**Arbuscular Mycorrhizal Fungi-Mediated Carbon Sequestration: Mechanisms, Influencing Factors, and Future Directions**

**ABSTRACT**

Arbuscular mycorrhizal fungi (AMF) are crucial in the fight against climate change as they help store carbon in the soil by forming beneficial relationships with plant roots, boosting nutrient absorption, and driving carbon captured during photosynthesis into the soil. The carbon is stored within the fungi’s hyphal networks and glomalin-related soil proteins, leading to its long-term stability in the environment. However, the important role of AMF in the global carbon cycle is often underrepresented in climate models. This review discusses how AMF contributes to carbon storage in the soil, focusing on processes such as nutrient cycling, soil aggregation, and interactions with soil microorganisms. It also considers the environmental and biological factors that affect AMF-mediated carbon sequestration, including soil characteristics, climatic factors, land-use practices, and AMF biodiversity. The potential benefits of using AMF to increase carbon storage are explored with a focus on the necessity to integrate AMF inoculation into sustainable land management strategies. Current research gaps, such as the AMF's impact on soil carbon levels and the molecular mechanisms of carbon transfer, are highlighted in this review. Future studies focusing on discovering new AMF strains, considering the effects of climate change on AMF functions, and producing scalable agricultural applications are required. Exploring AMF-mediated carbon sequestration could offer a significant strategy for improving ecosystem resilience and reducing the impacts of global warming.

***Keywords:*** *Arbuscular Mycorrhizal, Fungi-Mediated, Carbon Sequestration, Nutrient Cycling, Soil Aggregation, Climate Change*

**INTRODUCTION**

Arbuscular mycorrhizal fungi (AMF) perform a critical role in the carbon sequestration process involving capturing of the atmospheric carbon dioxide (CO2) and loading it in terrestrial ecosystems (Wilson et al. 2009). This symbiotic relationship between plants and AMF has gathered immense attention due to its potential to mitigate climate change by improving the carbon storage potential of soil. The importance of AMF-Mediated Carbon Sequestration is immense (Tao and Liu 2024) with several ecological and environmental significances such as enhancing soil carbon storage, which supports plant diversity and influences community dynamics. These symbiotic relationships are widespread and critical, as they promote the sharing of nutrients and resources, such as amino acids, among plant species. This mutualistic interaction contributes to the stability and maintenance of ecosystem diversity and hence, it is important to understand the processes through which AMF facilitates carbon sequestration (Smith et al. 2009).

Interest in the impact of arbuscular mycorrhizal (AM) symbiosis on soil organic carbon (SOC) sequestration has recently increased, with research underscoring the importance of AM fungal (AMF) biomass and their extracellular products in enhancing long-term carbon storage within soils (Li et al. 2023; Zhang et al. 2023). The partnership between AM fungi and plants plays a vital role in SOC accumulation, a key aspect of carbon sequestration. Gaining insights into the processes, significance, and factors influencing AMF-driven carbon sequestration is critical to utilizing it as an ecosystem service, with potential benefits for slowing climate change and promoting sustainable land practices (Parihar et al. 2020).

Projections indicate that ecosystems with a dominance of arbuscular mycorrhiza, such as grasslands, croplands, and shrublands, have promising potential for future soil carbon (C) accumulation, especially under conditions of elevated CO₂ (eCO₂). However, this could contribute to reduced SOC levels in forests dominated by ectomycorrhiza (EcM) (Terrer et al. 2021). Conversely, recent meta-analyses show a reduction in SOC stocks in arbuscular mycorrhiza forests, while EcM forests show SOC gains in response to eCO₂ and nitrogen deposition (Yang et al. 2024). This underscores a complex discussion about the dual role of arbuscular mycorrhizal fungi (AMF) in both SOC degradation and accumulation, with implications for carbon storage and mitigating rising CO₂ levels (Chourasiya et al. 2021). Understanding SOC turnover and sequestration dynamics in AMF-rich ecosystems is crucial for evaluating AMF's role in soil C storage, a key element in climate change mitigation efforts.

The impact of arbuscular mycorrhiza symbiosis on plant growth and phenotype largely depends on soil nutrient availability, particularly nitrogen (N) and phosphorus (P), with plants generally benefitting more when phosphorus is limited compared to nitrogen (Johnson et al. 2015). However, how soil nutrient levels specifically affect soil organic carbon (SOC) dynamics through arbuscular mycorrhizal fungi (AMF) is still not well understood. Additionally, evolutionary divergence and environmental adaptations within AMF clades have resulted in variations in resource use efficiency, though these differences are rarely accounted for in studies assessing AMF's role in carbon sequestration (Chagnon et al. 2013). Many experimental studies tend to evaluate plant benefits and SOC storage associated with arbuscular mycorrhiza independently, potentially overlooking the fungi’s contributions in contexts where plant biomass or nutrient uptake is not the primary outcome (Ryan and Graham, 2018). Figure 1 demonstrates the essential role of arbuscular mycorrhizal fungi (AMF) in plant-soil interactions, focusing on carbon sequestration and soil structure enhancement. The figure also highlights the critical role played by AMF in boosting soil health, sustaining ecosystems, protecting soil carbon, and increasing plant productivity.

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**Figure 1.** Illustration of the role of arbuscular mycorrhizal fungi (AMF) in enhancing soil health, promoting carbon sequestration, and improving plant productivity through interactions with root exudates and soil organic matter.

**Factors Influencing AMF-Mediated Carbon Sequestration**

Various Factors such as weather, biotic interactions, soil quality, land management practices, host plant identification, and other environmental variables might influence the quantity and efficiency of carbon sequestration facilitated by AMF. Other than that, different plant species require different amounts of AMF in order to absorb and increase nutrients. Some plant species have very effective symbioses with AMF, which leads to an increase in the distribution of carbon to the fungal partner and an improvement in carbon sequestration (West and Post 2002).

