International Journal of Science and Research Archive
eISSN: 2582-8185
Cross Ref DOI: 10.30574/ijsra
Journal homepage: https://ijsra.net/

(REVIEW ARTICLE)

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Investigating the effect of environmental factors on Arbuscular Mycorrhizal Fungi (AMF) Colonization

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International Journal of Science and Research Archive, 2023, 10(02), 568–577

Publication history: Received on 25 October 2023; revised on 01 December 2023; accepted on 03 December 2023

Article DOI: https://doi.org/10.30574/ijsra.2023.10.2.1014

Abstract

Arbuscular mycorrhizal fungi (AMF) plays a crucial role in plant growth by establishing mutually beneficial partnerships with the roots of most terrestrial plants. This symbiotic partnership yields many benefits to the fungi and the plants, including enhanced nutrient uptake, augmented defense against harmful organisms, and heightened resilience to various environmental challenges. Gaining insight into the factors influencing AMF colonization is critical for implementing advanced land management strategies and fostering sustainable agriculture. Moreover, acknowledging the significance of environmental components like light, temperature, pH, and organic matter in AMF colonization is crucial in promoting sustainable land management strategies. Past research on the influence of these factors on AMF colonization provides valuable insights for maximizing the potential of these beneficial microbes. However, some gaps necessitate further studies to comprehend AMF's effectiveness fully. Investigating the interrelationships between multiple ecological variables, exploring the impact of pollutants and heavy metals, studying the function of root exudations and the plant's response to environmental stress, and examining the potential for AMF-supported phytoremediation are all significant research areas in this domain. By acquiring a deeper understanding of these aspects, it becomes feasible to devise strategies to enhance the establishment and effectiveness of AMF, thereby fostering sustainable farming and land management practices.

Keywords: Arbuscular Mycorrhizal Fungus; AMF colonization; Environmental factors; land management

1. Introduction

Arbuscular mycorrhizal fungi (AMF) are vital microbes crucial in initiating a mutually beneficial association with 80% of terrestrial plants. They dwell within the plant roots, creating intricate filamentous networks that extend the soil surface area, thereby increasing nutrient absorption [1]. By forming a symbiotic association, plants and AMF fungi exchange nutrients and carbohydrates, with the fungi receiving sugars from their hosts and the plants acquiring essential nutrients, such as phosphorus [2]. Furthermore, AMF facilitates plant health by promoting the plant's defense mechanisms against diseases and environmental stressors, improving drought tolerance and water absorption efficiency. The presence of AMF in soil is intricately connected to diverse ecological aspects. The structure of the soil is a significant determinant that affects the colonization of AMF [3,4]. Different soil types possess different nutrient proportions and physical characteristics that can either aid or impede the growth of fungi. For instance, soils with a sandy texture and deficient organic matter might restrain AMF colonization due to their inability to hold water effectively and lack nutrient accessibility [5]. Conversely, clay soils containing substantial organic matter create a favorable setting for AMF by retaining moisture and nutrients efficiently.

Besides soil, pH levels also play a significant role in AMF colonization. Most AMF species prefer slightly acidic to neutral pH conditions for optimal growth and establishment [6]. Acidic or alkaline soils can inhibit or alter the activity of these

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fungi, leading to reduced colonization rates. Temperature is another critical factor influencing AMF colonization [7,8]. Different AMF species have specific temperature requirements for their survival and growth. Generally, moderate temperatures between 20-25°C are ideal for most AMF species' development and function [9]. Moisture availability is essential for both plant root growth and fungal hyphae extension in the soil [10,11]. Adequate moisture promotes root development and facilitates hyphal exploration of the surrounding soil matrix by providing a continuous water supply required for nutrient absorption. Light availability also affects AMF colonization indirectly through its influence on plant photosynthesis. In addition to moisture, plants need light energy for photosynthesis, which provides carbohydrates for root exudation, an important food source for AMF [12,13]. Despite recognizing the importance of these environmental factors in shaping AMF colonization patterns, understanding the specific mechanisms behind these interactions remains challenging. Further research is needed to unravel the complex interplay between soil composition, pH levels, temperature, moisture, light availability, and their effects on AMF colonization dynamics.

