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(Review Article)

Understanding the mechanisms of nutrient transfer between Arbuscular Mycorrhizal Fungi (AMF) and Host Plants

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Abstract

Understanding the mechanisms of nutrient transfer between AMF and host plants is essential for enhancing our knowledge of plant nutrition and improving agricultural practices. Transporters are protein substances that enable the movement of nutritional elements between the host plant and AMF. They ensure even and adequate distribution and uptake of micronutrients, phosphorus, and nitrogen. Apart from transporters, AMF also have a crucial role in the distribution of nutrients within the host plants. These beneficial microbes establish an intricate system of hyphae that spreads in soil, assimilating limited nutrients that would otherwise be inaccessible to the host plant. These fungal networks augment the plant's ability to obtain nourishment, particularly in environments where some elements are limited. The mechanisms underlying the transporter network involved in nutrient exchange between AMF and host plants remain to be fully deciphered. Examining the connections of this network can bring to light the coordination between incongruent transporters and the entire process of nutrient interchange. Future studies should prioritize investigating the particular molecules and genes engaged in nutrient exchange to understand this essential mutual relationship better. Furthermore, assessing the impact of environmental factors on AMF associations can help devise strategies to optimize nutrient absorption in agricultural systems. By manipulating ecological factors such as soil nutrients or pH levels, it may be possible to increase the efficiency of nutrient transfer, thus improving plant growth and productivity.

Keywords: Arbuscular mycorrhizal fungi; AMF associations; Nutrient exchange; Transporters; Strigolactones

1. Introduction

The establishment of associations between arbuscular mycorrhizal fungi (AMF) and the specific host plants consists of complex molecular signaling pathways, making it an intricate process. Strigolactones, a class of plant hormones, are crucial in instigating AMF colonization and the formation of fungal hyphae [1]. Equally, specific receptors and intracellular signaling cascades are vital for the intricate molecular interaction between AMF and plant roots [2,3]. Essentially, plant roots release strigolactones that act as signals to initiate the functionality of AMF. These hormones encourage the growth of AMF spores and direct this growth towards the host plant's roots. Once the hyphae reach the surface of the roots, they create a symbiotic relationship with the plant. The receptors on the surface of both AMF and plant cells identify strigolactones, triggering a cascade of interior pathways that lead to mutually advantageous interactions between the fungus and plant [4,5]. These interactions involve the transfer of essential nutrients, where AMF supplies plants with phosphorus while gaining carbon compounds. This complex molecular interaction is crucial in establishing a successful symbiotic relationship [6,7]. Notably, receptor specificity ensures the development of exclusively compatible associations. These internal signaling pathways control various processes linked to colonization and nutrient exchange. Understanding these mechanisms can provide valuable insights into increasing crop productivity by enhancing the symbiotic relationships between plants and beneficial fungi like AMF.

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1.1. Role of transporters in nutrient transmission

Transporters are proteins that bear the responsibility of facilitating the transportation of nutrients across cell membranes. In relation to AMF and host plants, these transporters have a vital function in facilitating the transfer of nutrients such as phosphorus and ammonia [8,9]. Phosphorus, which plays a critical role in supporting plant growth, may experience limitations in soil availability. AMF aid in surpassing this limitation by obtaining phosphate from the soil and conveying it to host plants using specialized transporters. Multiple studies have indicated that mycorrhiza-induced phosphate transporters play a critical role in optimizing nutrient exchange between AMF and host plants [10,11,12]. These transporters experience increased expression in both fungal hyphae and plant roots during symbiotic interactions, suggesting their significant function in facilitating nutrient exchange. Additionally, transporters for ammonium ions play a significant role in the nutrient exchange facilitated by AMF [13]. Ammonium, being a crucial nutrient for plant growth, is facilitated in its absorption by plant roots via specialized transporters. Studies have indicated that AMF can boost ammonium uptake by upregulating the expression of these specific transporters.