Soil characteristics such as pH, consistency, organic matter concentration, and nutrient availability all have an impact on the number and activity of AMF. When soil conditions are favorable for AMF colonization and growth, more carbon is stored. Farming practices including tilling the soil, providing fertilizer, rotating crops, and employing agrochemicals can affect both the quantity and variety of AMFs. Two examples of sustainable land management techniques that increase carbon sequestration by encouraging AMF symbiosis include organic farming and minimum tillage (Wilson et al. 2009). The colonization and function of AMF can be affected by its relationships with other soil microorganisms. Soil carbon sequestration & nutrient cycling can be improved by positive interactions, such as mycorrhizal partnerships with nitrogen-fixing bacteria. The rate of carbon sequestration and AMF activity in terrestrial ecosystems are influenced by climatic variables such as precipitation, temperature, and atmospheric CO2 concentrations (Beer et al. 2010).

Basiru and Hijri’s (2024) research highlights the pivotal influence of arbuscular mycorrhizal fungi (AMF) in shaping soil organic carbon (SOC) dynamics. AMF can deliver plant-derived carbon to the soil in forms with varying degrees of stability—specifically, labile and recalcitrant materials—that each uniquely impact SOC reserves. Labile carbon inputs may increase microbial biomass but can also elevate respiration, accelerating organic matter breakdown. In contrast, the accumulation of recalcitrant materials, such as AMF biomass and glomalin-related soil protein (GRSP), fosters long-term carbon storage by enhancing soil structure and promoting mineral-associated organic carbon formation, thus supporting SOC sequestration. These diverse impacts of AMF products on SOC continue to fuel discussions on the fungi's role in carbon capture, particularly as atmospheric CO₂ levels rise. Recent studies indicate that the evolutionary diversity within AMF influences their ability to mobilize soil organic matter and conduct nutrient exchange with plants. This functional diversity, or resource use efficiency among AMF species, affects not only the outcomes of their symbiosis with plants but also their impact on SOC. AMF species that focus on producing recalcitrant carbon compounds, such as glomalin and mineral-bound organic matter, can contribute to sustained SOC storage. Conversely, those promoting plant growth through labile carbon exudates like sugars may accelerate SOC turnover, possibly leading to SOC reduction. Although mutualistic AMF might deplete SOC stocks, they can mitigate this by enhancing plant carbon fixation and photosynthesis. How different AMF species manage these trade-offs warrants further research to clarify their roles in SOC dynamics fully. Figure 2highlights the various influencing factors, substances and relevant processes associated with AMF-mediated soil organic carbon stabilization.

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**Figure 2.** Various factors, substances and processes associated with AMF-mediated soil organic carbon stabilization

**Carbon Sequestration Mediated by Arbuscular Mycorrhizal Fungi: Current Knowledge Gaps and Possible Future Directions**

As they develop symbiotic relationships with the roots of the majority of land plants, arbuscular mycorrhizal fungi (AMF) play an essential role in terrestrial ecosystems. Among the many important ecological functions offered by AMF is carbon sequestration, the process by which these fungi remove carbon dioxide (CO2) from the air and store it in organic matter in the soil. The processes and significance of AMF-mediated carbon sequestration have become better understood, although there are still many unanswered questions. The present review addresses these knowledge gaps and suggests new avenues for further study.

Quantification of Carbon Sequestration Rates: One of the primary research gaps in AMF-mediated carbon sequestration is the requirement for more precise measurement of carbon sequestration rates in different ecosystems. Even though there is evidence suggesting that AMF contribute to soil carbon storage, the extent of their contribution and the factors influencing carbon sequestration rates still remain uncertain. Current methods for quantifying soil carbon dynamics often neglect the role of AMF, leading to the depreciation of their contribution to the process of carbon sequestration (Genre et al., 2020).

In their 2024 study, Tao and Liu examined the potential of arbuscular mycorrhizal fungi (AMF) inoculation to promote soil carbon (C) sequestration. Through meta-analysis and logistic regression, they analyzed the effects of AMF inoculation on soil organic carbon (SOC) turnover and plant growth, taking into account different inoculation techniques, plant traits, and soil conditions. The study found that AMF inoculation typically increased SOC levels and plant biomass. Soil sterilization, the addition of non-mycorrhizal filtrates in control treatments, experimental setups, and specific AMF species influenced microbial biomass carbon (MBC) but showed limited effects on SOC turnover. Factors like plant root type, baseline SOC content, and soil pH emerged as key influencers on SOC turnover mediated by AMF. In particular, fertile or acidic soils might experience SOC depletion from AMF inoculation, while AMF associations with tap-rooted plants showed a greater capacity for C sequestration compared to fibrous-rooted plants. Plant biomass largely depended on its own photosynthetic efficiency, regardless of AMF presence. The study concludes that AMF inoculation holds promise as a method for increasing soil C sequestration.

Mechanistic Understanding of Carbon Transfer: Although it is well-established that AMF enables the transfer of carbon from host plants to the soil, the underlying molecular and biochemical mechanisms of carbon transfer from host plants to AMF and subsequent storage in soil organic matter are still not fully understood. Explaining these mechanisms is essential for predicting how environmental changes may affect AMF-mediated carbon sequestration (Liao et al. 2018).

Role of AMF Diversity: The influence of AMF diversity on carbon sequestration dynamics represents another important research gap. Despite evidence highlighting that different AMF species exhibit varying degrees of efficiency in nutrient uptake and carbon transfer, the implications of AMF diversity for carbon sequestration remain inadequately comprehended. Therefore, it is critical to investigate how changes in AMF community composition affect carbon sequestration rates and soil carbon stability for predicting the response of terrestrial ecosystems to various environmental changes (Romero et al. 2023).