1.1. Search strategy

The research employed English journals ranging from 2007 to 2023. The search involved segmenting the research topic into different search terms, specifically "Arbuscular Mycorrhizal Fungi colonization" and "Effect of Environmental Factors." The sufficiency of a study hinged solely on its incorporation of any of the indicated keywords. Upon concluding the search, a total of 51 journal articles were discovered, with the exclusion of 3 duplicates, resulting in a final count of 48 individual articles. The abstracts of all these journals underwent examination, and pertinent papers were bookmarked for subsequent evaluation. The study relied on a 16-year threshold as the primary determinant for inclusion and exclusion. Upon fulfilling this requirement, a comprehensive analysis of 46 journal articles was conducted to determine their applicability to the research topic. At this stage, 2 of these journals were dismissed as the study solely prioritized peer-reviewed articles. A comprehensive examination of 44 peer-reviewed journals was conducted to ascertain their suitability for inclusion in this analysis. Four of these journals were deemed insignificant as they failed to contribute to identifying keywords. Hence, the research strategy resulted in 40 publications that were cited and referenced in this review (Figure 1).

2. Effect of environmental factors on AMF colonization: Findings from previous studies

2.1. Effect of organic matter on AMF colonization

In the research conducted by Maji et al., it was uncovered that humic acid-rich worms-made compost, also identified as HARV, had a remarkable positive influence on plant and soil vitality compared to chemical fertilizers (CF) [14]. This study illuminates the advantages of utilizing natural fertilizers over their synthetic counterparts. One of the significant discoveries of this research was that HARV increased the soil-based microbial variety. This is crucial for sustaining a healthy ecosystem, as diverse microbial communities are pivotal in nutrient cycling and disease control. In contrast, CF negatively affects microbial diversity because of its high salt content and lack of organic material. In addition, [14] established that organic fertilizers enhanced the formation of root nodules and the colonization of arbuscular mycorrhizal fungi (AMF). Root nodules are crucial for nitrogen fixation in leguminous plants, while AMF establishes symbiotic relationships with plant roots, enhancing the absorption of nutrients. These findings indicate that HARV can potentially improve plant nutrition and growth. Overall, Maji et al.'s study emphasizes the benefits of HARV compared to CF in enhancing the well-being of plants and soil health. By increasing the variety of microorganisms and promoting beneficial interactions between plants and soil organisms, organic fertilizers like HARV can offer a more sustainable approach to agriculture. However, further research should examine the long-term consequences of deploying such organic transformations on crop productivity and environmental sustainability.

Zeng et al. conducted a separate study that unearthed that biochar, a type of organic matter derived from charcoal, independently enhanced water resilience in soil clusters. Notably, it was revealed that when combined with symbiotic partnerships between plant roots and arbuscular mycorrhizal fungi, it enhances plant growth, improves soil structure, increases soil compactness, and intensifies microbial functions [15]. The results obtained from this investigation bear noteworthy consequences for advancing sustainable farming practices and safeguarding the environment. The deterioration of soil is a significant international problem that causes a decline in agricultural productivity and a greater risk of erosion. The utilization of organic charcoal can aid in preventing soil erosion and enhancing nutrient retention by fostering water stability in soil clusters. Of utmost significance is the combination of charcoal made from organic matter and AMF, which has exhibited promising outcomes in augmenting the colonization of these fungi and consequently promoting the growth of plants [15]. AMF establish mutualistic associations with plant roots, facilitating nutrient absorption and enhancing plants' overall well-being (Table 1). When partnered with biochar, these beneficial fungi can further optimize nutrient accessibility for plants. Moreover, this combination's enhancement of soil pore structures fosters improved drainage and aeration within the soil profile. This plays a pivotal role in the growth of roots and creates favorable conditions for microbial activities. Equally, enhanced microbial activities contribute to the efficient cycling of nutrients and the decomposition of organic matter within the soil. Overall, Zeng et al.'s research highlights the potential advantages of employing biochar and AMF to promote sustainable farming practices. The findings underscore the significance of embracing holistic approaches that integrate diverse ecological factors, thereby enhancing soil health and maximizing crop productivity while minimizing adverse environmental effects.

