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Evaluating the Interaction between Arbuscular Mycorrhizal Fungi (AMF) and Plant Pathogens

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Abstract

The presence of arbuscular mycorrhizal fungi (AMF) in the rhizosphere has been shown to exert a substantial influence on plant disease resistance. The colonization of AMF induces a cascade of defense responses in plants, resulting in heightened resistance to pathogen invasion. The current study unveils the essential role of AMF in initiating systemic defense responses in plants. When plants undergo colonization by AMF, they initiate a variety of molecular and biochemical mechanisms that enhance their immune system. These systemic defense responses equip the plant with the ability to both withstand invading pathogens and ready neighboring uninfected tissues for potential future attacks. In addition, the establishment of AMF in the roots can induce physical alterations in the root architecture, thereby increasing the difficulty for pathogens to infiltrate and infect plants. While there have been notable advancements in understanding the overall impact of AMF colonization on plant disease resistance, further investigation is needed. Future investigations should delve into the mechanisms of AMF colonization on plant disease resistance, with a particular emphasis on elucidating the signaling pathways and biochemical factors that trigger systemic defense responses. This will offer valuable insights into the molecular foundation of plant immunity and aid in the development of precise disease management strategies. AMF can also serve as biocontrol agents for sustainable management of plant diseases, thereby decreasing dependency on chemical pesticides and encouraging environmentally-conscious practices. The efficiency of AMF colonization and the expression of plant defense responses can be significantly altered by environmental factors, such as soil conditions and nutrient availability. Comprehending these factors will facilitate the formulation of efficient management tactics to enhance biotic interactions in agricultural systems.

Keywords: AMF Colonization; Pathogens; Defense Response; Disease Resistance

1. Introduction

The crucial role of arbuscular mycorrhizal fungi (AMF) associations in plant nutrient uptake has been widely recognized for a long time. The advantageous symbiotic relationships between plants and AMF can exert substantial influence on plant health and productivity [1,2]. While there has been significant research on the benefits of AMF for plant nutrition and growth, the impact they may have on plant disease resistance is a relatively new field of investigation. AMF establish mutualistic associations with the roots of nearly all land-dwelling plants [3,4,5], thereby enabling the reciprocal transfer of nutrients between the two collaborating organisms. The fungi facilitate the uptake of vital elements like phosphorus, nitrogen, and micronutrients from the soil, subsequently transferring them to the host plant. This augmented nutrient accessibility stimulates plant growth and progress. Furthermore, AMF can also enhance a plant's resistance against diseases caused by diverse pathogens. Recent studies have revealed that AMF can trigger systemic resistance in plants against a diverse array of pathogens, encompassing bacteria, fungi, and viruses [6,7]. This heightened disease resistance is credited to multiple mechanisms that encompass both direct interactions between AMF and pathogens and indirect effects facilitated by alterations in plant physiology. One method through which AMF boost disease resistance is by priming the defense responses of host plants. The existence of these advantageous fungi prompts an early induction of

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defense-related genes in plants, rendering them better equipped to mount an efficient response in the face of pathogenic attacks [8,9,10]. Moreover, AMF can generate antifungal compounds that directly impede pathogen proliferation or trigger systemic acquired resistance (SAR), a comprehensive defense mechanism that safeguards plants from various pathogens [11,12]. Studies also disclose that AMF associations can also regulate other facets of plant physiology that contribute to disease resistance. For example, they can enhance root architecture and boost root biomass production, thus improving a plant's capacity to compete for resources against potential pathogens [13,14,15]. Moreover, AMF colonization has demonstrated the ability to induce the synthesis of secondary metabolites with antimicrobial properties in certain plants. In spite of these encouraging findings regarding the potential influence of AMF on plant disease resistance, there is still much that needs to be comprehended. The precise mechanisms that underlie AMF-mediated disease resistance and the factors that impact its efficacy remain incompletely understood [16,17]. More extensive research is necessary to unravel the intricate interplay among AMF, plants, and pathogens and to delve into their potential applications in sustainable agriculture.