Interactive Effects with Climate Change: While AMF-mediated carbon sequestration has the potential to mitigate climate change by sequestering atmospheric CO2, there is limited understanding of how climate change will affect AMF symbiosis and carbon sequestration dynamics. Climate change factors such as elevated CO2 levels, temperature, and altered precipitation patterns may impact the abundance, activity, and host-plant interactions of AMF, thereby affecting carbon sequestration processes (Johnson et al. 2015).

Integration with Land Management Practices: Another important research gap represented is incorporating AMF-mediated carbon sequestration into sustainable land management practices. While there is growing interest in utilizing AMF to enhance soil carbon storage in agricultural systems, there is limited knowledge of how different land management practices, such as tillage, crop rotation, and organic amendments, interact with AMF symbiosis to influence the outcomes of carbon sequestration processes (Verbruggen 2012).

**Future Prospects of Research Directions**

Future research should focus on developing advanced techniques for quantifying AMF-mediated carbon sequestration rates in different ecosystems. Incorporating isotopic labeling, molecular tracing, and high- resolution imaging techniques can provide understanding into the changing aspects of carbon transfer and storage in AMF symbioses, allowing for more accurate assessments of their contribution to soil carbon pools. Adopting omics approaches as a tool for mechanistic understanding such as transcriptomics, genomics, metabolomics and proteomics, can enhance our understanding of carbon transfer processes in AMF symbioses. By elucidating the genetic and biochemical basis of carbon allocation and utilization in AMF, omics studies can provide novel insights into the molecular mechanisms driving AMF-mediated carbon sequestration (Ventura et al. 2022).

Future research should investigate the effects of AMF diversity on carbon sequestration dynamics through experimental manipulations of AMF communities. By comparing carbon sequestration outcomes across gradients of AMF diversity, researchers can assess the importance of AMF community composition for soil carbon storage and stability, helping to inform conservation and restoration strategies. Experimental manipulations that simulate climate change conditions, such as elevated CO2, warming, and altered precipitation regimes, can provide valuable insights into the interactive effects of climate change on AMF symbiosis and carbon sequestration processes. Long-term field experiments coupled with molecular analyses can help elucidate the mechanisms underlying AMF responses to climate change and their implications for ecosystem carbon dynamics. Future research should explore the integration of AMF- mediated carbon sequestration into sustainable agricultural practices. Field trials that evaluate the effectiveness of AMF inoculation, cover cropping, reduced tillage, and organic amendments for enhancing soil carbon storage can provide practical insights into harnessing AMF symbioses to promote climate-smart agriculture and soil carbon sequestration. Other than this, Arbuscular mycorrhizal fungi play a crucial role in mediating carbon sequestration in terrestrial ecosystems, yet there are several research gaps that need to be addressed to advance our understanding of this process. By quantifying carbon sequestration rates more accurately, elucidating the mechanisms of carbon transfer, exploring the role of AMF diversity, investigating interactive effects with climate change, and integrating AMF-mediated carbon sequestration into sustainable land management practices, future research can contribute to unlocking the full potential of AMF for climate change mitigation and ecosystem resilience.

The present review aims to evaluate the rate of carbon sequestration in agricultural and designated open areas using arbuscular mycorrhizal fungi (AMF) and investigate mechanisms responsible for the molecular and biochemical processes that allow the transfer of carbon from host plants to AMF. Additionally, the review will analyze how changes in AMF community composition influence the rates of carbon sequestration and stabilization of soil carbon. Lastly, the research seeks to understand the influence of climate change factors such as increased temperatures, elevated CO2 concentrations, and changing precipitation patterns on the abundance, activity, and interactions of AMF with host plants, thereby affecting the processes of carbon sequestration.

**Mechanisms of AMF-Mediated Carbon Sequestration**

Arbuscular mycorrhizal fungi (AMF) derive all of their carbon from host plants, with a considerable portion being stored in the soil as fungal chitin or glomalin-related soil protein (GRSP). The carbon contributed by fungi and other microorganisms typically persists in the soil longer than that from plant origins. AMF are vital for enhancing soil carbon storage by adding significant organic material in the form of hyphal biomass, GRSP, and various hyphal exudates, which release organic carbon during decomposition and senescence (Parihar et al., 2020). In this comprehensive review, we will explore these mechanisms in detail, drawing on recent research findings and theoretical insights.

**Nutrient Cycling**

When it comes to the cycling of nutrients in terrestrial ecosystems, arbuscular mycorrhizal fungi are absolutely crucial, especially when it comes to carbon, nitrogen, & phosphorus. The symbiotic relationship between AMF and host plants allows for the uptake of soil resources, including organic substances like sugars, amino acids, and minerals like phosphate and micronutrients. Soil carbon sequestration can be aided by mycorrhizal plants' improved nutrient acquisition, which in turn boosts plant biomass output and transfers carbon below ground (Trumbore 2009).

The capacity of AMF to boost the uptake of phosphorus (P) by host plants is one of the main ways in which they increase carbon sequestration. The availability of phosphorus has a significant impact on plant development and carbon allocation, and it is frequently an essential mineral in many terrestrial ecosystems (Wilkes 2021). Soil hyphae networks formed by AMF are vast and extensive, with a high surface area that allows them to explore more soil volume than plant roots alone can. Because of this, AMF is able to consume phosphorus from organic phosphorus compounds including soil particles that the host plant would not be able to reach on its own. Enhanced plant growth & distribution of carbon to the roots, as well as improved soil carbon sequestration, are outcomes of AMF uptaking and transferring phosphorus to the host plant (Yang et al. 2014).