1.2. The influence of AMF on plant nutrient distribution

The association between plants and AMF has been acknowledged for a considerable time as a mutually advantageous symbiotic interaction. This cooperative alliance enhances the assimilation of phosphorus and the utilization of nutrients in plants while also influencing the absorption of nitrogen, incorporation, and distribution of carbon. AMF play an indispensable role in enhancing phosphorus assimilation by plants [14,15]. These fungi create intricate networks of hyphae that reach into the soil, thereby augmenting the available surface area for nutrient uptake. Moreover, AMF secrete enzymes that degrade organic phosphorus compounds into forms that plants can easily absorb [16,17]. This heightened phosphorus acquisition enables plants to get through constraints in nutrient availability and bolster their growth and development [18]. Additionally, AMF have been discovered to have an effect on nitrogen uptake and assimilation in plants. Research has demonstrated that AMF can augment the uptake of ammonium and nitrate ions from the soil by expanding the root surface area via hyphal extensions [19,20]. Additionally, these fungi can promote the activity of enzymes participating in nitrogen assimilation within plant tissues. This leads to enhanced nitrogen utilization efficiency in plants. Apart from nutrient intake, AMF also have an impact on carbon allocation within plants [21]. The presence of AMF in a symbiotic association enhances host plant photosynthetic rates by improving nutrient availability. As a consequence, photosynthesis results in the generation of more carbohydrates that are then distributed towards belowground formations like roots or fungal structures such as arbuscules [22]. Overall, the symbiotic relationship between plants and AMF plays a critical role in enhancing phosphorus uptake and nutrient utilization while also affecting nitrogen uptake, assimilation, and carbon allocation. Comprehending these complex interactions can aid in optimizing agricultural practices by leveraging the advantages offered by this symbiotic relationship between plants and fungi.

1.3. Search strategy

The investigation utilized a variety of English publications spanning from 2015 to 2023. The exploration required dividing the research subject into various search terms, specifically "Colonization of Arbuscular Mycorrhizal Fungi" and "Impact of Environmental Factors." The adequacy of a study depends solely on its inclusion of any of the specified keywords. After completing the search, a total of 58 journal articles were found, excluding 9 duplicates, resulting in a final count of 49 individual articles. The abstracts of all these journals underwent rigorous scrutiny, and pertinent papers were flagged for subsequent assessment. The study based its inclusion and exclusion criteria primarily on an 8-year threshold. Following the fulfillment of this requirement, a thorough analysis of 45 journal articles was undertaken to ascertain their pertinence to the research topic. At this stage, 3 of these journals were dismissed as the study solely emphasized peer-reviewed articles. A comprehensive evaluation of 42 peer-reviewed journals was conducted to assess their eligibility for inclusion in this analysis. Two of these journals were deemed inconsequential as they failed to contribute to keyword identification. Hence, the research approach resulted in 40 publications that were cited and referenced in this study (Figure 1).

2. Literature from previous studies

2.1. The role of strigolactones in AMF colonization

In their recent scholarly article, Kleman and Matúšová extensively explore the captivating subject of strigolactones and their pivotal function in plant reactions to abiotic stress factors [23]. The authors emphasize the importance of these compounds in alleviating the negative impacts of nutrient deficiency, high salinity, drought, extreme temperatures, and toxic elements on plant growth and development. They [23] elucidate these hormones' pivotal role in optimizing nutrient uptake efficiency in situations of limited availability (Table 1). According to their explanation, strigolactones activate the symbiotic relationship between plants and arbuscular mycorrhizal fungi (AMF), thereby facilitating the absorption of nutrients from the soil. Moreover, they elaborate on the role of strigolactones in promoting plant resilience against high salinity, emphasizing their impact on regulating ion transport mechanisms. They [23] highlight the significance of these hormones in increasing drought resistance by emphasizing the importance of stomatal closure and modifications to the architecture of the root system. Furthermore, Kleman and Matúšová emphasize the correlation between strigolactones and the presence of N-fixing bacteria. According to their [23] explanation, these hormones enhance nodulation in legume plants, thus facilitating the process of nitrogen fixation by symbiotic bacteria. Overall, this comprehensive review by Kleman and Matúšová provides valuable insights into the multifaceted roles of strigolactones in plant responses to abiotic stressors. Their research findings lay the groundwork for future studies focused on utilizing these hormones to create crop varieties that can withstand stress and ultimately improve agricultural productivity.

