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(Review Article)

Investigating the Ecological Role of Arbuscular Mycorrhizal Fungi (AMF) in Natural Ecosystems

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Abstract

Arbuscular mycorrhizal fungi (AMF) have a vital role in natural ecosystems, intensifying nutrient cycling, plant competition, and species interactions. These microbes establish symbiotic relationships with a multitude of plant species, promoting optimal nutrient absorption and plant development. The expansive mycelium network of AMF improves nutrient assimilation, particularly for phosphorus, which is commonly restricted in various ecosystems. AMF also promotes plant competition by empowering specific plant species to gain a competitive edge, thus influencing plant community dynamics. The presence of these microbes can influence the growth, reproductive processes, and overall vitality of plants. Likewise, mycorrhizal connections possess the capacity to enhance inter-species associations, thereby bolstering the overall stability and functioning of the ecological system. Future research should give priority to investigating the mechanisms behind AMF-mediated interactions, assessing the effects of AMF on ecosystem response to global environmental changes, and exploring potential applications in ecosystem restoration and conservation efforts. By promoting plant growth, improving nutrient absorption, and optimizing ecosystem functionality, AMF can be utilized as an effective method for restoring damaged ecosystems and safeguarding endangered plant species.

Keywords: Arbuscular mycorrhizal fungi; Species interactions; Nutrient absorption; Nutrient recycling

1. Introduction

The ecological role of arbuscular mycorrhizal fungi (AMF) in natural ecosystems is a topic of great interest and importance. AMF are symbiotic organisms that form mutualistic associations with the roots of most land plants, facilitating nutrient uptake and enhancing plant growth [1,2]. This relationship has profound implications for the functioning and stability of natural ecosystems. One key role of AMF is their ability to enhance nutrient acquisition by plants [3,4]. They have a remarkable capacity to extract nutrients, particularly phosphorus, from soil particles that are otherwise inaccessible to plants. In return, the fungi receive carbohydrates produced by the plant through photosynthesis [5]. This mutual exchange benefits both partners and contributes to increased plant productivity. Furthermore, AMF play a crucial role in soil structure and stability. Their extensive network of hyphae binds soil particles together, creating aggregates that improve water infiltration and retention [6,7,8]. This enhances soil fertility and reduces erosion, ultimately promoting ecosystem resilience. According to [9,10], AMF have been found to influence plant community composition and diversity. They can selectively associate with certain plant species based on their nutritional requirements or other factors such as root exudates. By influencing plant competition dynamics, AMF contribute to maintaining species diversity in ecosystems. Overall, the ecological role of AMF in natural ecosystems is multifaceted and essential for ecosystem functioning. Their ability to enhance nutrient acquisition, improve soil structure, and influence plant community composition highlights their significance in maintaining healthy and resilient ecosystems. Understanding these interactions is crucial for effective conservation strategies aimed at preserving biodiversity and ecosystem services provided by natural habitats.

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1.1. Role of AMF in nutrient cycling

AMF play a crucial role in nutrient cycling processes within ecosystems. Their extensive mycelium network allows them to transport and shuttle nutrients, especially phosphorus, to their plant hosts [11]. This process significantly increases nutrient availability for plants, leading to improved growth and nutrient utilization. Consequently, this fosters conditions conducive for various plant species. The mycelium network of AMF acts as a bridge between the soil and plant roots [12,13]. It extends far beyond the reach of plant roots, exploring the surrounding soil for nutrients. Through this exploration, AMF can access phosphorus that is otherwise unavailable to plants due to its low mobility in soil. The fungi then transfer these nutrients directly to their plant hosts through specialized structures called arbuscules [14,15]. The increased availability of phosphorus has profound effects on plant growth and development. Phosphorus is an essential element required for various physiological processes in plants, including energy transfer and DNA synthesis. By enhancing the uptake of phosphorus, AMF enable plants to allocate more energy towards growth and reproduction [16]. Moreover, AMF also improve nutrient utilization efficiency in plants. They enhance the absorption of other essential elements such as nitrogen and potassium by increasing root surface area through their mycelium network. According to [17], this allows plants to extract more nutrients from the soil while minimizing losses through leaching or volatilization. Overall, the influence of AMF on nutrient cycling processes within ecosystems is undeniable. Their ability to transport and shuttle nutrients like phosphorus greatly benefits their plant hosts by increasing nutrient availability, improving growth, and enhancing nutrient utilization efficiency. As a result, AMF contribute significantly to creating favorable conditions for various plant species within ecosystems.

1.2. AMF-Mediated Plant Competition

In the complex network of interactions within an ecosystem, plant competition plays a pivotal role in determining the makeup and variety of plant species. This competition can be alleviated by the symbiotic connection between plants and AMF. These fungi performs a crucial function in moderating plant competition by facilitating the access of plants to restricted resources like water and nutrients [18]. One of the main methods through which AMF moderates plant rivalry is by augmenting nutrient uptake. These fungi establish a mutually beneficial association with plants, where they colonize the roots and extend their hyphae into the soil. This extensive network allows them to scavenge for nutrients that are otherwise inaccessible to plants. By transporting these nutrients back to the host plant, AMF provide a competitive advantage, enabling plants to thrive even in nutrient-poor environments [19]. Similarly, AMF also assist plants in accessing water resources. The hyphal network of these fungi acts as an extension of a plant's root system, effectively increasing its surface area for water absorption. This enhanced water uptake allows plants to withstand drought conditions and outcompete other species that may be less efficient at acquiring this vital resource. By facilitating nutrient uptake and enhancing water absorption, AMF reduce inter-specific competition among plants. With access to limited resources secured through their symbiotic association with AMF, a wider range of plant species can coexist within an ecosystem. According to [20], this increased diversity not only enhances ecosystem stability but also promotes resilience against environmental disturbances. Overall, arbuscular mycorrhizal fungi play a vital role in mediating plant competition by helping plants access limited resources such as water and nutrients. By means of their mutual alliance with host plants, these fungi offer competitive benefits that enable the coexistence of a wider variety of plant species within an ecosystem. Acknowledging the significance of this symbiotic connection is crucial for effective conservation and monitoring techniques, as it enhances the overall health and functioning of ecosystems.