By nitrogen fixation along with transfer activities, AMF can improve host plants' uptake of nitrogen (N) in addition to phosphorus (P). Research has revealed that certain AMF species develop partnerships with bacteria such as Rhizobia and Frankia that can fix the nitrogen in the atmosphere in the form of ammonia that plants can easily absorb. Soil carbon sequestration is promoted by improved plant development and root exudation as a result of the nitrogen fixed with these microbe-symbionts and transmitted to the plant they live in via the AMF hyphae as stated by Govindarajulu and colleagues (2005).

Zhang et al. (2017) found that glomalin-related soil protein (GRSP) exhibits a much higher recalcitrance index than soil organic carbon (SOC), which enhances carbon sequestration both by directly retaining carbon and indirectly through its durable properties. In a related study, Wang et al. (2017) reported that GRSP plays a more significant role in carbon sequestration within deeper soil horizons. This phenomenon can be explained by the spatial dissociation of soil organic matter, microbial communities, and extracellular enzymatic activity, along with a scarcity of fresh organic carbon to serve as an energy source for microbes in those deeper layers.

**Soil Aggregation**

Soil aggregation is another process by which AMF improves soil carbon sequestration. Improved soil structure, water absorption, and nutrient retention can be achieved through soil aggregation, which is the process of binding soil particles into bigger aggregates. Soil aggregation is aided by arbuscular mycorrhizal fungi in multiple ways, such as via hyphal networks, microbial interactions, and glomalin synthesis activity (Rumpel and Kögel-Knabner 2011). AMF contributes to soil aggregation by producing the glycoprotein glomalin within their hyphae and spores, which helps bind soil particles together. Factors such as root exudates, soil moisture levels, and temperature influence the production of glomalin, which plays a key role in forming stable soil aggregates by bonding with clay particles and organic matter, thereby improving the soil's resistance to erosion as well as decomposition. The two outcomes of the increased carbon capture and stability brought about by glomalin-bound aggregates are reduced greenhouse gas emissions and improved soil health as outlined by Rillig and fellow researchers in their 2002 study.

In a study conducted by Rillig and fellow researchers in 2001, Glomalin's carbon (C) and nitrogen (N) pools contributed significantly more to the overall soil C and N pools than did the biomass of microorganisms. The hyphae of AMF are one of many different microorganisms that make up the biomass of soil bacteria. Therefore, it is safe to say that the glomalin C pool is significantly larger than the standing hyphal biomass C stock. Living hyphae of obligate biotrophic AMF produce globulin. This indicates that the carbon did not enter the soil by a saprobically generated source of organic matter from dead plants, which is how most other microbially changed soil carbon entered the soil. The significance of AMF and their products in soil carbon storage is highlighted by our work. Significantly, our findings suggest that terrestrial ecosystems may have a far greater carbon sink from mycorrhizal fungus than previously thought.

The table 1 presents data from Rilling’s (2001) study, which examines microbial carbon (C), glomalin carbon and nitrogen (C and N), and soil carbon and nitrogen (C and N) across a chronosequence spanning from 0.3 to 4100 thousand years. The measurements, given in mg cm⁻³, are provided for both organic (O) and mineral (A) soil horizons, with mean values and standard errors derived from five replicates. Microbial carbon levels vary throughout the chronosequence. In the organic horizon (O), concentrations start at 0.209 mg cm⁻³ at 0.3 thousand years, rise to 0.345 mg cm⁻³ at 150 thousand years, and then decrease to 0.245 mg cm⁻³ at 4100 thousand years. The mineral horizon (A) shows a similar trend, though at lower levels. Glomalin carbon and nitrogen concentrations also fluctuate over time. Glomalin carbon peaks at 2.26 mg cm⁻³ in the organic horizon at 20 thousand years, while nitrogen shows a more stable, gradual increase. Soil carbon and nitrogen decline significantly from younger to older soils. Specifically, soil carbon in the organic horizon decreases from 61.41 mg cm⁻³ at 0.3 thousand years to 48.4 mg cm⁻³ at 4100 thousand years, with nitrogen demonstrating a similar downward trend.

**Table 1.** Study examining microbial carbon (C), glomalin carbon and nitrogen (C and N), and soil carbon and nitrogen (C and N) across a chronosequence spanning from 0.3 to 4100 thousand years. (Source: Rillig et al. 2001)

|  |  |  |  |
| --- | --- | --- | --- |
| **Age (10³ years)** | **Microbial C (mg cm-3)** | **Glomalin C (mg cm-3)** | **Soil C (mg cm-3)** |
|  | **Carbon** | **Carbon** | **Nitrogen** | **Carbon** |  | **Nitrogen** |
|  | **O** | **A** | **O** | **A** | **O** | **A** | **O** | **A** | **O** | **A** |
| **0.3** | 0.209 | 0.191 | 0.77 | 1.13 | 0.062 | 0.072 | 61.41 | 51.8 | 3.42 | 3.3 |
|  | -0.018 | -0.03 | -0.09 | -0.1 | -0.008 | -0.006 | -3.7 | -8.9 | -0.12 | -0.6 |
| **2.1** | 0.106 | 0.162 | 0.96 | 0.85 | 0.092 | 0.067 | 54.13 | 34.4 | 3.63 | 2.58 |
|  | -0.012 | -0.021 | -0.13 | -0.32 | -0.012 | -0.025 | -5.1 | -3.7 | -0.26 | -0.2 |
| **20** | 0.331 | 0.279 | 2.26 | 2.88 | 0.181 | 0.163 | 121.5 | 108.2 | 6.87 | 6.63 |
|  | -0.029 | -0.022 | -0.07 | -0.34 | -0.006 | -0.019 | -4.8 | -7.9 | -0.2 | -0.64 |
| **150** | 0.327 | 0.333 | 3.14 | 4.53 | 0.214 | 0.24 | 105.2 | 113.6 | 5 | 6.91 |
|  | -0.028 | -0.014 | -0.31 | -0.64 | -0.021 | -0.033 | -2.8 | -8.2 | -0.32 | -0.33 |
| **1400** | 0.343 | 0.226 | 3.33 | 2.36 | 0.247 | 0.107 | 114.3 | 69.1 | 4.4 | 4.2 |
|  | -0.02 | -0.031 | -0.08 | -0.16 | -0.006 | -0.007 | -2.3 | -7.8 | -0.07 | -0.42 |
| **4100** | 0.245 | 0.195 | 4.92 | 12 | 0.263 | 0.484 | 108.4 | 233.6 | 5 | 12.84 |
|  | -0.024 | -0.011 | -0.12 | -0.66 | -0.006 | -0.026 | -6.7 | -13.4 | -0.32 | -0.78 |