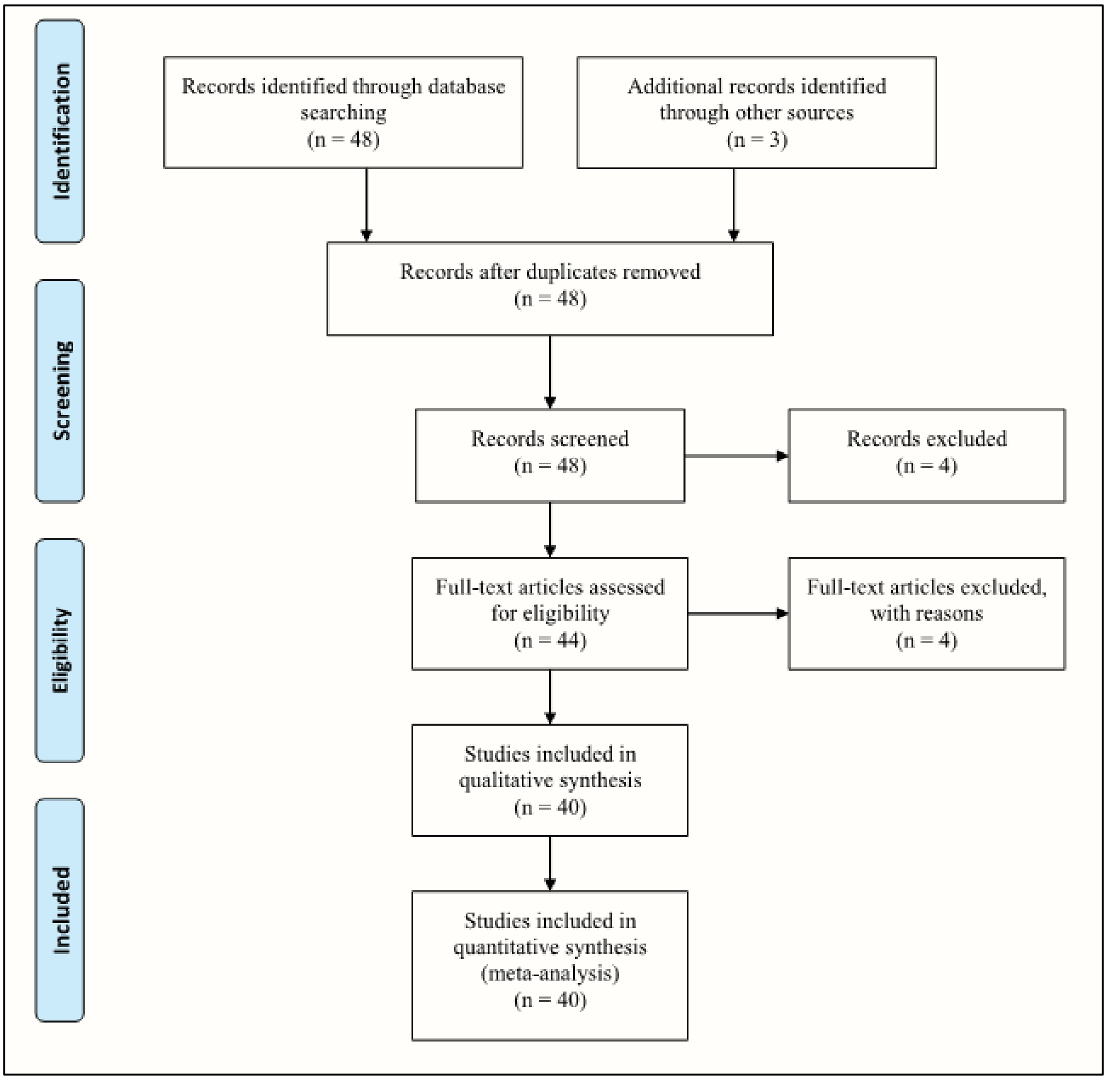

Figure 1 PRISMA diagram showing how papers were selected, excluded and included

In the study conducted by Fallah et al., the researchers aimed to examine the effects of combining mycorrhiza, vermicompost, and green fertilizer on the growth of Lingrain. Their research demonstrated a variety of significant advancements in plant variables. A notable observation was the elevation of leaf moisture content [16]. This indicates that a synergistic treatment augmented the plant's capacity for water retention, which is vital for its overall well-being. Moreover, Lingrain plants subjected to the combined treatment displayed elevated levels of root AMF colonization. This indicates that the mutually beneficial association between mycorrhiza and roots was fortified, resulting in improved nutrient assimilation. Apart from root colonization, Lingrain plants treated with the consortium demonstrated elevated nitrogen levels [16]. Nitrogen is a crucial nutrient for plant growth and development, implying that the combined treatment promoted enhanced nutrient availability for the plants. The study also discovered that Lingrain plants treated with all three elements exhibited enhanced levels of carotenoids. According to [16], the fusion treatment augmented the nutritional worth of these crops. Besides a rise in carotenoids, the merged treatment also led to elevated activity of antioxidant enzymes in the plants. These enzymes are crucial in protecting plants from oxidative stress induced by environmental factors like drought or high temperatures. The most notable result of this exploration was the increase in grain and oil yield. The researchers [16] determined a significant increase in both parameters by combining mycorrhiza, vermicompost, and green fertilizer. This result carries substantial implications for agricultural techniques, proposing a possible means to enhance crop yield. In summary, Fallah et al.'s study shows that integrating mycorrhiza, vermicompost, and green manure can yield advantageous outcomes for Lingrain plants and AMF activity. These findings highlight the potential of employing these integrated remedies to enhance crop yield and increase nutritional value.

2.2. Effect of soil pollutants on AMF colonization