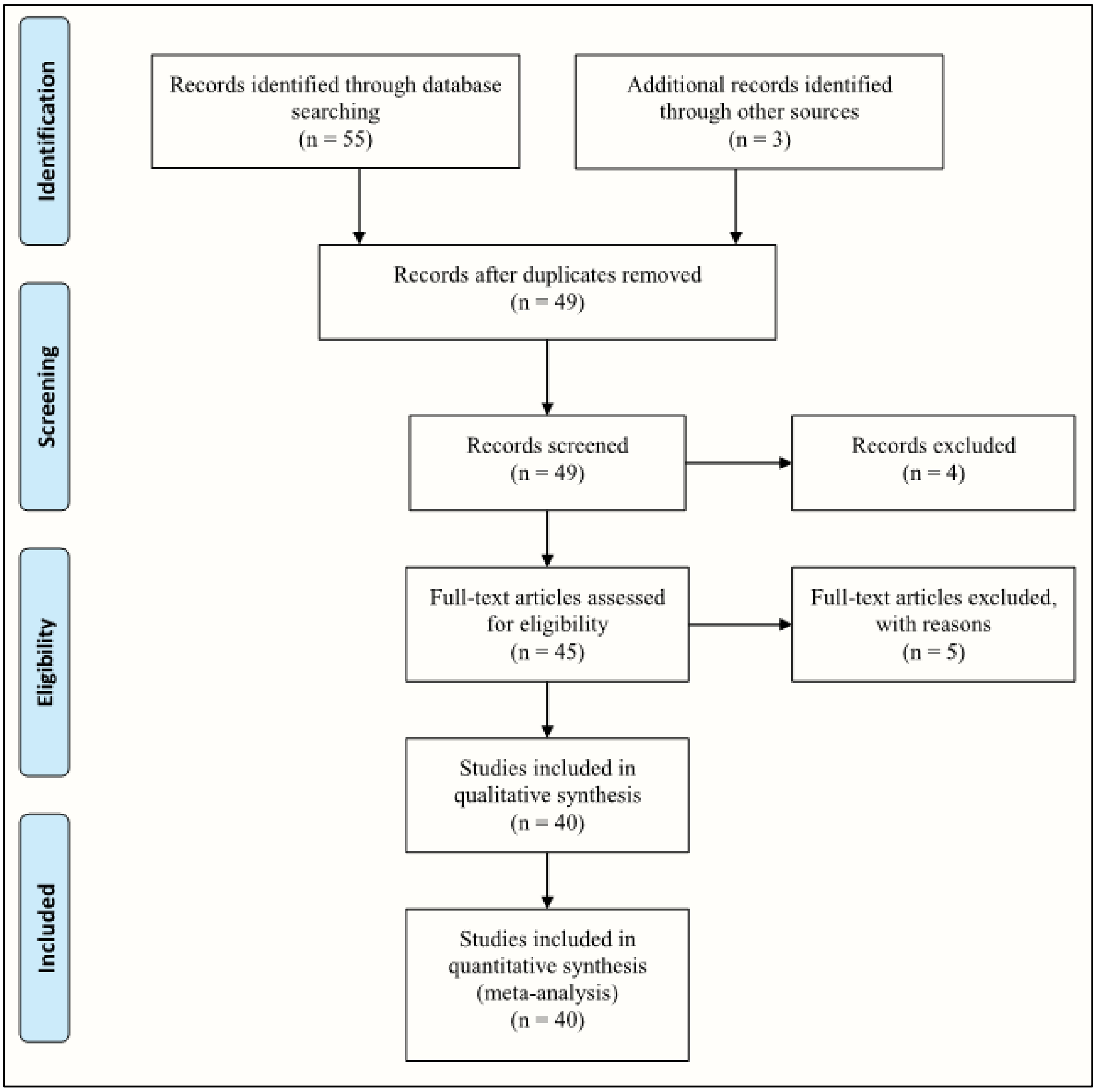

Figure 1 PRISMA diagram showing how papers were selected, excluded and included

The study by Yee Jia Kee et al. highlights the evolution of D14/kai2 receptors and their role in regulating different SLs or SL-like compounds in controlling downstream signaling in host plants [24]. This study points out the intricate relationship between plants and their rhizosphere. In their research, they [24] elucidate how plants have established a complex mechanism to interact with their environment, particularly the soil area adjacent to the roots of plants. The presence of diverse microorganisms in this region fulfils a vital function in nutrient cycling and plant growth processes. According to [24], to effectively respond to these environmental cues, plants have developed receptors like D14/kai2 that have a significant role in the perception of specific compounds, specifically strigolactones (SLs) or similar compounds (SL-like). By identifying these molecules, D14/kai2 receptors initiate downstream signaling pathways that control various physiological functions in plants. In particular, these receptors enable plants to perceive a wide range of SLs or SL-like compounds in the rhizosphere [24]. This perception allows the involved plants to modulate their growth patterns, root architecture, and interactions with advantageous microbes within the soil. This research highlights the intricate interplay between plants and their environment mediated by D14/kai2 receptors. Understanding these interactions can offer valuable insights into improving crop yield through targeted plant-microbe interactions in agricultural systems.