**Table 2.** Carbon sequestration by AMF under various management conditions.

(WSC water soluble carbon, POM particulate organic matter, T-GRSP total-glomalin related soil protein, EE-GRSP easily extractable glomalin-related soil protein, ↑-increases; ↓-decreases; BIOC biomass carbon, HWSC hot water-soluble carbon, HA humic acid, FA fulvic acid)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Crop (cultivar)** | **AGRO ecology/contaminate site** | **AMF** | **Effect on carbon pool** | **References** |
| **Active pool**  | **Passive pool** |
| N/A | eCO2 @380 and 580 (ppmv) | + | N/A  | AMF ↓ SOC by 9% and total C by 15% | Cheng et al. (2012) |
| Maize (Zea mays L.)  | Pot experiment | + | WSC ↑16.1–116.1% POM ↑25–200% in AMF (+) over control | SOC ↑3.7–23.3 and HA and FA ↑ 25–283 and 50–191% resp. while T-GRSP and EE-GRSP ↑210–520 and 63.6–163.65% resp. in AMF (+) over control | Srimathi et al. (2014) |
| Wild cherry, Cerasushumilis Yellow horn and apricot  | Coalfields | + | N/A | SOC ↑ 52–61% and EE-GRSP and T-GRSP ↑ 55–70 and 36–44% respectively in AMF (+) | Wang et al. (2016) |
| Long-term meadow  | Field incubation and glasshouse Experiment | + | The presence of arbuscular mycorrhizal fungi (AMF) has been shown to inhibit decomposing saprobes, suggesting that AMF may play a beneficial role in enhancing carbon persistence in the soil. | Verbruggen et al. (2016) |
| Sophoraviciifolia  | Heavy metal cont. site | N/A | N/A | SOC was sig. correlated with T-GRSP (0.48–0.61) and EE-GRSP (0.39–0.57) under various depth | Yang et al. (2017) |
| Grassland, forest and arable land  | High-elevation Tibetan ecosystem | + | In forest and grassland ecosystems, AMF showed + correlations with EE-GRSP, T-GRSP, SOC, and both unprotected and physically protected carbon fractions; however, this relationship was not observed in arable land. | Xu et al. (2017) |
| Cereal-legume  | Long-term fert. exp | + | Bio-C ↑ 38%, WSC ↑ 20.8 HWSC ↑ 9.3% in AMF (+) over control | GRSP ↑ 33%, SOC ↑ 6.3% in AMF (+) over C and ↑ signifcantly (p≤0.05) ↑ both HA and FA fractions | Subramanian et al. (2019) |

**Table 3**. presents the various AMR and microbe interactions, their mechanisms and effects.

|  |  |  |  |
| --- | --- | --- | --- |
| **Interactions AMF + microbes** | **Mechanisms** | **Effects** | **References** |
| AMF Rhizobia, and phosphorus solubilizing microorganisms (PSM) | The tripartite relationship involves the solubilization of phosphorus through mineralization at low soil pH, as well as the chelation and production of phosphatase, organic acids, and protons. | Improve host plant phosphorus uptake. | Afkhami and Stinchcombe (2016); Kalayu (2019); Nacoon et al. (2020) |
| AMF and Plant Growth Promoting Rhizobacteria (PGPR) | AMF collaborate with plant growth-promoting PGPR to enhance ammonia production, nitrogen fixation, and the solubilization of mineral phosphates and other vital nutrients. This partnership also stimulates the production of plant hormones and increases the accumulation of ascorbate peroxidase and glutathione peroxidase. Additionally, they secrete organic acids that aid in dissolving phosphorus phytate, mineralizing organic phosphorus, and solubilizing inorganic phosphorus. Furthermore, PGPR present within AMF mycelia produce siderophores and indole-3-acetic acid. | Soil fertility and plant growth can be enhanced by increasing the diversity and abundance of soil antagonists that target parasites which can help reduce damage caused by water deficits and improve tolerance to water stress, as seen in species like Cupressus arizonica. | Battini et al. (2016); Moreira et al. (2020) |
| AMF and Bacillus subtills | AMF enhance the activities of nitrate and nitrite reductase and nitrogenase, as well as the production of osmoprotectants like glycine, betaine, and proline by Bacillus subtilis. | Enhance the dry weight of both shoots and roots, increase the number of nodules, and boost leghemoglobin levels. | Hashem et al. (2017) |
| AMF and Pseudomonas fluorescens | Glomus intraradices (AMF) promotes the synthesis of the antibiotic 2,4-diacetylphloroglucinol by Pseudomonas fluorescens. | The antibiotic protects the host plants against Gaeumannomyces graminis | Ma et al. (2019) |
| AMF and saprotrophic fungi | AMF increase the biomass of saprotrophic fungi. | Dissolution of soil organic matter into mineral matter | Carteron et al. (2021) |