In the research by Kuang et al., the scholars aimed to explore the impacts of diverse cadmium (Cd) levels on the translocation ratio and mycorrhizal efficiency in E. Grandis with AMF colonization. The findings revealed intriguing discoveries that illuminated the interaction between cadmium (Cd), AMF, and plant physiology [17]. The scientists administered varying quantities of Cd to E. Grandis, with a range of sizes from 50 μm to 500 μm. It was observed that with the rise of Cd concentration, the translocation ratio of Cd in E. Grandis steadily declined. Specifically, at a Cd concentration of 50 μm, the translocation ratio exhibited a 56.41% decrease compared to untreated plants in the control group. The decline became more conspicuous as the amount escalated, with reductions of 62.89%, 66.67%, and 42.79% transpiring at concentrations of 150 μm, 300 μm, and 500 μm, respectively [17]. Interestingly, while there was a notable decrease in translocation factor at higher concentrations of Cd, the efficacy of mycorrhizal fungi was only significant at lower Cd concentrations. This implies that the colonization of AMF may significantly improve plant resistance to mild Cd toxicity but may be less effective in cases of higher toxicity levels. Overall, these findings offer valuable insights into the impact of AMF colonization on plant reactions to heavy metal stress, such as Cd contamination. Further study is required to delve into the fundamental processes behind these findings and their ramifications for sustainable agricultural methods and ecological restoration approaches.

2.3. Effect of soil pH on AMF colonization

The research conducted by Ouzounidou et al. aimed to explore the chemical makeup and growth responses of Chia plants to arbuscular mycorrhiza fungal inoculum in various soil pH treatments. The researchers were particularly intrigued by how Chia plants respond to acidic and alkaline soil circumstances. The outcomes of the research uncovered some intriguing discoveries. Firstly, it was observed that Chia plants displayed inhibited growth when cultivated in acidic soil [18]. This indicates that the plants could not flourish and reach their maximum potential in these conditions. However, when grown in alkaline soil, the Chia plants demonstrated increased fresh biomass, suggesting a more advantageous environment for their development. They [18] also analyzed the chemical composition of Chia plants. The finding showed increased concentrations of stearic, oleic, linoleic, and A-linolenic acids in acidic and alkaline soil conditions. This research provides valuable knowledge about the impact of different soil pH treatments on Chia plant development and chemical composition. The results by [18] emphasize the significance of maintaining optimal soil pH levels to cultivate robust crops with desirable qualities. Further investigation could explore additional variables influencing plant growth in different soil conditions, enhancing agricultural methods and augmenting crop yields.

