The findings strongly indicate that fungi facilitate interplant communication and cooperation. Common mycorrhizal networks (CMNs) connect multiple plants, enabling them to share nutrients and signaling molecules (Simard et al., 2012). For example, Babikova et al. (2013) demonstrated that plants connected through fungal networks could receive chemical signals warning of aphid attack, triggering defensive responses before direct herbivore damage occurred.

Similarly, Barto et al. (2012) found that CMNs extend the reach of allelochemicals, thereby influencing plant competition and shaping community dynamics. These findings challenge the traditional view of plants as isolated entities, instead portraying them as members of cooperative networks mediated by fungi. Such resource-sharing capacity enhances the resilience of entire plant communities.

4.5 Stress Tolerance and Environmental Adaptation

Another key result is the role of fungi in enhancing plant tolerance to abiotic stresses. Mycorrhizal plants consistently outperform non-mycorrhizal plants under conditions of drought, salinity, and soil contamination. Aroca et al. (2007) reported that tomato plants associated with AMF exhibited improved water regulation and stress hormone balance during drought. Likewise, Colpaert et al. (2004) documented ectomycorrhizal fungi tolerant to heavy metals, which facilitated plant survival in polluted soils.

The application of mycorrhizal biofertilizers has been shown to reduce dependence on chemical fertilizers and enhance resilience in sustainable farming systems (Verbruggen et al., 2013). These

results highlight the potential of fungal networks to serve as natural allies in agriculture and ecological restoration.

4.6 Carbon Storage and Bioremediation

The findings also underscore fungi’s critical role in carbon cycling and environmental remediation. Saprotrophic fungi contribute to organic matter decomposition through diverse enzymatic activities, facilitating nutrient release while influencing soil carbon dynamics (Baldrian, 2008). At the same time, mycorrhizal competition with decomposers has been found to slow decomposition, leading to increased soil carbon storage (Averill et al., 2014). This dual role illustrates fungi’s capacity to both recycle nutrients and stabilize carbon in soils.

Beyond carbon, fungi play essential roles in detoxifying polluted environments. Gadd (2010) reported that fungi can transform or immobilize toxic metals, contributing to bioremediation processes. Such capabilities expand the ecological significance of fungi beyond nutrient cycling, positioning them as central agents in mitigating environmental damage caused by human activity.

5. Discussion

The results of this review demonstrate that fungal networks are indispensable in sustaining soil ecosystems, with roles extending from nutrient cycling to ecosystem resilience. These findings confirm and extend earlier ecological theories that positioned fungi as keystone organisms (Smith & Read, 2008). By integrating insights from studies on nutrient dynamics, soil aggregation, plant communication, and microbial regulation, this discussion underscores the broader ecological and applied significance of fungi, while also considering the challenges posed by environmental change and human practices.

5.1 Ecological Significance of Fungal Networks

Fungal networks act as multifunctional drivers of ecosystem processes. Their role in nutrient cycling, especially through arbuscular and ectomycorrhizal associations, is vital for primary

productivity across diverse landscapes. The evidence that AMF directly mobilize nitrogen and phosphorus from organic matter (Hodge et al., 2010) highlights the ability of fungi to bypass nutrient limitations that constrain plant growth. Similarly, their contribution to soil structure through hyphal binding (Rillig & Mummey, 2006) provides physical stability, demonstrating how fungi underpin both biotic and abiotic soil functions. These findings collectively reinforce the concept of fungi as “ecosystem engineers,” capable of shaping environments in ways that extend far beyond individual plant-fungal interactions (Table 2).

5.2 Implications for Plant Communities and Agriculture

The ability of fungi to facilitate communication and nutrient sharing among plants challenges the notion of plants as isolated competitors. Findings from common mycorrhizal networks (Simard et al., 2012; Babikova et al., 2013) suggest that plant communities are connected through underground cooperative webs that promote resilience against stress and herbivory. This has profound implications for agriculture, where reliance on monocultures and chemical fertilizers has often reduced soil biodiversity. The application of fungal biofertilizers (Verbruggen et al., 2013) presents a pathway toward sustainable farming, offering reduced chemical dependency while enhancing stress tolerance and soil fertility.