**Methods that Improve Carbon Sequestration**

To lessen the severity of climate change, carbon sequestration involves removing carbon dioxide (CO2) from the air and storing it in places where it will remain for an extended period of time, such as oceans, forests, or soil. Soil characteristics, weather, agricultural practices, and relationships with other creatures, especially plants, are some of the environmental and managerial variables that impact the various processes that increase carbon sequestration. Improving carbon sequestration and reducing climate change requires a thorough understanding of these processes (Scharlemann et al. 2014). When it comes to carbon sequestration, soil characteristics are a crucial factor. The biggest terrestrial carbon pool, soil organic carbon or SOC, is affected by things including soil structure, pH, nutrient availability, and soil texture (Sleutel et al. 2007). For instance, clay soils have higher carbon storage capacity due to their higher surface area and greater potential for organic matter adsorption (Lal 2004). Moreover, well-aggregated soils with good drainage facilitate the formation and stabilization of SOC, while acidic soils may inhibit carbon sequestration by impeding microbial activity (Rumpel and Kögel-Knabner 2011).

Cheng et al. (2012) suggest that in conditions of elevated CO₂, the type of nitrogen is more crucial than the total nitrogen content in regulating carbon decomposition below ground and plant nitrogen uptake. Therefore, as environmental CO₂ levels rise in the future, it will be important to manage nitrogen transformations in conjunction with terrestrial carbon cycling. Arbuscular mycorrhizal fungi (AMF) are believed to play a role in nutrient dynamics for other microbes, potentially decreasing respiratory losses from both stable and labile carbon reserves and enhancing carbon retention in the soil (Nottingham et al., 2015). Furthermore, Kowalchuk (2012) introduced a conceptual framework to clarify the interactions between AMF and soil saprotrophs concerning carbon sequestration under certain conditions. According to this framework, a weak relationship between AMF and less stimulated soil saprotrophs is seen as the most advantageous scenario for achieving optimal net carbon sequestration.

Climate conditions also significantly impact carbon sequestration rates. Temperature and precipitation influence primary productivity, decomposition rates, and soil microbial activity, thereby affecting carbon fluxes (Trumbore 2009). Warmer temperatures generally accelerate decomposition rates, potentially reducing carbon storage in soil and vegetation (Davidson and Janssens 2006). Conversely, in colder climates, carbon can be stored for longer periods due to slower decomposition rates (Schuur et al. 2008). However, extreme climate events such as droughts or heavy rainfall can disrupt carbon sequestration processes by altering vegetation dynamics and soil moisture levels (Knapp et al. 2008).

Mohan et al. (2014) examined how warming influences arbuscular mycorrhizal (AM) fungi, finding that mycorrhizal abundance increased in 63% of studies, decreased in 17%, and remained neutral or insignificant in 20% of instances as temperatures rose. While the precise role of AM fungi in soil carbon regulation is not fully understood, their impact on the soil carbon balance is crucial in the context of changing temperatures. Increased temperatures can modify carbon allocation to fungi, potentially leading to higher carbon respiration or enhanced soil carbon storage through reduced respiration rates or greater fungal mycelial biomass. Additionally, elevated temperatures may promote more efficient carbon distribution to AM fungi, improve phosphorus uptake, and increase root colonization rates. Changes in temperature can also affect root biomass morphology and lifespan, thereby further impacting the soil carbon balance (Parihar et al., 2020). However, there is a lack of comprehensive research on the combined effects of elevated CO₂ and temperature on AM fungi-mediated carbon cycling. To deepen our understanding of how global climate change impacts plant-mycorrhizal relationships and ecosystem functions, it is important to adopt multifactorial approaches that incorporate multidisciplinary research and long-term field experiments.

Land use practices can either enhance or diminish carbon sequestration potential. Afforestation and reforestation efforts can significantly increase carbon stocks by establishing new forest ecosystems or restoring degraded ones (Houghton et al. 2012). Sustainable agricultural practices such as conservation tillage, cover cropping, and agroforestry promote carbon sequestration in soils by reducing soil disturbance and enhancing organic matter inputs (West and Post 2002). Conversely, deforestation, land degradation, and intensive agricultural practices can release large amounts of carbon stored in vegetation and soils, exacerbating climate change (Foley et al. 2005).

Soil management techniques play a crucial role in shaping soil properties and supporting microbial diversity. The application of mineral fertilizers, chemical pesticides, and herbicides is essential for supplying vital nutrients to crops, replenishing those lost during harvesting, controlling weed populations, and managing pests (Rana et al., 2019). Nevertheless, prolonged use of high rates of inorganic fertilizers can reduce plants' dependence on arbuscular mycorrhizal fungi (AMF), resulting in decreased diversity and abundance of these beneficial fungi (Kour et al., 2020). This reduction is linked to the energetically demanding nature of the plant-AMF symbiosis; as soil nutrient levels increase, plants typically allocate fewer carbohydrates to AMF, which adversely affects the production of spores and hyphae (Tian et al., 2013).

Interactions with other organisms, particularly plants, also play a crucial role in carbon sequestration processes. Plant photosynthesis is the primary mechanism for atmospheric CO2 uptake, converting carbon into organic compounds that are stored in biomass and soil (Beer et al. 2010). Moreover, plant roots release carbon-rich exudates that stimulate microbial activity and soil aggregation, enhancing carbon stabilization in soil (Rasse et al. 2005). Moreover, symbiotic connections between mycorrhizal fungi and plants promote the intake of nutrients and the allocation of carbon, which improves carbon sequestration (Khaliq et al. 2022).