1.3. Mycorrhizal Networks and Species Interactions

Mycorrhizal networks, the interconnected underground systems formed by fungi, play a crucial role in facilitating species interactions. These networks enable plants to communicate, share nutrients, and defend against pathogens and herbivores [21]. By enhancing communication and collaboration among various plant species, mycorrhizal networks promote a wide range of unique and mutually advantageous interactions. One of the primary roles carried out by these mycorrhizal networks involves the exchange of valuable information [22]. Chemical signals transmitted through these networks allow plants to effectively communicate with one another. For instance, in the event of an attack by pathogens, a plant can emit chemical signals that notify neighboring plants to prepare for defensive actions. This mode of communication enables plants to synchronize their responses and significantly enhance their chances of survival [23]. Moreover, mycorrhizal networks play a vital role in facilitating the sharing of vital nutrients between different plant species. While certain plants may have access to resources, others may encounter limitations in nutrient availability. Through these underground connections, [24] reveal that plants can transfer excess nutrients to those in need. This mutual sharing ensures the overall health and growth of all participating species. Additionally, mycorrhizal networks contribute to defense mechanisms against pathogens and herbivores. Fungi within these networks can produce compounds that deter or inhibit the growth of harmful organisms [25]. By connecting multiple plant species together, these networks create a united front against potential threats. In summary, mycorrhizal networks are vital for promoting diverse and mutually beneficial interactions among plant species. They enable communication, nutrient sharing, and defense mechanisms that enhance the overall health and resilience of ecosystems. Understanding the significance of these underground connections is crucial for conservation efforts and sustainable management practices in our natural world.

1.4. Role of AMF in Plant reprograming

The reprogramming of biochemical routes in plants by AMF is a captivating phenomenon that has been extensively investigated in recent times. AMF are symbiotic fungi that establish mutually beneficial partnerships with the roots of most land-dwelling plants, offering them various advantages such as improved nutrient absorption and heightened resilience to environmental pressures [26]. One of the core mechanisms by which AMF exert their influence on plant metabolism is by regulating the expression of genes involved in biochemical routes. AMF can prompt alterations in the levels of gene expression encoding enzymes participating in primary and secondary metabolism, resulting in changes in plant physiology and biochemistry [27]. For instance, research has revealed that AMF can boost the expression of genes involved in nitrogen integration, leading to augmented nitrogen uptake and utilization by plants. Similarly, AMF can reinforce the production of secondary compounds like flavonoids and phenolic substances, which have vital functions in plant defense against pathogens [28]. The reprogramming of metabolic processes by AMF is believed to be facilitated through a complex communication system involving both direct physical connections between fungal hyphae and plant cells, as well as chemical signals released by both partners. These signals initiate a series of molecular events that ultimately lead to modifications in gene expression and metabolic function [29]. Comprehending how AMF reprogram the metabolic routes of plants is not only crucial from a fundamental scientific perspective but also holds practical implications for agriculture. By harnessing the advantageous impacts of AMF on plant metabolism, it may be feasible to devise innovative strategies for enhancing crop productivity and sustainability. Additionally, deciphering the intricate mechanisms behind this mutually beneficial interaction could open the doors for new biotechnological applications aimed at augmenting plant performance under demanding environmental conditions.

1.5. Search strategy

The research encompassed English journals ranging from 2013 to 2023. The search process involved segmenting the research topic into specific search terms, including "Arbuscular Mycorrhizal Fungi colonization" and "Ecological Role of AMF." Following the search, a total of 64 journal articles were identified, with 7 duplicates removed, leaving a final count of 57 individual articles. The abstracts of all these journals underwent a comprehensive examination, and pertinent papers were labeled for subsequent evaluation. The study relied on a 10-year threshold as the main factor for determining inclusion and exclusion. Following the completion of this requirement, a comprehensive examination of 52 journal articles was undertaken to evaluate their pertinence to the research topic. At this stage, 2 of these journals were disregarded since the study prioritized peer-reviewed articles only. A thorough examination of 50 peer-reviewed journals was undertaken to ascertain their eligibility for inclusion in this analysis. Three of these journals were regarded as irrelevant as they provided no input in identifying keywords. As a result, the research strategy yielded 47 publications that were cited and referenced in this review (Figure 1).

2. Ecological Role of AMF in Natural Ecosystems: Findings from Previous Studies

2.1. Role of AMF in nutrient cycling

In the study conducted by Bender et al., it was discovered that arbuscular mycorrhizal fungi (AMF) have the capacity to enhance sustainable nutrient cycling. Despite this, the influence of AMF on nitrogen (N) cycling was determined to be situation-specific. The researchers found that AMF resulted in lower $N2O$ fluxes and reduced $NH4+$ leaching in both soil types. Surprisingly, the leaching of dissolved organic nitrogen was only diminished by 24% in the heath soil [30] [Table 1]. This implies that the influence of AMF on nitrogen cycling could fluctuate based on the unique attributes of the soil. It is likely that particular soil types foster a more propitious environment for AMF to bolster nutrient cycling. Furthermore, the nitrogen content of plants was elevated by 13% in the pasture soil, whereas it did not exhibit any significant impact in the heath soil [30]. This suggests that AMF might exert a more pronounced impact on plant nutrient assimilation in specific ecological settings. These findings emphasize the crucial role of considering contextual factors in studying the effects of AMF on nutrient cycling. According to [30], understanding the intricate relationship between various soil types and environmental conditions is crucial in determining the overall impact of AMF on sustainable nutrient cycling. Overall, this study provides valuable insights into the impact of AMF on nutrient cycling, highlighting the necessity for additional research to fully grasp their contribution to sustainable agricultural practices.