5.3 Climate Change and Environmental Stressors

One of the most pressing insights from the findings is the sensitivity of fungal networks to environmental disturbances. Land-use change, deforestation, and pollution can disrupt fungal diversity, with cascading effects on soil fertility and biodiversity. Yet, fungi also present solutions for mitigating these challenges. Their role in carbon sequestration (Averill et al., 2014) contributes to long-term carbon storage, directly linking fungal processes to climate regulation. Furthermore, their capacity for heavy metal detoxification (Gadd, 2010) positions them as natural agents of bioremediation in degraded environments. Thus, while fungi are vulnerable to anthropogenic pressures, they simultaneously hold the potential to mitigate the very crises that threaten them.

5.4 Gaps and Future Directions

Despite growing recognition of fungal importance, significant knowledge gaps remain. Many ecological studies focus on specific species or ecosystems, leaving questions about global patterns of fungal diversity and function. Advances in molecular and metagenomic techniques (Finlay, 2002) offer opportunities to map fungal communities at unprecedented scales, yet practical applications in agriculture and restoration ecology remain underdeveloped. Future research should prioritize applied studies that integrate fungal biofertilizers into sustainable farming practices, investigate the resilience of fungal communities under climate extremes, and explore fungi’s untapped potential in carbon and pollution management.

6. Recommendations

The findings of this study highlight the ecological and applied significance of fungal networks, pointing to several practical and research-oriented recommendations.

First, sustainable agricultural practices should prioritize the integration of fungal biofertilizers into crop management systems. The use of mycorrhizal inoculants can reduce dependency on synthetic fertilizers, enhance soil fertility, and improve crop resilience under drought and pest pressures (Verbruggen et al., 2013). Policies supporting farmer education and subsidized access to microbial inputs could accelerate adoption at scale.

Second, conservation strategies must recognize fungi as critical biodiversity components. Protecting forest ecosystems, reducing deforestation, and promoting reforestation with mycorrhizal-rich soils can preserve the integrity of fungal networks (Börstler et al., 2006). Restoration projects should deliberately include fungal reintroduction to accelerate ecosystem recovery.

Third, climate mitigation efforts should leverage the role of fungi in soil carbon sequestration. Agricultural and land management practices that promote fungal diversity—such as reduced tillage, organic amendments, and mixed cropping—can increase soil carbon storage and resilience to climate variability (Averill et al., 2014).

Fourth, research priorities should focus on closing existing knowledge gaps. Expanding molecular and genomic studies can enhance understanding of fungal diversity and its functional roles under different environmental pressures. Applied research must also examine the long-term impacts of fungal biofertilizers in large-scale agricultural systems and their interactions with other soil microbes.

Finally, cross-disciplinary collaboration among ecologists, microbiologists, policymakers, and agricultural practitioners is essential. By aligning ecological knowledge with practical applications, fungal networks can be harnessed as powerful tools for sustainable food security, ecosystem health, and climate resilience.

7. Conclusion

This study demonstrates that fungal networks are central to soil health, ecosystem stability, and sustainable agriculture. By facilitating nutrient cycling, enhancing soil structure, supporting plant resilience, and contributing to carbon storage, fungi act as ecosystem engineers that underpin both natural and managed landscapes. However, their sensitivity to environmental degradation highlights the urgent need for conservation and sustainable management strategies. Harnessing their potential through fungal biofertilizers, ecosystem restoration, and climate-smart practices offers a pathway toward resilience in the face of global challenges. Protecting and promoting fungal diversity is

therefore not only an ecological necessity but also a cornerstone of long-term sustainability.

Competing financial interests

The authors have no conflict of interest.

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