1.1. Search strategy

The research utilized English journals spanning from 2012 to 2023. The search required the division of the research topic into separate search terms, specifically “Arbuscular Mycorrhizal Fungi” and “Plant pathogens.” The adequacy of a study depended entirely on its inclusion of any of the specified keywords. Following the completion of the search, a total of 57 journal articles were identified, after eliminating 6 duplicates, resulting in a final tally of 51 unique articles. The abstracts of all these journals underwent thorough examination, and relevant papers were bookmarked for subsequent evaluation. The study rested on an 11-year limit as the key determinant for inclusion and exclusion. After fulfilling this requirement, a thorough analysis of 45 journal articles was carried out to ascertain their relevance to the research topic. During this phase, 3 journals were excluded on the grounds that the study solely prioritized peer-reviewed articles. We rigorously examined 42 peer-reviewed journals to establish their eligibility for inclusion in this analysis. 2 of these journals were deemed negligible as they did not contribute to the identification of keywords. As a result, the research strategy used 40 publications that were cited and referenced in this review (Figure 1).

2. The interaction between AMF and plant pathogens: Findings from Previous Studies

2.1. The impact of AMF colonization on plant disease resistance

In the study conducted by Ma et al., the measurement and analysis of root exudates and allelopathic effects of maize were carried out following colonization by arbuscular mycorrhizal fungi (AMF) [18]. Furthermore, the enzymatic robustness and microbial variety of maize rhizosphere soil were also assessed. The results unveiled that AMF colonization exerted significant effects on diverse facets of plant-microbe interactions. One of the primary conclusions was that AMF colonization resulted in a reduction of allelopathy indexes on seedling growth. Allelopathy is the term used to describe the capability of plants to produce chemicals that hinder the growth of neighboring plants. This decrease in allelopathic effects implies that AMF colonization may augment plant growth by reducing competition from neighboring plants [18] [Table 1]. Moreover, the study revealed that AMF colonization led to heightened enzymatic activities in the rhizosphere soil. Enzymes like dehydrogenase, sucrase, cellulase, polyphenol oxidase, and neutral protein exhibited elevated activity levels in soils linked to maize roots colonized by AMF. These enzymes perform vital functions in the cycling of nutrients and decomposition of organic matter, suggesting an enhancement in soil health as a result of AMF colonization. In summary, this study underscores the advantageous effects of AMF colonization on both plant growth and soil health [18]. Through the reduction of allelopathic effects and enhancement of enzymatic activities, AMF can play a role in sustainable agriculture practices by fostering plant-microbe interactions and enhancing soil fertility. However, Ma and research peers indicate that additional investigation is required to comprehensively comprehend the mechanisms underlying these advantageous effects and optimize their implementation in agricultural systems.