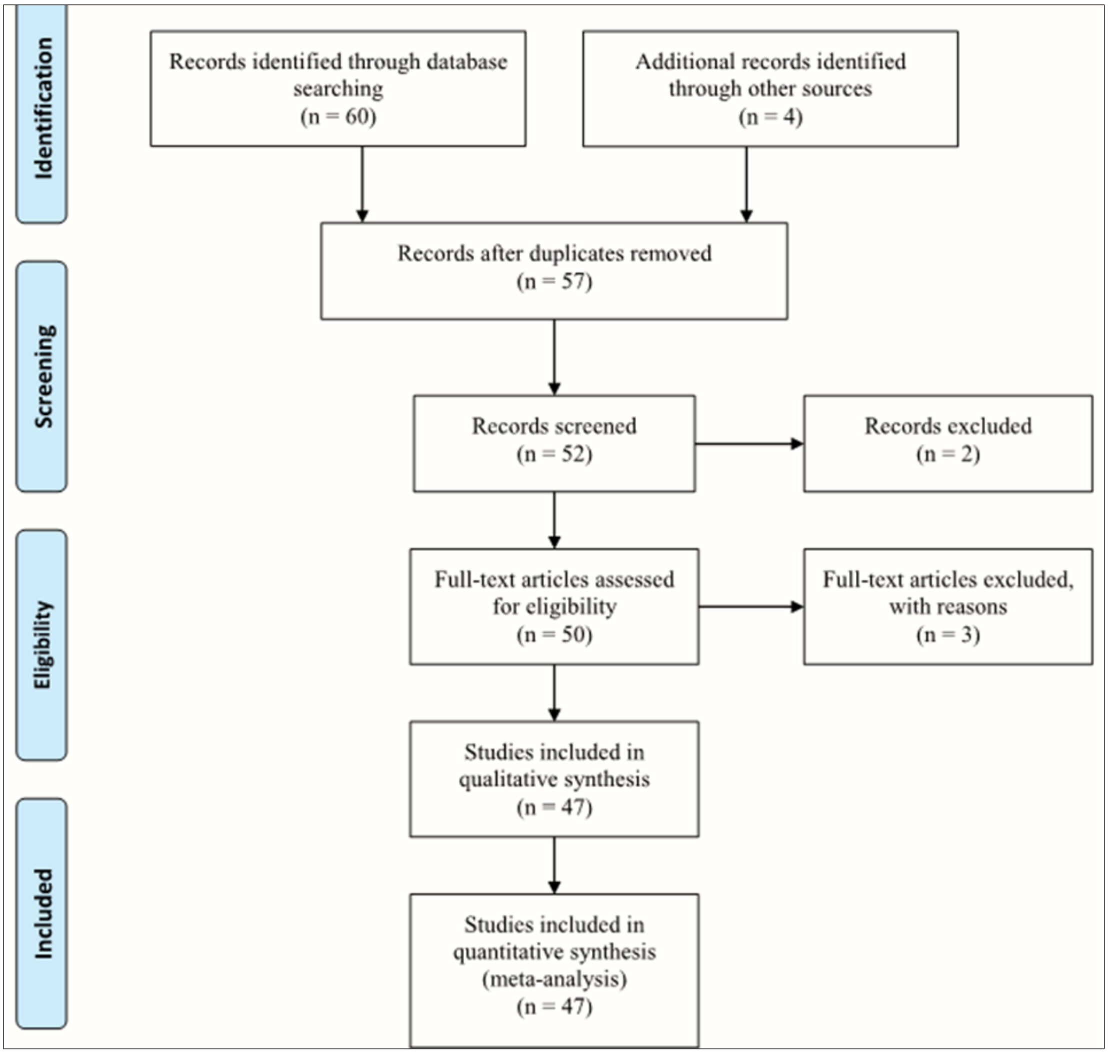

Figure 1 PRISMA diagram showing how papers were selected, excluded and included

In a separate study conducted by Yu et al., it was discovered that the combination of AMF and PGPR resulted in synergistic effects on various aspects of plant growth. The research focused on root morphology, soil nutrient availability, and plant growth in general. The study observed a significant increase in the overall nitrogen content in the soil under the inoculation treatments. This proposes that the inclusion of AMF and PGPR heightened the availability of this pivotal nutrient for plants [31] [Table 1]. In addition, the soil showed an increase in alkaline phosphatase and urease activities. These enzymes play essential roles in the recycling and availability of nutrients, further reinforcing the favorable effects of AMF and PGPR [31]. In addition, it was observed that soil electrical conductivity and pH underwent a notable decrease under the inoculation treatments. This indicates that the involvement of AMF and PGPR helped enhance soil quality by mitigating salinity and stabilizing pH levels, ultimately fostering an environment conducive to plant growth [31]. In conclusion, this study underscores the beneficial effects of the AMF and PGPR combination on root morphology, soil nutrient availability, and plant growth. By enhancing nutrient uptake efficiency, these microorganisms contribute to sustainable agricultural practices through improving root morphology and elevating enzyme activities in the soil. Further investigation is needed to thoroughly explore their potential applications in crop production systems, with the aim of maximizing yield and minimizing environmental effects.

In a study conducted by Meng et al., it was determined that the introduction of both earthworms and AMF to contaminated soil resulted in a substantial enhancement of plant growth. This was ascribed to heightened soil enzyme activities, which are imperative for nutrient cycling. Moreover, there were observed variations in soil nutrient availability, which further contributed to the improvement of plant growth [32] [Table 1]. Heavy metal pollution is an urgent environmental concern that presents significant risks to both ecosystems and human well-being. It can result in decreased plant productivity, hindered nutrient absorption, and elevated levels of toxicity. Nevertheless, this study posits that the simultaneous inoculation of earthworms and AMF can alleviate these adverse impacts [32]. The presence of earthworms is essential for enhancing soil structure through increased porosity and water infiltration. They also aid in the decomposition of organic matter, thus releasing necessary nutrients for plants. On the other hand, AMF form symbiotic relationships with plant roots, facilitating nutrient uptake from the soil. By merging these two beneficial organisms, [32] emphasize their synergistic influence on plant growth when exposed to heavy metal pollution. The enhanced activity of soil enzymes fosters the circulation of nutrients, while modifications in soil nutrient availability secure a satisfactory availability of vital elements for plants. In summary, this research presents valuable findings on potential approaches to mitigate the deleterious consequences of heavy metal pollution on plants and soils. Further research should investigate the practical implementation of dual inoculation techniques as an environmentally conscious method for sustainable agricultural practices.

2.2. AMF-Mediated Plant Competition

A study conducted by Buhadur et al. has illuminated the potential advantages of mycorrhizal associations in augmenting the growth and nutrient absorption of host plant species when cultivated alongside non-host plant species. This research proposes that these linkages can indirectly influence their competitive prowess in the presence of N-addition. Mycorrhizal associations have been observed to aid in the uptake of nutrients, specifically phosphorus, by host plants. Nonetheless, [33]'s study explores deeper into the matter by examining how mycorrhizal associations can affect mixed-culture situations that involve non-host plants [Table 1]. The results indicate that the presence of mycorrhizal associations improves the growth and nutrient absorption of host plants when cultivated alongside non-host plants. This can be credited to the enhanced access to nutrients facilitated by these fungal partners. As a result, host plants demonstrate enhanced competitive prowess compared to non-host plants. Furthermore, [33]'s research underscores a secondary influence of mycorrhizal associations on competitive prowess through N-addition. The application of nitrogen (N) is a customary agricultural procedure, which can have detrimental repercussions on both plant diversity and ecosystem functioning. However, in mixed-culture systems with N-addition, mycorrhizal associations help alleviate the detrimental impacts on host plants' growth and nutrient absorption. In general, [33]’s study highlights the crucial role of mycorrhizal associations in promoting the growth and nutrient assimilation of host plant species when grown alongside non-host plant species in mixed-culture settings. Moreover, it provides insight into how they indirectly influence competitive ability under N-addition circumstances. This research provides valuable insights into comprehending the intricate dynamics within plant communities and presents potential applications for sustainable agriculture practices.