**Role of AMF on Improving Soil Biological Properties**

Arbuscular mycorrhizal fungi (AMFs) interact with a diverse array of microorganisms in the soil, contributing to enhanced soil fertility. Studies have shown that the secretions produced by AMFs can significantly influence the composition and activity of microbial communities in the rhizosphere (Veresoglou and Rillig, 2012). These interactions can be positive, neutral, or negative, depending on various factors. Numerous soil microbes collaborate with AMFs to promote plant growth and health. Positive effects include better nutrient uptake, biological control of root pathogens, increased plant tolerance to abiotic stresses, and improvements in overall soil fertility. Furthermore, AMF communities play a crucial role in altering the physicochemical properties of the rhizosphere and in regulating various soil microbial interactions (Alimi et al., 2021).

The process of mycorrhization affects the quantity and quality of root exudates, which subsequently influences the microbial composition in the rhizosphere (Baltrus, 2017). However, these interactions are influenced by the availability of nutrients such as phosphorus and nitrogen. Research by Xu et al. (2018) has shown that the synergistic relationships between AMFs and certain bacterial (e.g., rhizobia) and fungal communities are dependent on the nitrogen and phosphorus levels in the soil. Despite these findings, significant knowledge gaps remain, particularly regarding how soil microorganisms may inhibit or disrupt AMF functions. Questions also arise about the role of AMFs within the trophic chain, including their vulnerability to predation or parasitism by soil microorganisms. Additionally, further investigation is required to examine the interactions between AMFs and free-living nematodes and how these relationships affect the development of cereal crops under conditions of water stress. Figure 3 Illustrates the various effects of AMF on improving the physical, chemical and biological properties of soil.

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**Figure 3.** Effects of AMF on improving soil fertility and carbon sequestration potential

**Future Perspectives**

**Exploration of Novel AMF Species and Strains**

Arbuscular mycorrhizal fungi (AMF) have been found to have improved carbon sequestration capability in novel strains and species. This discovery opens up exciting possibilities for increasing soil carbon storage. By forming symbiotic relationships with plant roots, arbuscular mycorrhizal fungi promote nutrient intake and accelerate plant growth (Kivlin et al. 2011).

These fungi perform an important role in carbon cycling, as they can transfer substantial amounts of carbon from plants to the soil through exudates and hyphal networks, contributing to soil organic carbon (SOC) accumulation (Rasse et al. 2005). Studies have highlighted the importance of AMF diversity in influencing carbon sequestration rates. New AMF species and strains may exhibit distinct functional traits, such as higher colonization efficiency, greater hyphal proliferation, and enhanced organic matter decomposition, leading to increased carbon inputs into the soil (Dong et al. 2016). For example, recent research has identified novel AMF species with improved nutrient uptake capabilities and greater carbon allocation to soil, thereby enhancing carbon sequestration potential (Kivlin et al. 2011). Furthermore, certain AMF strains have been found to promote the formation of stable soil aggregates, facilitating SOC stabilization and protection from decomposition (Lehmann et al. 2019). By enhancing soil structure and aggregation, these AMF strains contribute to long-term carbon storage in soils, mitigating the effects of climate change. Incorporating new AMF species and strains with enhanced carbon sequestration potential into agricultural and restoration practices holds promise for improving soil carbon storage. Harnessing the symbiotic relationship between plants and AMF can enhance ecosystem resilience to environmental stressors while mitigating climate change through increased carbon sequestration in soils. (Rillig et al. 2015).

**Understanding AMF-Microbiome Interactions**

The interactions between arbuscular mycorrhizal fungi (AMF) and other soil microorganisms are complex and multifaceted, playing a crucial role in determining soil carbon sequestration rates. Understanding these interactions is essential for harnessing their collective potential to enhance carbon storage in soils. AMF acts together with a variety of soil microorganisms, including fungi, bacteria, and archaea, forming intricate networks known as the soil microbiome (Van Der Heijden et al. 2015). These interactions can be mutualistic, as both the associates reap the advantages, or antagonistic, where one associate may inhibit the growth or activity of another (Dakora and Phillips 2002). For example, mutually beneficial interactions between soil bacteria and AMF can improve nutrient cycling and encourage plant growth, which in turn increases the amount of carbon added to the soil above and beyond root exudates (Treseder and Cross 2006). AMF also engage in symbiotic relationships with other fungi, such as saprotrophic and pathogenic fungi, influencing carbon dynamics in soils. Coexistence with saprotrophic fungi can accelerate organic matter decomposition, releasing carbon and nutrients for plant and microbial uptake (Dong et al. 2015). Conversely, AMF may compete with pathogenic fungi for root colonization sites, thereby reducing plant disease incidence and enhancing plant productivity, indirectly contributing to carbon sequestration (Barto et al. 2012).

Furthermore, interactions between AMF and soil archaea, such as ammonia-oxidizing archaea (AOA), can impact nitrogen cycling and soil carbon dynamics. AMF may promote AOA activity by supplying them with carbon substrates derived from plant photosynthates, thereby enhancing nitrification rates and nitrogen availability for plant uptake (Zhou et al. 2019). This interaction highlights the potential for AMF to indirectly influence carbon sequestration through their effects on nitrogen dynamics in soils. Harnessing the collective potential of AMF and other soil microorganisms for carbon sequestration requires an integrated approach that considers the complexity of soil microbial communities. Strategies aimed at promoting beneficial interactions between AMF and soil bacteria, fungi, and archaea, while minimizing antagonistic interactions, can enhance carbon storage in soils. For example, incorporating diverse cover crops or crop rotations that support AMF and microbial diversity can promote synergistic interactions and improve soil carbon sequestration (Hestrin et al. 2019).