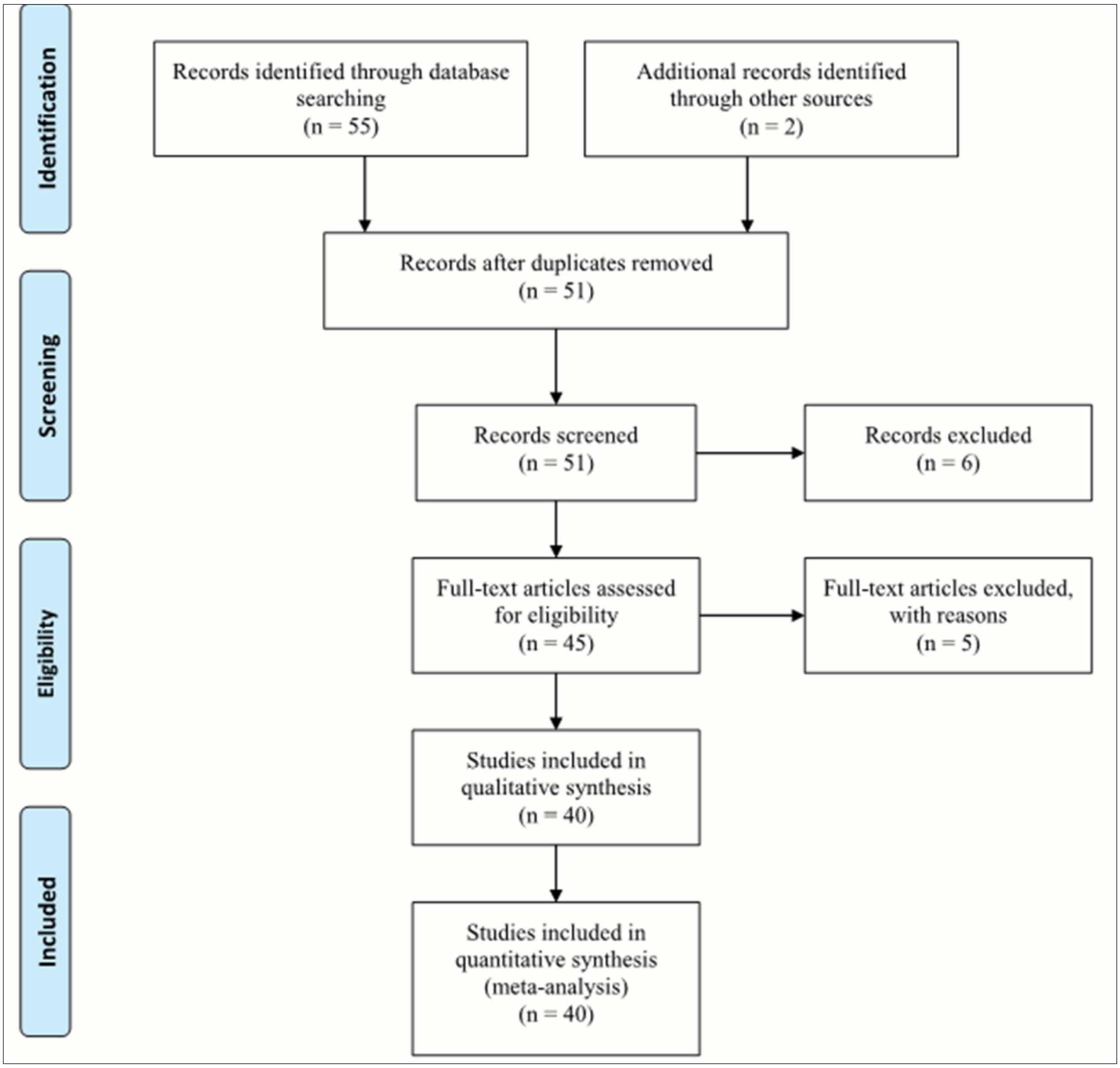

Figure 1 PRISMA diagram showing how papers were selected, excluded and included

The study conducted by Weng et al. unveiled that AMF not only enhances soil fertility but also augments water-holding capacity and mitigates erosion. Additionally, AMF fosters the proliferation of advantageous microorganisms in the soil [1] [Table 1]. These microorganisms play an integral role in the decomposition of organic matter and the release of nutrients for plant absorption. Furthermore, they contribute to the suppression of diseases through resource competition with pathogenic microorganisms. The findings of this study underscore the relevance of including AMF in agricultural approaches. By enhancing soil properties and fostering the proliferation of beneficial microorganisms, farmers can bolster crop productivity while decreasing reliance on chemical fertilizers and pesticides. In summary, Weng et al.'s study reveals the extensive benefits derived from the incorporation of AMF in agriculture. From enhancing soil properties to regulating nutrient distribution and establishing plant defense mechanisms, AMF proves to be an indispensable resource for sustainable agricultural methods.

In the study conducted by Pu et al., it was discovered that mycorrhizal colonization can provide protection for Salvia Miltiorrhiza Bunge, a plant susceptible to Fusarium wilt disease. This colonization not only improves the protein content of the plant but also enhances defense enzyme activities and defense-related genes [19] [Table 1]. The study revealed a notable rise in protein content within the Salvia Miltiorrhiza Bunge plant when it was colonized by mycorrhizal fungi. Proteins play a crucial role in numerous physiological processes in plants, such as their defense mechanisms against pathogens. The increased protein content signifies an enhanced capacity of the plant to fend off Fusarium wilt. Moreover, mycorrhizal colonization additionally resulted in heightened defense enzyme activities in Salvia Miltiorrhiza

Bunge. These enzymes have a crucial function in safeguarding plants against pathogen invasion by degrading harmful compounds generated by pathogens or triggering defense mechanisms within the plant [19]. Furthermore, mycorrhizal colonization elicited the upregulation of defense-related genes in Salvia Miltiorrhiza Bunge. These genes are responsible for producing proteins that aid in the plant's defense mechanisms. The augmented expression of these genes implies an elevated capacity of the plant to withstand Fusarium wilt. Overall, Pu et al.'s study showcases the protective potential of mycorrhizal colonization against Fusarium wilt disease in Salvia Miltiorrhiza Bunge. This protection is attained through enhancing protein content, defense enzyme activities, and the expression of defense-related genes. These findings offer invaluable insights into potential strategies for the management of Fusarium wilt and the protection of susceptible plant species. Pu et al. recommend that additional investigation in this field could result in the advancement of pragmatic approaches for agricultural practices focused on the prevention and management of this destructive illness.