The study conducted by Wagg et al. accentuates the essential role of AMF in fostering the coexistence of plants. The study found that various plant species exhibit varying degrees of dependence on AMF for their growth and survival. Based on [20]'s investigation, plant species that are highly reliant on AMF display diminished convergence in ecological habitats with their competitors. This decreased overlap of ecological niches enhances resource allocation efficiency and mitigates competition for scarce resources like nutrients and water. As a result, these plant species can coexist more effectively in diverse ecological communities. This research suggests that plants utilize mycorrhizal dependence as a strategic adaptation to minimize niche overlap with competitors, thereby enhancing coexistence [20] [Table 1]. By relying on AMF for nutrient acquisition, plants can effectively exploit a broad spectrum of resource niches in their surroundings, thereby minimizing direct competition with other species. In conclusion, [20]'s research offers valuable insights into the mechanisms that foster the coexistence of plant species. The inherent growth response of plants to AMF appears to be a pivotal factor in reducing niche overlap and fostering increased diversity within ecological communities. Acquiring an in-depth comprehension of these dynamics is essential to encourage effective conservation initiatives and nurture sustainability.

The study conducted by Lin et al. unveiled that the mycorrhizal sensitivity of focal and adjacent plant species is a pivotal characteristic in shaping the impacts of AMF on competitive outcomes, subsequently exerting a profound influence on plant species abundance [18]. Regardless of disparities in studies, this research uncovers the nuanced correlation between AMF and plant communities. Mycorrhizal symbiosis is a mutually beneficial association between plants and fungi, with the fungi providing nutrients to the plants in exchange for carbon compounds. Nonetheless, there is disparity in the reaction of distinct plant species to AMF colonization. Some exhibit a high level of responsiveness, whereas others display a lower degree of it. This variability in responsiveness can shape competitive relationships among plants. The study by [18] discovered that if both the target and neighboring plant species were highly receptive to AMF colonization, it led to an augmentation in plant species diversity within the community. This is due to the fact that AMF can enhance nutrient absorption for both target and adjacent plants, thereby decreasing resource competition. Additionally, the study found that if only the target plant species exhibited a robust reaction to AMF colonization while neighboring plants did not, it caused a decline in the overall plant diversity within the community. In this context, the target plant gained benefits from increased nutrient uptake facilitated by AMF, giving it a competitive edge over neighboring plants [18]. These findings emphasize the role of mycorrhizal responsiveness in shaping competitive outcomes and impacting plant species diversity and community composition. It underscores the importance of comprehending these intricate interactions for successful ecosystem management and conservation endeavors. However, to obtain a comprehensive understanding of these relationships, it is imperative to conduct further research that investigates how environmental factors influence mycorrhizal responsiveness across various ecosystems.

In the study conducted by Zhang et al., it was found that aerobic AMF in a wetland ecosystem have a vital impact on promoting plant diversity. The research discovered that these fungi facilitate favorable interactions among neighbors and exert a positive influence on plant interactions. One of the key findings of the study was that P. Australis, a common wetland plant, increases oxygen concentration in the soil [34] [Table 1]. This rise in oxygen levels establishes an optimal environment for AMF colonization. Thus, more plants are able to develop symbiotic relationships with these fungi, leading to heightened nutrient absorption and improved overall fitness. The positive neighbor interactions, which are facilitated by AMF, also play a substantial role in promoting increased plant diversity. By means of their elaborate underground networks, AMF establish links between neighboring plants and facilitate the transfer of nutrients [34]. This mutually beneficial relationship enables less competitive plants to capitalize on the resources acquired by more dominant ones, fostering coexistence and bolstering overall ecosystem productivity. Moreover, AMF have been shown to have a beneficial effect on plant interactions by inhibiting pathogenic organisms and boosting disease resistance. By colonizing plant roots and creating defensive barriers against harmful pathogens, these fungi actively support the survival and proliferation of different plant species in the wetland ecosystem. In conclusion, [34]'s study underscores the crucial role of aerobic AMF in facilitating favorable neighbor interactions and shaping plant dynamics in wetland ecosystems. Their capacity to improve nutrient absorption, foster species coexistence, and offer defense against pathogens greatly enhances plant diversity and overall ecosystem health.

2.3. Mycorrhizal Networks and Species Interactions

The study by Guo et al. reveals that plants respond differently to AMF depending on their unique relationship with AMF. It examined two plant types, P. annua and C. microphylla, and their AMF communities. P. annua's native AMF was beneficial to desert flora and showed potential for revitalization, with a significant biomass increase. C. microphylla's AMF community had a reduced growth rate, but when combined with P. annua, it showed a 292.4% increase [35] [Table 1]. These findings suggest that there is a unique interaction between plants and their associated AMF communities that affects their growth response in different manners. It underscores the significance of considering plant-AMF specificity when implementing restoration strategies in arid environments [35]. The substantial increase in biomass observed in P. annua with its native AMF community highlights its potential as a crucial species for restoring vegetation in dry regions affected by desertification. Overall, this investigation provides valuable insights into understanding how different plant-AMF interactions can influence plant growth and offers promising avenues for future research on techniques for restoring desert vegetation using specific plant-AMF pairings, such as P. annua and its native AMFs.

According to a study by Hernando et al., the intricate framework of plant-AMF interactions has a significant influence on both the functional and structural aspects of plant-plant interactions. The AMF networks play a crucial role in enabling nutrient absorption and influencing recruitment dynamics in these communities [36] [Table 1]. By incorporating multiple layers of interaction networks, the study provides a nuanced understanding of the impacts of AMF on plant recruitment. The management and restoration of Mediterranean forests are profoundly impacted by [36]'s findings. Achieving a thorough understanding of the intricate correlation between plants and AMF can serve as a vital factor in recognizing essential species for conservation or restoration endeavors. Additionally, this research emphasizes the need to incorporate subterranean interactions when analyzing aboveground ecological processes. To summarize, [36]'s study uncovers information about the role of AMF networks in plant-plant recruitment interactions in Mediterranean forest communities. By integrating these networks within a multilayer architecture and introducing the INNI metric, this research uncovers the functional and structural dimensions of plant-plant interactions influenced by AM.