In the research conducted by Audry Tshibangu Kazadi et al., it was discovered that AMF colonization is considerably elevated at pH 5.8 (Table 1). It was observed that at this pH level, the height of plants reached an average of 56-58 cm, and the amount of harvested crops was recorded at an impressive 2095 kg ha-1 [19]. The research also revealed a contrasting outcome when the pH level exceeded 6.2. At higher pH levels, root colonization by AMF was significantly reduced, and the height of plants varied from a mere 27-39 cm. Furthermore, the yield of pods in this situation was between 631 and 1479 kg ha-1. These findings highlight the significance of maintaining optimal soil pH levels to support AMF colonization, thus promoting the growth and productivity of plants. The findings by [19] propose that a marginally acidic soil environment with a pH of approximately 5.8 is advantageous for establishing AMF, resulting in taller plants and enhanced crop production. Understanding the relationship between soil pH and AMF establishment can significantly affect agricultural practices. Farmers can utilize this knowledge to adapt their soil management techniques accordingly, ensuring that crops receive adequate AMF establishment for optimal development and productivity. Overall, Audry Tshibangu Kazadi et al.'s research emphasizes the influence of soil pH on AMF establishment, plant height, and crop production. By maintaining a slightly acidic soil environment with a pH of around 5.8, farmers can encourage AMF establishment and attain superior agricultural outcomes regarding plant growth and yield.

In the study by Zhu et al., the researchers explored the impact of soil acidity on the colonization of AMF, alkaline phosphatase activity, and the stimulatory growth effect. They assessed the outcomes by introducing AMF to white clover under two distinct soil acidity conditions. The results showed that increased acidity negatively affected the colonization and density of native AMF, while non-native AMF were unaffected [20]. Interestingly, it was observed that increased levels of acidity enhanced the development of arbuscules. Notably, various soil properties and microbial processes are heavily impacted by the soil's acidity levels. Understanding the impact of soil acidity on AMF establishment is highly valuable due to its crucial role in nutrient uptake, especially phosphorus, necessary for plant growth. The reduction in establishment and hyphae density in native AMF under high soil pH conditions can be ascribed to the adverse impact of alkaline conditions on their survival and growth [20]. This implies that native AMF are adapted to flourish in acidic environments, making it challenging for them to establish symbiotic relationships with plants in high pH conditions.

Exotic AMF exhibited no notable changes in colonization under elevated pH circumstances. This suggests that such species may have specific adaptations or mechanisms that allow them to withstand alkaline environments better than native species. Remarkably, high pH levels were observed to boost the formation of specialized structures known as arbuscules. These structures are formed within plant roots during the cooperative association between plants and AMF, aiding in the exchange of nutrients between the two partners. According to [20], the increase in arbuscule formation under high pH conditions could be seen as an adaptive response from both plant hosts and AMF to overcome nutrient limitations caused by alkaline soils. This study emphasizes the intricate interplay among soil acidity, plant hosts, and different types of AMF. It provides valuable insights into the mechanisms that govern AMF colonization and their responses to changing soil conditions. However, further investigation is necessary to explore the specific adaptations of exotic AMF to alkaline environments and their potential implications in agriculture and ecosystem management.

2.4. Effect of temperature on AMF colonization

Mário de Carvalho and his study peers conducted a study in 2015 to establish the relationship between soil temperature and the efficacy of AMF colonization in selected farming environments. Before this investigation, they were suggestive of the potential variability based on the plant variety. To explore this concept, they [21] conducted a bioassay utilizing non-sterile soil to test their hypothesis. Contrary to their initial assumption, it was discovered that the impact of temperature on AMF did not depend on the type of host plant. This suggests that soil temperature is crucial to AMF growth, regardless of the studied plant variety. Findings by [21] have significant implications, particularly in the farming sector, where many farmers depend on AMF to improve nutrient uptake and plant growth. As Mário de Carvalho et al. disclosed, acquiring knowledge about how soil temperature affects AMF can enable farmers to elevate their farming techniques and attain the utmost crop output. Additionally, research by [21] elucidates the intricate interplay between plants and microorganisms in agricultural contexts. It underscores that elements like soil temperature can profoundly impact these relationships, even when other factors remain unchanged. In conclusion, this inquiry provides valuable insights into the relationship between soil temperature and AMF colonization in agricultural systems. It challenges previous assumptions regarding the selectivity of host plants and underscores the significance of delving further into this field of study.