According to Alvi et al., SLs are complex β-carotene derivatives that govern diverse aspects of plant growth and development and the regulation of root architecture [25]. In particular, they stimulate the development of lateral roots and improve root elongation, a factor that increases the efficiency of nutrient absorption. These derivatives also play a role in regulating shoot branching through their inhibitory characteristic on axillary bud growth [25]. This, in turn, contributes to optimizing plant architecture and nutrient allocation (Table 1). Alvi et al. also discloses that SLs play an essential role in the synthesis of chlorophyll, which is vital in the process of photosynthesis and plant productivity. These compounds stimulate the build-up of chlorophyll in host plant leaves, leading to increased energy production. Another notable SL function is their involvement in the defense responses against various stresses. According to Alvi and peers, they stimulate the plants' ability to water stress by regulating stomatal closure and the process of transpiration [25]. SLS plays a role in helping plants adapt to salinity stress by maintaining ion equilibrium and mitigating salt-related harm. These derivatives are also instrumental in guarding plants against heavy metal toxicity. They control the uptake and transportation of metals in the plant system, preventing excessive accumulation that can harm plant health [25]. In addition, SLs participate in nutrient deprivation responses by facilitating symbiotic associations with advantageous soil microorganisms like mycorrhizal fungi. This amplifies the capacity to acquire nutrients in circumstances of scarce nutrient availability. Lastly, SLs have been discovered to be involved in mechanisms that enhance heat stress tolerance. They control the modulation of heat shock protein expression and antioxidant enzyme activity, thereby alleviating oxidative damage from high temperatures [25]. Overall, strigolactones are intricate molecules that govern a wide range of plant growth and development processes. Their roles go beyond the scope of root architecture and shoot branching control. Acquiring a deep understanding of the functions of SLs is essential in crafting strategies to bolster plant resilience and boost crop productivity amid changing environmental conditions.

In their 2021 research, Mitra et al. comprehensively explored the various roles of strigolactones (SLs) as plant hormones in the multiple aspects of plant growth and physiology. They emphasize that SLs control plant structure, germination, formation of nodules, development of root hairs, and their responses to non-living factors [26]. One of the key findings from this study is that SLs encourage symbiotic relationships between plants and AMF. The presence of AMF hyphae allows plants to extract essential nutrients from the soil, fostering a mutually beneficial relationship. Additionally, they [26] revealed that SLs facilitate the transfer of nutrients from mature roots to younger ones, thus enabling nutrient redistribution within the plant. They [26] also found that SLs trigger alterations in the actin framework within roots. Actin is a protein involved in diverse cellular procedures, comprising cell separation and expansion. By altering actin dynamics, SLs impact root expansion and development. The researchers also examined the correlation between SLs and AMF in relation to root expansion. They [26] observed that AMF colonization positively impacted root extension but did not influence lateral root density or branching. Overall, this study illuminates the varied roles of SLs in regulating plant growth and their intricate interplay with AMF. Understanding how these mechanisms work can have significant implications for enhancing crop productivity and sustainability through targeted manipulation of these hormonal pathways.