**Scaling-Up AMF Applications**

Scaling up arbuscular mycorrhizal fungi (AMF) inoculation techniques for broader application in agriculture and ecosystem restoration requires the development of effective and practical strategies. Several approaches can be employed to achieve this goal, including the production of high-quality inoculum, the optimization of inoculation methods, and the integration of AMF inoculation into existing agricultural and restoration practices. Firstly, the production of high-quality AMF inoculum is essential for successful large- scale application. This involves cultivating AMF spores or propagules under controlled conditions to ensure their viability and effectiveness. Commercial production methods, such as in vitro cultivation or trap culture systems, can be utilized to produce large quantities of AMF inoculum (Corkidi et al. 2004). Moreover, advances in biotechnology, such as the use of bioreactors or synthetic biology approaches, hold promise for enhancing the efficiency and scalability of AMF inoculum production (Gianinazzi et al. 2010).

Secondly, maximizing AMF establishment and colonization in target environments requires the optimization of injection techniques. When planting seeds or transplanting plants, AMF inoculum can be applied to the plants using methods including seed coating, soil soaking, or root dipping (O'Callaghan et al. 2022). Moreover, the use of carrier materials, such as vermiculite or peat, can enhance the survival and dispersal of AMF inoculum in soil (Hart et al. 1994).

Additionally, incorporating AMF inoculation into conservation tillage or agroforestry practices can also facilitate the integration of AMF into agricultural landscapes (Rillig et al. 2019). Finally, integrating AMF inoculation into existing agricultural and restoration practices is essential for broadening its application. This involves raising awareness among farmers, land managers, and policymakers about the benefits of AMF symbiosis for soil health, plant productivity, and ecosystem resilience. Furthermore, providing incentives, such as subsidies or technical assistance, can encourage widespread adoption of AMF inoculation techniques in agriculture and ecosystem restoration projects (Lehmann et al. 2019).

**Climate Change Adaptation Strategies**

The resilience of arbuscular mycorrhizal fungi (AMF)-mediated carbon sequestration to climate change depends on understanding and managing the interactions between AMF, plants, and soil in a changing environment. Research indicates that AMF symbiosis can increase plant tolerance to environmental stressors, such as drought or elevated CO2 levels, hence enhancing carbon sequestration, even though climate change may alter AMF diversity, activity, and distribution (Zhu and Miller 2003). However, the effectiveness of AMF-mediated carbon storage may vary depending on local climatic conditions and soil properties, hence adaptive management practices are required that promote AMF diversity, optimize soil carbon inputs, and enhance soil resilience such as implementing conservation tillage, promoting agroforestry, or restoring degraded ecosystems (Lehmann et al. 2019).

**CONCLUSION**

Translating laboratory findings into field applications, particularly in the context of Arbuscular Mycorrhizal Fungi (AMF)-mediated carbon sequestration, presents numerous challenges and requires interdisciplinary collaboration to bridge knowledge gaps and overcome technical barriers. Arbuscular Mycorrhizal Fungi are symbiotic fungi that form mutualistic associations with the roots of most plant species, playing a crucial role in nutrient uptake, plant growth, and soil carbon dynamics. Harnessing their potential for carbon sequestration in field settings necessitates a comprehensive understanding of the complexities involved. One significant challenge lies in the inherent complexity of the soil ecosystem. Laboratory experiments often simplify environmental conditions to isolate specific variables, which may not accurately reflect the intricate interactions present in natural ecosystems. For instance, factors such as soil texture, moisture levels, microbial communities, and plant species composition can significantly influence AMF colonization and their carbon sequestration potential. Translating findings from controlled laboratory experiments to diverse field environments requires careful consideration of these factors to ensure the effectiveness of AMF-mediated carbon sequestration strategies.

Moreover, technical challenges hinder the scalability and applicability of laboratory-derived techniques to field conditions. For example, while molecular techniques such as DNA sequencing have revolutionized our understanding of AMF diversity and community structure in laboratory settings, their application in field studies is often constrained by cost, time, and the complexity of soil matrices. Developing robust and cost-effective methodologies for assessing AMF abundance and activity in field soils is essential for accurately evaluating their contribution to carbon sequestration. Furthermore, addressing knowledge gaps surrounding the mechanisms underlying AMF-mediated carbon sequestration is critical for optimizing field applications. While laboratory studies have elucidated some aspects of AMF physiology and their interactions with plant hosts, significant gaps remain in our understanding of how these processes translate to carbon sequestration in real-world ecosystems. Interdisciplinary collaboration between soil scientists, microbiologists, plant ecologists, and biogeochemists is essential for integrating knowledge from various disciplines and developing holistic approaches to tackle these challenges. Interdisciplinary collaboration also offers opportunities to leverage complementary expertise and resources to overcome technical barriers. For instance, soil scientists can provide insights into the physical and chemical properties of soils that influence AMF colonization and carbon sequestration, while microbiologists can contribute expertise in microbial ecology and physiology to elucidate the mechanisms driving AMF-mediated carbon dynamics. Plant ecologists can offer insights into the role of plant-mycorrhizal interactions in ecosystem carbon cycling, while biogeochemists can employ advanced analytical techniques to quantify carbon fluxes in field settings (Middleton et al. 2015).

Interdisciplinary research initiatives can facilitate the development of innovative field-based experimental approaches that capture the complexity of natural ecosystems. For example, mesocosm experiments, which involve simulating field conditions in controlled environments, allow researchers to manipulate key variables while maintaining a level of ecological realism that is often lacking in laboratory studies. By integrating field observations with laboratory experiments and modeling approaches, interdisciplinary teams can generate comprehensive insights into the factors influencing AMF-mediated carbon sequestration and inform the development of sustainable land management practices. Therefore, translating laboratory findings to field applications and advancing our understanding of AMF-mediated carbon sequestration requires interdisciplinary collaboration to address knowledge gaps and overcome technical barriers. By integrating expertise from diverse disciplines, researchers can develop holistic approaches that capture the complexities of natural ecosystems and pave the way for effective strategies to mitigate climate change through enhanced carbon sequestration in soils.

**COMPETING INTERESTS DISCLAIMER:**

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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