In the investigation by Li et al., a greenhouse bioassay was conducted to examine the impacts of AMF on the development and biomass of Snapdragon plants under conditions of low temperature and insufficient light. The findings of this experiment unveiled that the introduction of AMF significantly amplified both the development and biomass of the plant [22]. One notable discovery from this study was that the Snapdragon displayed higher mycorrhizal colonization and root activity when inoculated with AMF. This indicates that AMF is vital in enhancing nutrient absorption and stimulating plant growth even under unfavorable environmental situations. Additionally, it was observed that the overall photosynthetic rate, transpiration rate, stomatal conductance, and water utilization efficiency were all enhanced in plants inoculated with AMF. The findings by [22] reveal that AMF not only enhances nutrient uptake but also improves the physiological processes associated with photosynthesis and water regulation in plants. These findings have significant implications for agricultural practices, particularly in regions where there are low temperatures and limited light conditions. By employing AMF inoculation techniques, farmers have the potential to boost crop yields and enhance overall plant health even in challenging environments. Overall, Li et al.'s greenhouse experiment demonstrated that introducing AMF to Snapdragon plants under low-temperature and weak-light conditions resulted in remarkable advancements in growth, biomass production, mycorrhizal colonization, root activity, net photosynthetic rate, transpiration rate, stomatal conductance, and water utilization efficiency. These findings underscore the importance of considering AMF as a valuable tool for enhancing plant performance under unfavorable environmental conditions.

The study by Tian et al. explored the impact of higher temperatures on wheat growth and colonization of AMF. One crucial finding uncovered in the research was that augmented temperature increased the quantity of fiber found in the grains while concurrently decreasing the concentrations of wet gluten, protein, overall soluble sugars, and starch [23]. This suggests that elevated temperatures adversely impact the nutritional makeup of wheat grains, which can substantially threaten food security. The study by [23] also revealed that the increased temperature had an adverse effect on the number of aphids. Aphids are well-known agricultural pests as they extract plant sap and spread diseases. The escalation in aphid abundance because of higher temperatures can result in additional crop harm and financial losses for farmers. They [23] also discovered that increased temperature reduced colonization rates of AMF. AMF has a vital function in the absorption of nutrients by plants through their mutual association with roots. Reducing AMF colonization rates can lead to decreased plant nutrient availability, compromising their development and productivity. Overall, the structural equation modeling carried out by Tian et al. indicated a direct adverse connection between increased temperature and different aspects of wheat growth, yield, quality of grain, aphid abundance, and AMF colonization rates.

2.5. Effect of light on AMF colonization

In the study carried out by Saha et al., the scholars set out to explore the impacts of a reduced ratio of red to far-red light (R:fr) on tomato crops and their interaction with the insect herbivore Chrysodeixis chalcites. They also analyzed the influence of mycorrhizal inoculation on these interactions. The results of this study unveiled that when exposed to low R:fr light conditions, tomato plants without mycorrhizal support exhibited a triggering of the shade avoidance syndrome (SAS), which resulted in increased biomass production [24]. This response can be attributed to the plants' endeavor to compete for limited light resources by elongating their stems. The heightened biomass production in these plants might benefit agricultural practices. Despite initial expectations, incorporating symbiotic fungi had an opposing influence on the systemic acquired resistance (SAS) reaction. The presence of symbiotic fungi reduced stem elongation in tomato plants exposed to low red-to-far-red light ratios. This suggests that symbiotic fungi may play a role in modulating the growth responses of plants in diverse environmental conditions. Likewise, they [24] observed that AMF inhibited the induction of defense genes in tomato plants in response to herbivory. This implies that these advantageous microorganisms could potentially impair the plant's defense mechanism against insect herbivores. Overall, this study emphasizes the intricate interplay between light conditions, symbiotic fungi, and insect herbivory in tomato plants. Extensive research is needed to understand these interactions and their potential consequences for agriculture and crop protection strategies.