2.4. AMF and Plant reprograming

The findings of a study by Amani Machiani et al. demonstrate the association's ability to reconfigure plant metabolic pathways, leading to shifts in the levels of primary and secondary metabolites in medicinal and aromatic plants [37] [Table 1]. The research revolved around investigating the effects of AMF on a range of plant species. The results showed that this symbiotic association greatly affected the metabolic pathways of plants [37]. It was observed that AMF could improve nutrient uptake, specifically phosphorus, which is critical for plant growth and development. Additionally, this study showcased the ability of AMF to regulate the levels of primary and secondary metabolites in medicinal and aromatic plants. Basic cellular functions rely on primary metabolites, whereas defense mechanisms against pathogens and herbivores are facilitated by secondary metabolites. By manipulating these concentrations, AMF has the capacity to amplify the therapeutic attributes of medicinal plants or refine the scent of aromatic plants. The research by [37] offers invaluable insights into the impact of plant-microbe interactions on plant metabolism. Acquiring a deep understanding of these mechanisms unlocks fresh possibilities for increasing crop production, enhancing medicinal properties, and optimizing flavors in agricultural techniques. However, additional research should prioritize the clarification of precise molecular mechanisms that underlie these changes in order to fully capitalize on their potential benefits.

In the study conducted by Kaur et al., it was discovered that AMF play a pivotal role in augmenting abiotic stress tolerance in host plants. The researchers observed an increase in the abundance of multiple primary metabolites, vital for plant growth and development in stressful conditions, as a result of AMF [38]. Surprisingly, the study also revealed that AMF initially represses the defense response of the host plant. This may initially appear counterintuitive, as one would anticipate plants to engage their defense mechanisms when confronted with stress. However, subsequent analysis unveiled that this initial suppression is actually advantageous for the host plant. By inhibiting the defense response, AMF prepares the host plant to better withstand both biotic and abiotic stresses [38] [Table 1]. This is achieved through the reprogramming of secondary metabolite biosynthesis, which plays a role in numerous physiological functions including pathogen defense and response to environmental challenges. This finding unveils a previously unexplored mechanism through which AMF enhances plants' ability to tolerate stress [38]. It suggests that instead of solely depending on immediate defense responses, plants can gain advantages from a priming effect caused by AMF. This priming enables them to enhance their resilience to future stresses by modifying their metabolic pathways and boosting the production of secondary metabolites. Overall, this study emphasizes the significance of comprehending the complex interplay between plants and beneficial microorganisms such as AMF. In-depth research in this realm may pave the way for innovative techniques to improve crop productivity and resilience amidst climate change.

The study conducted by Zou et al. in response to drought stress provides valuable insights into the intricate mechanisms involved in plant-fungal interactions. Drought stress is a major concern for agricultural productivity worldwide. Understanding how plants respond to this stress can help develop strategies for crop improvement. [39]'s study highlights the role of AMF in mitigating drought-induced damage by modulating various metabolic pathways. The up-regulation of Juglone and 2,3,5-trihydroxy-5–7-dimethoxyflavanone suggests their involvement in enhancing plant tolerance to drought stress [Table 1]. These compounds have previously been documented to possess antioxidant properties that safeguard plants from oxidative damage induced by environmental stressors [39]. Additionally, the triggering of oxidative phosphorylation signifies an upsurge in energy synthesis within plant cells amidst drought conditions. This adaptation allows plants to maintain essential cellular processes despite limited water availability. In addition, the induction of phenylalanine metabolism and biosynthesis suggests a potential role in osmotic adjustment and synthesis of secondary metabolites involved in stress responses [39]. Phenylalanine-derived compounds such as lignin and flavonoids are known to contribute to cell wall reinforcement and antioxidant defense systems. Overall, [39]'s study sheds light on the complex molecular mechanisms underlying AMF-mediated plant responses to drought stress. Further research is needed to fully elucidate these processes and exploit them for sustainable agriculture practices.

3. Potential for Future Research

3.1. Investigating the mechanisms underlying AMF-mediated interactions

The field of arbuscular mycorrhizal fungi (AMF) and their ecological role in natural ecosystems has experienced notable advancements in recent years. Nevertheless, despite these advancements, numerous unanswered questions persist, compelling the need for additional research to delve further into the intricacies of AMF-mediated interactions. One domain that calls for deeper investigation is the particular mechanisms through which AMF amplify nutrient uptake in plants. Despite the well-established knowledge on AMF's ability to enhance phosphorus uptake through their extensive hyphal network, the precise molecular mechanisms remain incompletely comprehended [40]. Understanding these mechanisms could have important implications for sustainable agriculture and ecosystem management. The impact of AMF on plant community dynamics and species interactions also remains an unanswered. It is widely recognized that AMF can have an impact on plant competition and promote the coexistence of various species [41]. In spite of that, the particular mechanisms through which this takes place are not adequately specified. Future research should strive to clarify these mechanisms in order to enhance comprehension of how AMF influence plant communities.

3.2. Exploring the effects of AMF on ecosystem response to global environmental changes

AMF play a crucial role in nutrient cycling and plant growth by forming mutualistic associations with the roots of most terrestrial plants. They enhance nutrient uptake and improve plant tolerance to various stresses, including drought and nutrient deficiency [42]. Consequently, AMF contribute to ecosystem stability and resilience [43].

Table 1 Summary of results from previous studies on the role of AMF in natural ecosystems

Ecological Role of AMF in Natural Ecosystems	Findings from Previous Studies	Reference
Nutrient Cycling	AMF resulted in lower N2O fluxes and reduced NH4+ leaching	[30]
	AMF and PGPR increase the overall nitrogen content in the soil	[31]
	Introduction of earthworms and AMF to contaminated soil enhance plant growth	[32]
AMF-Mediated Plant Competition	AMF improves the growth and nutrient absorption of host plants	[33]
	AMF displays diminished convergence in ecological habitats with their competitors	[20]
	AMF shapes competitive outcomes and impacts plant species diversity	[18]
	AMF exert a positive influence on plant interactions	[34]
Mycorrhizal Networks and Species Interactions	Plant-AMF interactions influence plant growth	[35]
	plant-AMF interactions influence both the functional and structural aspects of plant-plant interactions	[36]
AMF and Plant reprograming	AMF symbiotic association greatly affected the metabolic pathways of plants	[37]
	AMF represses the defense and stress response of the host plant	[38]
	AMF up-regulates Juglone and 2,3,5-trihydroxy-5–7-dimethoxyflavanone in response to drought stress	[39]

With global environmental changes such as climate change and land-use alterations becoming increasingly prevalent, it is imperative to investigate how AMF will respond and influence ecosystem dynamics under these conditions. For instance, how will increased temperatures affect the symbiotic relationship between AMF and plants? Will altered precipitation patterns impact their ability to enhance drought tolerance? Understanding the effects of AMF on ecosystem response to global environmental changes is vital for predicting future ecological dynamics accurately. It can inform conservation strategies, guide land management practices, and aid in mitigating the negative impacts of environmental disturbances.