2.2. The role of nutrient transporters in AMF symbiosis

The presence of mineral nutrient transporters (MNTs) in plant-microbe associations play a crucial role in enhancing the functionality of mycorrhizae or rhizobium interactions. According to Sun et al., these transporters control the process of nutrient transfer, encourage the growth of beneficial microbes, and establish the needed defense mechanism in the host plant [27]. Sun and his research peers state that the primary function of MNTs is the ability to transfer essential materials between the host plant and the microorganisms. This exchange ensures the involved organisms' growth and development and the beneficial microbes' colonization and degradation process. MNTs also act as protectors that selectively control the entry and establishment of beneficial microbes within the plant tissues. This regulation is essential when establishing harmonious symbiotic associations and inhibiting over-colonization that would harm the host plant [27]. In addition, MNTs have been seen to alter pathogen growth and the host's defense mechanisms. By modulating nutrient availability in plant tissues, these transporters can facilitate or hinder pathogen growth. In addition, they can also induce plant-specific defense reactions that contribute to the defense against invading pathogens. MNTs can influence plant-microbe interactions directly and indirectly [27]. Direct effects are related to their role in facilitating nutrient exchange and regulating microbial colonization within plants. Indirect effects involve their consequences on the growth of pathogens and the defense mechanisms of hosts. Overall, mineral nutrient transporters are vital in establishing symbiotic relationships between host plants and microorganisms such as rhizobium or mycorrhizae. Their capacity to coordinate nutrient transportation, regulate microbial colonization, and impact pathogen proliferation and host defense mechanisms renders them indispensable constituents in plant-microbe interactions. Understanding the intricate workings of MNTs can provide valuable insights into enhancing agricultural practices and developing sustainable methods for crop production.

In the research conducted by Francis et al., it was uncovered that plants can establish symbiotic connections with fungi and bacteria to amplify nutrient absorption [28]. This finding illuminates the complex associations between plants and microorganisms, highlighting their mutually beneficial interactions for survival and development. To guarantee efficient nutrient assimilation, plants heighten the expression of nutrient transporters, which play a crucial function in facilitating the movement of vital nutrients from the ground into the plant's roots. Additionally, plants intensify the release of acid phosphatases, which assist in decomposing organic phosphates into simpler forms that plant roots can readily absorb [28]. Equally, plants stimulate proton expulsion and excrete organic acids to generate an acidic environment around their root zone. This acidity aids in dissolving minerals present in the soil, rendering them more accessible for uptake by vegetation roots. Anthocyanin accumulation and ROS (reactive oxygen species) release were also observed in plants grown under symbiotic associations with fungi and bacteria. According to [28], anthocyanins are pigments that give fruits and flowers vibrant colors. Their accumulation suggests an enhanced defense mechanism against environmental stressors. ROS release is a typical response to stimuli such as pathogen attacks or abiotic stressors like drought or high temperatures. Overall, this study highlights plants' sophisticated strategies to optimize nutrient absorption through symbiotic associations with microorganisms. Understanding these mechanisms can have significant implications for agriculture and sustainable food production systems by improving nutrient availability for crop plants while reducing reliance on chemical fertilizers.

According to Pierre-Emmanuel Courty et al., arbuscular mycorrhiza (AM), ectomycorrhiza (ECM), and nitrogen fixation through rhizobia symbioses (RS) play a critical role in plant nutrient use efficiency in natural ecosystems, particularly those characterized by nutrient limitation, especially regarding nitrogen and phosphate [29]. Substantial evidence has accumulated about how the rational use of these symbiotic associations can enhance plant growth and productivity. AM is a mutualistic association between plants and fungi, where the fungi colonize the roots and facilitate nutrient uptake, particularly phosphorus. This association is widespread in natural ecosystems, as it allows plants to access otherwise unavailable nutrients. Similarly, ECM is another mutualistic association between plants and fungi, primarily found in forest ecosystems [29]. ECM fungi form a sheath around the root tips of trees, enhancing nutrient uptake, especially nitrogen. Furthermore, RS involves the interaction between leguminous plants and bacteria called rhizobia. These bacteria fix atmospheric nitrogen into a form plants can use for growth. This symbiosis is crucial for nitrogen-limited environments as it provides an alternative source of this essential nutrient [29]. The rational use of AM, ECM, and RS can significantly improve plant nutrient use efficiency in natural ecosystems with limited nutrients such as nitrogen and phosphate. The researchers [29] indicate that promoting these symbiotic associations through appropriate agricultural practices or ecological restoration efforts can enhance plant productivity while reducing the need for chemical fertilizers. Overall, understanding the importance of AM, ECM, and RS in plant nutrient use efficiency is vital for sustainable agriculture and ecosystem management. By harnessing these natural processes effectively, we can optimize resource utilization while minimizing environmental impacts associated with chemical fertilizers.