A study led by Ballhorn et al. revealed that in conditions where light is limited, microscopic root associates had an unfavorable impact on the growth and reproductive characteristics of Lima bean plants infused with AMF and rhizobia [25]. The researchers observed a decline in seed production, which was particularly noteworthy in plants treated with AMF and rhizobia, indicating that these associates resulted in cumulative expenses and ultimately reduced plant suitability. The findings by [25] illuminate the intricate interactions between plants and their microscopic partners. Although past research has demonstrated that AMF and rhizobia can enhance plant development by supporting nutrient absorption, this study emphasizes the potential compromises linked with these mutually beneficial connections. In conditions where light is scarce, and energy resources are limited, the advantages provided by these mutually beneficial microorganisms may not be worth the outlay. The observed reduction in seed production in Lima bean plants exposed to both AMF and rhizobia suggests a potential competition for limited resources between these symbiotic partners. This competition could lead to a decline in the overall health and vigor of the plants as resources are directed toward maintaining multiple mutually beneficial relationships [25]. Overall, Ballhorn et al. highlight the importance of environmental factors and their fundamental role in affecting plant-microbe connections. This means that further research is necessary to clarify the fundamental mechanisms implicated in these associations.

In their research, Hoz and colleagues examined the effects of different levels of light intensities on plant nutrition and their ability to fight leaf necrosis caused by *Botrytis cinerea* in lettuce plants. The study also considered the influence of mycorrhizal symbiosis on these factors. The investigation findings confirmed that light intensity heavily impacts mycorrhiza formation, affecting both root colonization expansion and fungal vesicle abundance [26]. Mycorrhiza is indispensable in amplifying nutrient assimilation and reinforcing plant defense mechanisms against pathogens. The study involved subjecting lettuce plants to five distinct levels of light intensity (low; moderate-low; moderate; moderate-high; high). Lettuce plants with symbiotic associations displayed markedly higher levels of root colonization and fungal vesicle abundance than plants lacking symbiotic associations across all light levels tested [26]. Moreover, they [26] noted that increased light levels facilitated a more robust formation of symbiotic relationships, as evidenced by both the expansion of root colonization and the abundance of fungal vesicles. This implies that adequate light availability is vital for effectively establishing symbiotic connections in lettuce plants. Overall, this study highlights the central importance of light intensity in impacting the establishment of symbiotic connections in plants. Future research could extensively explore the underlying mechanisms of this relationship and assess its implications for plant nutrition and disease resistance.

3. Potential for Future Research

3.1. Exploring the relations between multiple ecological variables and their collective effect on AMF colonization

Despite making noteworthy advancements in understanding the influence of environmental factors on the effectiveness and applicability of AMF, multiple areas necessitate further exploration. Subsequent investigation, for example, could focus on exploring the interplay among different environmental elements and their collective impact on AMF colonization. At present, the majority of research has explored the function of AMF in nutrient uptake and plant development, establishing their significance in terrestrial ecosystems [6,27,28,29,30]. Nevertheless, these investigations have not thoroughly recorded the possible correlations among these factors. Examining the combined influence of numerous environmental factors on AMF colonization, it is possible to understand how these microorganisms interact with their surroundings. For instance, it is feasible that heightened soil moisture levels may boost AMF colonization in certain pH conditions while suppressing it in other situations. Likewise, temperature or moisture levels can influence the effects of nutrient availability. Understanding these intricate interactions is paramount in anticipating how AMF populations adapt to changing environmental conditions, such as climate change or land use practices. By identifying critical combinations of environmental factors that either facilitate or impede AMF colonization, it is possible to devise precise management approaches to amplify ecosystem functionality and agricultural output.

3.2. Investigating the impact of specific pollutants and heavy metals on AMF diversity and functionality

Another potential area of study would involve investigating the impact of specific pollutants and heavy metals on the diversity and functionality of AMF. These fungi play a pivotal role in plant growth and nutrient absorption by establishing symbiotic connections with plant roots. They strengthen plant resilience due to various stressors such as pollutants and heavy metals [31,18,32,33]. Nevertheless, the precise impacts of multiple pollutants on AMF colonization are still poorly comprehended. Investigating the effect of particular pollutants on AMF diversity would yield valuable insights into their capacity to adapt to polluted environments.