3.3 Investigating the potential applications of AMF in ecosystem restoration and conservation

Arbuscular mycorrhizal fungi (AMF) play a pivotal role in nutrient cycling and plant growth through mutualistic symbiosis with the roots of nearly all land plants [44,45]. Gaining an understanding of the interaction between AMF and various plant species and environmental conditions is crucial for successful ecosystem management. One area that requires further investigation is the potential use of AMF in ecosystem restoration. The introduction of AMF to degraded areas has the potential to improve soil fertility and expedite the recovery process [46,47]. Thus, conducting research on the potential of AMF to enhance the establishment and survival rates of indigenous plant species could contribute to the restoration of biodiversity in degraded ecosystems. Furthermore, it is crucial to examine the potential of AMF in conservation efforts. Several endangered plant species rely on distinct mycorrhizal associations for their survival. Exploring methods to manipulate these associations in order to facilitate the growth and reproduction of endangered plants could offer significant benefits to conservationists.

4. Conclusion

Ultimately, the investigation of the ecological function of arbuscular mycorrhizal fungi AMF is essential for comprehending and preserving natural ecosystems. One pivotal aspect of AMF's ecological role lies in their contribution to soil health. Through the formation of intricate networks of hyphae, AMF enhance soil structure and augment its capacity to retain water. This not only provides benefits to plant life but also sustains a diverse array of organisms within the ecosystem. Furthermore, AMF have been noted to augment plant resistance against diseases and herbivores through multiple strategies, including the secretion of antimicrobial agents. A comprehensive understanding of the ecological role of AMF is vital for the preservation of natural ecosystems. Human activities such as deforestation and land degradation can disturb these fungal associations, resulting in adverse effects on plant communities and overall ecosystem functionality. By examining the impact of AMF on nutrient cycling, biodiversity maintenance, and ecosystem stability, it is viable to establish successful conservation strategies for long-term sustainability.

References

[1] Huang, R.; Li, Z.; Shen, X.; Choi, J.; Cao, Y. The Perspective of Arbuscular Mycorrhizal Symbiosis in Rice Domestication and Breeding. International Journal of Molecular Sciences 2022, 23 (20), 12383. https://doi.org/10.3390/ijms232012383.

[2] Pei, Y.; Siemann, E.; Tian, B.; Ding, J. Root Flavonoids Are Related to Enhanced AMF Colonization of an Invasive Tree. Aob Plants 2020, 12 (1). https://doi.org/10.1093/aobpla/plaa002.

[3] Shen, K.; He, Y.; Xu, X.; Umer, M.; Liu, X.; Xia, T.; Guo, Y.; Wu, B.; Xu, H.; Zang, L.; Gao, L.; Jiao, M.; Yang, X.; Yan, J. Effects of AMF on Plant Nutrition and Growth Depend on Substrate Gravel Content and Patchiness in the Karst Species Bidens Pilosa L. Frontiers in Plant Science 2022, 13. https://doi.org/10.3389/fpls.2022.968719.

[4] Ioanna Kakabouki; Stavropoulos, P.; Ioannis Roussis; Antonios Mavroeidis; Dimitrios Bilalis. Contribution of Arbuscular Mycorrhizal Fungi (AMF) in Improving the Growth and Yield Performances of Flax (Linum Usitatissimum L.) to Salinity Stress. Agronomy 2023, 13 (9), 2416–2416. https://doi.org/10.3390/agronomy13092416.

[5] Bahadur, A.; Jin, Z.; Long, X.; Jiang, S.; Zhang, Q.; Pan, J.; Liu, Y.; Feng, H. Arbuscular Mycorrhizal Fungi Alter Plant Interspecific Interaction under Nitrogen Fertilization. European Journal of Soil Biology 2019, 93, 103094–103094. https://doi.org/10.1016/j.ejsobi.2019.103094.

[6] Li, Y.; Xu, J.; Hu, J.; Zhang, T.; Wu, X.; Yang, Y. Arbuscular Mycorrhizal Fungi and Glomalin Play a Crucial Role in Soil Aggregate Stability in Pb-Contaminated Soil. International Journal of Environmental Research and Public Health 2022, 19 (9), 5029. https://doi.org/10.3390/ijerph19095029.

[7] Yang, Y.; He, C.; Huang, L.; Ban, Y.; Tang, M. The Effects of Arbuscular Mycorrhizal Fungi on Glomalin-Related Soil Protein Distribution, Aggregate Stability and Their Relationships with Soil Properties at Different Soil Depths in Lead-Zinc Contaminated Area. PLOS ONE 2017, 12 (8), e0182264. https://doi.org/10.1371/journal.pone.0182264.

[8] Qiang, W.; Gunina, A.; Kuzyakov, Y.; He, L.; Zhang, Y.; Liu, B.; Pang, X. Contributions of Mycorrhizal Fungi to Soil Aggregate Formation during Subalpine Forest Succession. CATENA 2023, 221, 106800. https://doi.org/10.1016/j.catena.2022.106800.

[9] Casazza, G.; Lumini, E.; Ercole, E.; Dovana, F.; Guerrina, M.; Arnulfo, A.; Minuto, L.; Fusconi, A.; Mucciarelli, M. The Abundance and Diversity of Arbuscular Mycorrhizal Fungi Are Linked to the Soil Chemistry of Screes and to Slope in the Alpic Paleo-Endemic Berardia Subacaulis. PLOS ONE 2017, 12 (2), e0171866. https://doi.org/10.1371/journal.pone.0171866.

[10] Yang, G.; Liu, N.; Lu, W.; Wang, S.; Kan, H.; Zhang, Y.-J.; Xu, L.; Chen, Y. The Interaction between Arbuscular Mycorrhizal Fungi and Soil Phosphorus Availability Influences Plant Community Productivity and Ecosystem Stability. Journal of Ecology 2014, 102 (4), 1072–1082. https://doi.org/10.1111/1365-2745.12249.