The mutual connection between terrestrial plants and advantageous soil microorganisms in plant science has long been acknowledged as a vital aspect of plant nourishment. Banasiak et al. affirm that microorganisms, such as AMF and nitrogen-fixing rhizobia, contribute substantially to plants' overall vitality and well-being through endosymbiotic processes [30]. Nonetheless, the intricate dynamics of this interrelated partnership have mostly remained unsolved. Functional genomics is a significant area of exploration that is bringing clarity to this subject. Advances in this field are narrowing the knowledge gap concerning the integration of plant membrane transport, a pivotal factor in facilitating nutrient exchange between plants and their microbial counterparts. According to [30], scientists are unraveling the genetic foundation of plant-microbe interactions through functional genomics investigation. By examining gene expression patterns and identifying particular genes associated with membrane transport mechanisms, researchers have acquired insights into how plants govern the movement of nutrients across their cellular membranes. This newfound understanding carries extensive implications for agriculture and ecosystem management. The researchers [30] indicate that understanding how plants integrate beneficial soil microbes into nutrient acquisition strategies can foster sustainable farming practices by reducing dependence on synthetic fertilizers. Furthermore, it may contribute to ecological restoration efforts by enhancing the establishment and growth of native plant species. Banasiak et al. highlight the importance of symbiotic relationships between land plants and beneficial soil microbes for plant nutrition. Functional genomics research is pivotal in unraveling the complex mechanisms underlying these relationships by elucidating plant membrane transport integration. This knowledge enhances our understanding of biological processes and finds practical use in agriculture and ecosystem management.

Plant processes like nitrogen fixation and photosynthesis heavily depend on the existence of transition elements. However, they are often found in limited amounts, establishing an intricate uptake and distribution system. A study by González-Guerrero et al. reveals that this complex process involves a synchronized coordination of the host plant, beneficial AMF, and endosymbiotic rhizobia [31]. The beneficial fungi dissolve the metal ions in the soil, making them available to the plant. They also induce the deficiency of these ions in host plants in host plants by actively competing for these limited resources. Moreover, these microbes act as intermediaries between rhizobia and host plants, facilitating the whole process of nutrient transfer. Endosymbiotic rhizobia, which usually forms symbiotic associations with legumes, can fix nitrogen into nitrates accessible to the host plant. This process requires transition metals as cofactors for the enzymes involved in nitrogen fixation [31]. Overall, the study by González-Guerrero et al. highlights the benefits of transition metals in coordinating the intricate association between host plants, fungal microbes, and endosymbiotic rhizobia in the process of nutrient supply. However, further research is needed to provide valuable insights into improving crop productivity and sustainability through enhanced metal uptake mechanisms in agricultural systems.

A study by Rui et al. provides invaluable insights into plant-fungi symbiosis and nutrient acquisition. The study reveals how transporters produced by host plants and AMF work in coordination to actualize the process of transmembrane nutrient transfer, ultimately benefiting the plants [32]. The researchers begin by highlighting the benefits of nutrient uptake by plants, indicating that the ability of plants to extract these elements to a greater extent impacts plant growth and development. They [32] then introduce the role of AM fungi in enhancing nutrient transfer by forming mutualistic associations with the host plants through their hyphal networks. Rui et al. suggest a synergistic association exists between the AM fungal transporters and the host plant, leading to a well-organized nutrient transfer at the symbiotic interface. They [32] offer evidence backing up this hypothesis by reviewing earlier studies on transporter genes expressed in both plants and AM fungi. The study explores mechanisms such as proton pumps and ion channels and deliberates on transporters, specifically those specialized for mycorrhizal interactions, implicated in nutrient transport. This research sheds light on an intricate aspect of plant-fungal interactions and emphasizes their crucial role in nutrient acquisition. Understanding these mechanisms enhances our knowledge of fundamental biological processes and holds potential implications for improving crop productivity through targeted manipulation of symbiotic associations [32]. Overall, Rui et al.'s study provides valuable insights into how transporters belonging to both plants and AM fungi synergistically process transmembrane transport of soil nutrients at the symbiotic interface. By elucidating these mechanisms, researchers can further explore strategies to optimize nutrient uptake in agricultural systems, ultimately contributing to sustainable food production.