Table 1 Summary of results from previous studies on the effects of environmental factors on AMF colonization

Environmental Factor	Effect on Arbuscular mycorrhizal fungi (AMF)	Reference
Organic matter	Increase the diversity of AMF microorganisms	[14]
	Augment the colonization of AM fungi	[15]
	Elevate levels of root AMF colonization	[16]
Soil pollutants	Lowers the efficacy of mycorrhizal fungi	[17]
Soil pH	AMF increases Chia plant chemical composition in alkaline soil	[18]
	AMF colonization is elevated at pH 5.8	[19]
	Acidity negatively affects AMF colonization	[20]
Temperature	Temperature affects AMF regardless of the host plant	[21]
	Low temperatures enhance nutrient uptake by AMF	[22]
	High temperature reduced colonization rates of AMF	[23]
Light	Low red-to-far-red light ratios inhibit AMF induction of defense genes	[24]
	Limited light reduces the efficacy of AMF	[25]
	Increased light levels increases robust AMF symbiotic relationships	[26]

This knowledge could be applied to construct strategies for bioremediation and ecosystem restoration. In addition, it is vital to understand how different pollutants impact AMF functionality to predict their ecological consequences over time. Similarly, examining the impact of heavy metals on AMF colonization is critical due to their abundant presence in contaminated soils. Heavy metals can disrupt AMF functioning by modifying their spore germination, hyphal growth, and nutrient transfer capacities [17]. Investigating these impacts would aid in evaluating the potential risks associated with heavy metal pollution and formulating efficient mitigation strategies.

3.3. Studying the role of root exudates and the plant's response to environmental stressors in modulating AMF colonization could provide crucial insights

The investigation of AMF and their symbiotic relationship with plants has long captivated the field of plant biology. However, another potential line of study could provide crucial insights into this intriguing interaction. It pertains to the significance of root exudates and a plant's response to environmental stresses. Root exudates are chemical compounds released by plant roots into the soil. These exudates play a crucial role in shaping the soil microbiome and can influence the establishment and functioning of AMF associations [15,34,35,36]. Understanding how different environmental stressors, such as drought or nutrient deficiency, affect root exudate composition and subsequently impact AMF colonization could provide valuable information on how plants adapt to challenging conditions. Studying this aspect of

AMF-plant interactions could have several practical implications. For instance, it can aid in devising strategies to augment the colonization of AMF in crops grown in challenging conditions, thus boosting their resilience and effectiveness. Furthermore, it may shed light on the mechanisms that govern plant adaptation to environmental stressors, a crucial aspect for cultivating agricultural methods that can endure climate challenges. To summarize, studying root secretions and the plant's response to environmental stressors in regulating AMF colonization offers significant opportunities for advancing our knowledge of this intricate mutualistic association. By deciphering these intricacies, it is possible to gain vital insights into plant adaptation strategies and devise innovative approaches to enhance crop effectiveness in harsh conditions.

3.4. Investigating the potential for AMF-assisted phytoremediation in contaminated soils holds promise for sustainable land management practices

Phytoremediation, the implementation of plants to eradicate toxins from the environment, has generated significant attention in contemporary times as a sustainable method for land management [37,38,39]. However, another potential avenue of inquiry in this domain is investigating the viability of AMF-supported phytoremediation in contaminated soils. AMF are mutualistic fungi that establish symbiotic associations with plant roots. They facilitate plant development and optimize nutrient assimilation in the soil, ultimately improving nutrient uptake. Additionally, they enhance the efficacy of phytoremediation by intensifying the absorption and breakdown of pollutants [40,13,11]. By exploring the use of AMF in phytoremediation, we can assess their potential for improving the efficiency of remediation techniques in contaminated soils. This could potentially result in adopting more sustainable land management practices that address polluted sites, foster plant growth, and restore ecosystems. Moreover, gaining insight into the mechanisms through which AMF enhances phytoremediation can facilitate the identification of optimal plant-fungal combinations for specific contaminants. This knowledge can then be implemented to create innovative approaches for addressing diverse forms of polluted sites. Investigating the potential of AMF-assisted phytoremediation in polluted soils provides exciting opportunities for sustainable land management practices. By utilizing the potential of these advantageous fungi, it is possible to cultivate more effective and precise methods to mitigate site contamination while facilitating ecological rehabilitation. Extensive research in this field is imperative to unleash its complete capabilities and make a substantial contribution to a more pristine and sustainable environment.

4. Conclusion

The findings from previous studies suggest that the soil composition, acidity levels, temperature, moisture levels, and sunlight availability all play crucial roles in determining the success of AMF partnerships. However, there are still knowledge deficiencies, suggesting the possibility for subsequent investigation to delve into more intricate relationships among these ecological factors. This research contributes to developing sustainable agricultural practices by unraveling the complex interplay between plants and AMF.

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