[11] Asmelash, F.; Bekele, T.; Birhane, E. The Potential Role of Arbuscular Mycorrhizal Fungi in the Restoration of Degraded Lands. Frontiers in Microbiology 2016, 7. https://doi.org/10.3389/fmicb.2016.01095.

[12] Wang, B.; Xiao, Q.; Geng, X. P.; Lin, K.; Li, Z.; Li, Y.; Chen, J.; Li, X. Arbuscular Mycorrhizal Fungi Alter Rhizosphere Bacterial Diversity, Network Stability and Function of Lettuce in Barren Soil. Scientia Horticulturae 2024, 323, 112533–112533. https://doi.org/10.1016/j.scienta.2023.112533.

[13] Saia, S.; Jansa, J. Editorial: Arbuscular Mycorrhizal Fungi: The Bridge between Plants, Soils, and Humans. Frontiers in Plant Science 2022, 13. https://doi.org/10.3389/fpls.2022.875958.

[14] Luginbuehl, L. H.; Oldroyd, G. E. D. Understanding the Arbuscule at the Heart of Endomycorrhizal Symbioses in Plants. Current Biology 2017, 27 (17), R952–R963. https://doi.org/10.1016/j.cub.2017.06.042.

[15] Huey, C. J.; Gopinath, S. C. B.; Uda, M. N. A.; Zulhaimi, H. I.; Jaafar, M. N.; Kasim, F. H.; Yaakub, A. R. W. Mycorrhiza: A Natural Resource Assists Plant Growth under Varied Soil Conditions. 3 Biotech 2020, 10 (5). https://doi.org/10.1007/s13205-020-02188-3.

[16] Etesami, H.; Jeong, B. R.; Glick, B. R. Contribution of Arbuscular Mycorrhizal Fungi, Phosphate–Solubilizing Bacteria, and Silicon to P Uptake by Plant. Frontiers in Plant Science 2021, 12. https://doi.org/10.3389/fpls.2021.699618.

[17] Xiao, Y.; Chen, L. Arbuscular Mycorrhizal Fungi Reduce Potassium, Cadmium and Ammonium Losses but Increases Nitrate Loss under High Intensity Leaching Events. BMC Plant Biology 2022, 22 (1). https://doi.org/10.1186/s12870-022-03741-3.

[18] Lin, G.; McCormack, M. L.; Guo, D. Arbuscular Mycorrhizal Fungal Effects on Plant Competition and Community Structure. Journal of Ecology 2015, 103 (5), 1224–1232. https://doi.org/10.1111/1365-2745.12429.

[19] Roger, A.; Colard, A.; Angelard, C.; Sanders, I. R. Relatedness among Arbuscular Mycorrhizal Fungi Drives Plant Growth and Intraspecific Fungal Coexistence. The ISME Journal 2013, 7 (11), 2137–2146. https://doi.org/10.1038/ismej.2013.112.

[20] Wagg, C.; McKenzie-Gopsill, A. Mycorrhizal Fungi Reduce Fitness Differences, but Coexistence Is Determined by Differences in Intrinsic Plant Mycorrhizal Responsiveness. Journal of Plant Ecology 2022. https://doi.org/10.1093/jpe/rtac081.

[21] Gorzelak, M. A.; Asay, A. K.; Pickles, B. J.; Simard, S. W. Inter-Plant Communication through Mycorrhizal Networks Mediates Complex Adaptive Behaviour in Plant Communities. AoB Plants 2015, 7, plv050. https://doi.org/10.1093/aobpla/plv050.

[22] Montesinos-Navarro, A.; Díaz, G.; Torres, P.; Caravaca, F.; Roldán, A. Phylogenetic Rewiring in Mycorrhizal–Plant Interaction Networks Increases Community Stability in Naturally Fragmented Landscapes. Communications Biology 2019, 2 (1). https://doi.org/10.1038/s42003-019-0700-3.

[23] Perez-Lamarque, B.; Petrolli, R.; Strullu-Derrien, C.; Strasberg, D.; Morlon, H.; Selosse, M.-A.; Martos, F. Structure and Specialization of Mycorrhizal Networks in Phylogenetically Diverse Tropical Communities. Environmental Microbiome 2022, 17 (1). https://doi.org/10.1186/s40793-022-00434-0.

[24] Castro-Delgado, A. L.; Elizondo-Mesén, S.; Valladares-Cruz, Y.; Rivera-Méndez, W. Internet de Las Plantas: Comunicación a Través de La Red Micorrízica. Revista Tecnología en Marcha 2020. https://doi.org/10.18845/tm.v33i4.4601.

[25] Zhang, X.; Yan, J.; Khashi u Rahman, M.; Wu, F. The Impact of Root Exudates, Volatile Organic Compounds, and Common Mycorrhizal Networks on Root System Architecture in Root-Root Interactions. Journal of Plant Interactions 2022, 17 (1), 685–694. https://doi.org/10.1080/17429145.2022.2086307.

[26] Recchia, G. H.; Konzen, E. R.; Cassieri, F.; Caldas, D. G. G.; Tsai, S. M. Arbuscular Mycorrhizal Symbiosis Leads to Differential Regulation of Drought-Responsive Genes in Tissue-Specific Root Cells of Common Bean. Frontiers in Microbiology 2018, 9. https://doi.org/10.3389/fmicb.2018.01339.

[27] Mateus, I. D.; Masclaux, F. G.; Aletti, C.; Rojas, E. C.; Savary, R.; Dupuis, C.; Sanders, I. R. Dual RNA-Seq Reveals Large-Scale Non-Conserved Genotype × Genotype-Specific Genetic Reprograming and Molecular Crosstalk in the Mycorrhizal Symbiosis. The ISME Journal 2019, 13 (5), 1226–1238. https://doi.org/10.1038/s41396-018-0342-3.

[28] Ramírez-Flores, M. R.; Perez-Limon, S.; Li, M.; Barrales-Gamez, B.; Albinsky, D.; Paszkowski, U.; Olalde-Portugal, V.; Sawers, R. J. The Genetic Architecture of Host Response Reveals the Importance of Arbuscular Mycorrhizae to Maize Cultivation. eLife 2020, 9. https://doi.org/10.7554/elife.61701.

[29] Salvioli di Fossalunga, A.; Novero, M. To Trade in the Field: The Molecular Determinants of Arbuscular Mycorrhiza Nutrient Exchange. Chemical and Biological Technologies in Agriculture 2019, 6 (1). https://doi.org/10.1186/s40538-019-0150-7.