2.3. The impact of AMF on nitrogen acquisition and allocation

In the study conducted by Luo et al., the focus is on interplant carbon (C) and nitrogen (N) transfer through common arbuscular mycorrhizal networks (CAMNs). The authors strive to elucidate the functionality of these transitions and their implications for plant cohabitation, species diversity, and community stability. Their findings demonstrate that CAMNs significantly influence one-way changes in C and N, ranging from 0.02% to 41% for C and 0.04% to 80% for N [33]. C and N transition through CAMNs significantly affect plant functionality and biodiversity. This interaction is of the utmost significance in the reutilization of nutrients within ecosystems, as it enables the exchange of resources among various plant species. This process encourages coexistence by mitigating competition for finite resources. Furthermore, the transfer of C and N through CAMNs has implications for species diversity. They [33] observed that higher levels of resource sharing lead to increased species richness within communities. This is because plants with lower resource availability can benefit from those with higher availability through these interplant transfers. Additionally, community stability is greatly influenced by CAMN-mediated nutrient transfers. By facilitating nutrient redistribution, CAMNs contribute to a more balanced nutrient supply across different plant individuals within a community [33]. This balance enhances overall ecosystem stability by reducing fluctuations in nutrient availability. Overall, Luo et al.'s review emphasizes the importance of interplant C and N transfer through CAMNs in promoting plancoexistence, species diversity, and community stability. The findings underscore the significance of these processes in shaping ecosystem dynamics and highlight their potential applications in ecological restoration efforts.

Jansa et al. highlight the significance of the mutually beneficial symbiotic relationship between AM fungi and plants in acquiring soil phosphorus for plant growth and development. With this mutual association, plants can gain the essential nourishment crucial to their progression and evolution [34]. The formation of AMF in plant roots initiates the growth of arbuscules, which are distinctive formations that boost the exchange of nutrients between the fungus and the plant. However, while AM symbiosis is critical for phosphorus uptake, its role in plant nitrogen (N) nutrition is not as pronounced. Nitrogen is a vital plant nutrient for essential physiological processes, including protein synthesis and photosynthesis. Unlike phosphorus, which can be directly sourced from soil minerals through AM symbiosis, plants primarily acquire nitrogen through organic compounds. Within this context, it has been postulated [34] that AM fungi might rely on alternative microorganisms to extract nutrients from organic substances, thereby facilitating plant nitrogen nutrition. These microorganisms may include bacteria or other fungi with enzymes capable of breaking down complex organic molecules into simpler forms that the fungus and the plant can absorb. The involvement of these microbes in nutrient liberation processes highlights the complexity of below-ground interactions in soil ecosystems [34]. Further research is needed to elucidate the specific microbes and mechanisms involved in this process and their impact on plant N nutrition. While AM symbiosis is crucial for phosphorus acquisition from soil to plants, its role in plant nitrogen nutrition is less prominent. AM fungi may rely on other microorganisms to liberate nutrients from organic compounds, emphasizing the intricate nature of below-ground interactions in soil ecosystems. Further investigation into these processes will enhance our understanding of nutrient cycling dynamics and potentially contribute to sustainable agricultural practices.

Table 1 Summary of results from previous studies on the mechanisms of nutrient transfer between AMF and host plants

Mechanism	**Role in the process of nutrient transfer**	**Reference**
Strigolactones in AMF colonization		
Strigolactones (SLs) hormone	Activate the symbiotic relationship between plants and AMF	[23]
D14/kai2 receptors	Regulate different SLs or SL-like compounds in controlling downstream signaling in host plants	[24]
SLs as complex β-carotene derivatives	Govern diverse aspects of plant growth and development and the regulation of root architecture	[25]
SLs in plant growth and physiology	Control plant structure, formation of nodules and root hairs, and their responses to non-living factors	[26]
Nutrient transporters in AMF symbiosis		
Mineral nutrient transporters (MNTs)	Enhancing the functionality of mycorrhizae or rhizobium interactions	[27]
Anthocyanin	Enhanced defense mechanism against environmental stressors	[28]
AMF and Ectomycorrhiza (ECM)	Improve plant nutrient use in natural ecosystems with limited nutrients such as nitrogen and phosphate	[29]
AMF and nitrogen-fixing rhizobia	Contribute substantially to plants' overall vitality and well-being through endosymbiotic processes	[30]
Endosymbiotic rhizobia	Forms symbiotic associations with legumes, which fix nitrogen into nitrates accessible to the host plant	[31]
AM fungal transporters	Play a crucial role in nutrient acquisition through proton pumps and ion channels	[32]
AMF on nitrogen acquisition and allocation		
Common arbuscular mycorrhizal networks (CAMNs)	Enables the exchange of resources among various plant species	[33]
AM symbiosis	Initiates the growth of arbuscules that boost the exchange of nutrients between the fungus and the plant	[34]

3. Potential for Future Research

3.1. Investigating specific molecules and genes in nutrient exchange

The widely studied partnership between AMF and host plants has proven beneficial. For example, there has been notable advancement in comprehending the complex mechanisms involved in nutrient transfer between AMF and host plants, unveiling the profound importance of this mutually beneficial association for plant nutrition [13,35,36]. Nonetheless, in light of these significant findings, there are still avenues that warrant further examination. One promising pathway for future research includes gaining knowledge about the specific molecules and genes involved in nutrient exchange between AMF and host plants. This understanding could facilitate a more profound comprehension of the complex molecular interactions during this mutually valuable relationship. By pinpointing the key molecules and genes that enable nutrient transfer, scientists can formulate targeted approaches to improve nutrient uptake efficiency in crops. Furthermore, understanding the specific molecules involved in nutrient exchange could also present possibilities for the advancement of groundbreaking biotechnological applications. For example, through the manipulation of these molecules or genes, it might be possible to engineer plants with increased proficiency in assimilating nutrients from their environment. This could have substantial impacts on sustainable agriculture by decreasing the requirement for chemical fertilizer usage and enhancing crop productivity. Overall, although significant progress has been made in understanding the mechanisms of nutrient transfer between AMF and host plants, there are still many potential areas for future research. Acquiring knowledge about the precise molecules and genes involved in nutrient exchange presents a highly promising opportunity to advance our understanding of this mutually beneficial relationship and its implications in agriculture.

3.2. Evaluating the influence of environmental factors on AMF associations

Another promising avenue for future study involves gaining insight into the impact of ecological factors on AMF interactions. The dynamics of AMF interactions are determined by various environmental factors, encompassing weather, soil pH, moisture content, and essential nutrients [37,38]. These specific ecological variables dictate the rate at which AMF forms mutually advantageous associations with plant roots and the effectiveness with which this fungus facilitates nutrient exchange with its host plant. Understanding the influence of these ecological factors on AMF interactions can offer valuable insights for improving agricultural practices and boosting crop yields. For instance, analyzing the impact of temperature on AMF connections can aid in determining the ideal temperature ranges for promoting symbiotic associations between fungi and plants. Likewise, investigating the connection between soil acidity and AMF colonization can yield valuable information on techniques for adjusting soil pH to optimize nutrient uptake in crops. In addition, studying the relationship between ecological variables and AMF connections can enhance our understanding of their ecological significance. Understanding the relationship between environmental conditions and these interactions can assist in anticipating their reaction to global climate change or other anthropogenic disruptions. Overall, although significant advancements have been made in comprehending the mechanisms of nutrient exchange between AMF and host plants, there are still numerous opportunities for future research. Exploring how ecological variables influence AMF connections is a promising avenue that can provide valuable insights into optimizing agricultural practices and comprehending their ecological significance.

3.3. Investigating the interactions of the transporter network

Another area for future study is to acquire a more comprehensive understanding of the interactions within the transporter network. AMF play a crucial role in enhancing the absorption of nutrients by plants, specifically phosphorus. They establish mutually advantageous connections with plant roots, facilitating the reciprocal exchange of nutrients [39,40]. Recent investigation has shed light on the complex molecular mechanisms involved in this procedure, including identifying carriers responsible for the exchange of nourishment [13,14]. Nonetheless, there is still significant undisclosed evidence regarding the correlation between these transporters and other aspects of the AMF-plant partnership. Understanding these interactions can provide valuable insights into the regulation and optimization of nutrient transfer. Exploring the transport network within the interactions between AMF and host plants can also help identify potential targets for enhancing nutrient uptake in agriculture. By recognizing essential conveyors and deciphering their governing mechanisms, it becomes possible to devise strategies to improve the efficiency of nutrient acquisition in agricultural systems. Despite the progress made in understanding nutrient exchange between AMF and host plants, numerous avenues remain for further investigation. Acquiring a deeper understanding of the interdependencies within the transport network presents significant possibilities for advancing our knowledge of this crucial, mutually advantageous association and its potential applications in agriculture.

4. Conclusion

In conclusion, understanding the mechanisms of nutrient transfer between AMF and host plants is vital for optimizing plant growth and improving agricultural practices. By examining molecular signaling pathways, investigating transporters' roles, and evaluating the impact on nutrient allocation, we can unravel the complexities of AMF associations and further enhance sustainable agricultural strategies.

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