[30] Bender, S. F.; Conen, F.; Van der Heijden, M. G. A. Mycorrhizal Effects on Nutrient Cycling, Nutrient Leaching and N2O Production in Experimental Grassland. Soil Biology and Biochemistry 2015, 80, 283–292. https://doi.org/10.1016/j.soilbio.2014.10.016.

[31] Yu, L.; Zhang, H.; Zhang, W.; Liu, K.; Liu, M.; Shao, X. Cooperation between Arbuscular Mycorrhizal Fungi and Plant Growth-Promoting Bacteria and Their Effects on Plant Growth and Soil Quality. PeerJ 2022, 10, e13080–e13080. https://doi.org/10.7717/peerj.13080.

[32] Meng, L.; K. Srivastava, A.; Kuča, K.; Giri, B.; Mahabubur Rahman, M.; Wu, Q. Interaction between Earthworms and Arbuscular Mycorrhizal Fungi in Plants: A Review. Phyton 2021, 90 (3), 687–699. https://doi.org/10.32604/phyton.2021.015427.

[33] Bahadur, A.; Jiang, S.; Zhang, W.; Sajjad, W.; Usman, M.; Nasir, F.; Muhammad Amir Zia; Zhang, Q.; Pan, J.; Liu, Y.; Chen, T.; Feng, H. Competitive Interactions in Two Different Plant Species: Do Grassland Mycorrhizal Communities and Nitrogen Addition Play the Same Game? Frontiers in Plant Science 2023, 14. https://doi.org/10.3389/fpls.2023.1084218.

[34] Zhang, Q.; Sun, Q.; Koide, R. T.; Peng, Z.; Zhou, J.; Gu, X.; Gao, W.; Yu, M. Arbuscular Mycorrhizal Fungal Mediation of Plant-Plant Interactions in a Marshland Plant Community. The Scientific World Journal 2014, 2014, 1–10. https://doi.org/10.1155/2014/923610.

[35] Guo, X.; Wang, P.; Wang, X.; Li, Y.; Ji, B. Specific Plant Mycorrhizal Responses Are Linked to Mycorrhizal Fungal Species Interactions. Frontiers in Plant Science 2022, 13. https://doi.org/10.3389/fpls.2022.930069.

[36] Hernando, L.; Alcántara, J. M.; Álvaro López-García; Ozuna, C. V.; Perea, A. J.; Prieto-Rubio, J.; Ana María Rincón; Concepción Azcón-Aguilar. The Structure and Ecological Function of the Interactions between Plants and Arbuscular Mycorrhizal Fungi through Multilayer Networks. Functional Ecology 2023, 37 (8), 2217–2230. https://doi.org/10.1111/1365-2435.14378.

[37] Amani Machiani, M.; Javanmard, A.; Habibi Machiani, R.; Sadeghpour, A. Arbuscular Mycorrhizal Fungi and Changes in Primary and Secondary Metabolites. Plants 2022, 11 (17), 2183. https://doi.org/10.3390/plants11172183.

[38] Kaur, S.; Suseela, V. Unraveling Arbuscular Mycorrhiza-Induced Changes in Plant Primary and Secondary Metabolome. Metabolites 2020, 10 (8), 335. https://doi.org/10.3390/metabo10080335.

[39] Zou, Y.-N.; Qin, Q.-Y.; Ma, W.-Y.; Zhou, L.; Wu, Q.-S.; Xu, Y.; Kamil Kuča; Hashem, A.; Al-Bandari Fahad Al-Arjani; Almutairi, K. F.; Elsayed Fathi Abd_Allah. Metabolomics Reveals Arbuscular Mycorrhizal Fungi-Mediated Tolerance of Walnut to Soil Drought. BMC Plant Biology 2023, 23 (1). https://doi.org/10.1186/s12870-023-04111-3.

[40] Chiu, C. H.; Paszkowski, U. Mechanisms and Impact of Symbiotic Phosphate Acquisition. Cold Spring Harbor Perspectives in Biology 2019, 11 (6), a034603. https://doi.org/10.1101/cshperspect.a034603.

[41] Wang, X.-Q.; Wang, Y.-H.; Song, Y.-B.; Dong, M. Formation and Functions of Arbuscular Mycorrhizae in Coastal Wetland Ecosystems: A Review. Ecosystem Health and Sustainability 2022, 8 (1). https://doi.org/10.1080/20964129.2022.2144465.

[42] Oluwaseun Adeyinka Fasusi; Olubukola Oluranti Babalola; Adejumo, T. O. Harnessing of Plant Growth-Promoting Rhizobacteria and Arbuscular Mycorrhizal Fungi in Agroecosystem Sustainability. CABI Agriculture and Bioscience 2023, 4 (1). https://doi.org/10.1186/s43170-023-00168-0.

[43] Jia, Y.; Heijden, M. G. A.; Wagg, C.; Feng, G.; Walder, F. Symbiotic Soil Fungi Enhance Resistance and Resilience of an Experimental Grassland to Drought and Nitrogen Deposition. Journal of Ecology 2020, 109 (9), 3171–3181. https://doi.org/10.1111/1365-2745.13521.

[44] Lanfranco, L.; Fiorilli, V.; Gutjahr, C. Partner Communication and Role of Nutrients in the Arbuscular Mycorrhizal Symbiosis. New Phytologist 2018, 220 (4), 1031–1046. https://doi.org/10.1111/nph.15230.

[45] Xu, X.; Chen, C.; Zhang, Z.; Sun, Z.; Chen, Y.; Jiang, J.; Shen, Z. The Influence of Environmental Factors on Communities of Arbuscular Mycorrhizal Fungi Associated with Chenopodium Ambrosioides Revealed by MiSeq Sequencing Investigation. Scientific Reports 2017, 7 (1). https://doi.org/10.1038/srep45134.

[46] Kalamulla, R.; Karunarathna, S. C.; Tibpromma, S.; Galappaththi, M. C. A.; Suwannarach, N.; Stephenson, S. L.; Asad, S.; Salem, Z. S.; Yapa, N. Arbuscular Mycorrhizal Fungi in Sustainable Agriculture. Sustainability 2022, 14 (19), 12250. https://doi.org/10.3390/su141912250.

[47] Matos, P. S.; Silva, C. F. da; Damian, J. M.; Cerri, C. E. P.; Pereira, M. G.; Zonta, E. Beneficial Services of Glomalin and Arbuscular Mycorrhizal Fungi in Degraded Soils in Brazil. Scientia Agricola 2022, 79 (5). https://doi.org/10.1590/1678-992x-2021-0064.