In another investigation conducted by Song et al., it was revealed that mycorrhizal colonization greatly contributes to improving tomato's resistance against early blight [20]. The researchers discovered that disease resistance, which is primed by mycorrhiza, is accomplished through the priming of the systemic defense response, with the JA signaling pathway playing a crucial role in this mechanism [Table 1]. Early blight, a globally prevalent and destructive disease, is caused by the fungus *Alternaria solani* and primarily targets tomatoes. It results in leaf spots, loss of foliage, and decreased yield. Thus, the development of successful techniques to counteract this disease is essential for tomato producers. The study showed that mycorrhizal colonization initiates a systemic defense response in tomato plants [20]. This implies that not only are the roots safeguarded against infection, but other components of the plant also develop heightened resistance to early blight. The researchers noted heightened expression of defense-related genes and build-up of defense-related compounds in mycorrhizal plants. Additionally, they discovered that the JA signaling pathway is crucial for this mycorrhiza-induced disease resistance. According to [20], this pathway is responsible for regulating diverse defense responses in plants and is recognized for its indispensable role in combating pathogens. In general, these findings emphasize the possibility of utilizing mycorrhizal colonization as a sustainable tactic to augment tomato resistance against early blight. By comprehending the intricate mechanisms at play in this process, scientists can devise specialized strategies to safeguard crops from this catastrophic ailment.

Chen et al. conducted a study investigating how Glomus Versiforme (GV) and Glomus Mosseae (GM) affect the growth and disease resistance of the invasive plant Wedelia Trilobata, with different nutrient conditions being considered. The results unveiled that both GV and GM had a significant positive impact on the growth of W. Trilobata under low-nutrient conditions compared to control groups without AMF inoculation [21] [Table 1]. Furthermore, these fungi bolstered disease resilience in W. Trilobata, indicating a potential mechanism for their prosperous colonization of particular ecosystems. These results underscore the significance of factoring in belowground interactions during the examination of invasive plant species. The impact of AMF on plant growth and defense mechanisms can significantly influence ecosystem dynamics and management strategies targeting invasive species [21]. In summary, Chen et al.'s study reveals valuable findings on the role of AMF in stimulating the growth and pathogenic defense of W. Trilobata under nutrient-poor conditions, contributing to its successful invasion into certain ecosystems. More in-depth study is necessary to gain a complete understanding of the underlying mechanisms behind these interactions and devise successful tactics for managing invasive species like W. Trilobata.

In the study conducted by Berdeni et al., commercial scions and rootstocks were employed to investigate the effects of industrial standard fertilizers on apple orchards. The results of this research unveiled multiple noteworthy discoveries, encompassing diminished arbuscular mycorrhizal fungi (AMF) colonization and root biomass, heightened resistance to *Neonectria ditissima*, and negligible alterations in leaf nutrient levels [22] [Table 1]. One of the pivotal findings in this study was the decline in AMF colonization and root biomass. AMF plays a vital role in optimizing nutrient absorption by plants through their symbiotic connection with roots. The decrease in AMF colonization implies that the application of industrial standard fertilizers could interfere with this advantageous symbiosis, potentially resulting in reduced nutrient uptake by apple trees. Additionally, the study discovered that apple trees treated with these fertilizers demonstrated heightened immunity against *Neonectria ditissima* [22]. This discovery is of great significance, as *Neonectria ditissima* is a prevalent pathogen responsible for canker formation on apple trees, resulting in substantial financial implications for orchard proprietors. The findings of this research indicate that the application of industrial standard fertilizers might contribute positively to disease management due to the observed enhanced resistance. Surprisingly, there were no substantial alterations observed in leaf nutrient levels after the application of fertilizer. This suggests that while there may be modifications happening at the foundational level as a result of fertilizer usage, it does not directly result in adjustments in leaf nutrient composition [22]. Overall, Berdeni et al.'s study sheds light on the significance of industrial standard fertilizers on apple orchards. The findings underscore possible disadvantages such as diminished AMF colonization and root biomass, while also unveiling benefits like heightened resistance to *Neonectria* *ditissima*. Nevertheless, it is imperative to conduct additional research in order to fully grasp the far-reaching implications of these discoveries and establish sustainable methods for the management of apple orchards.

The research carried out by Hoz et al. explored how light intensity affects plant nutrition and resistance to *Botrytis cinerea* in lettuce plants. The researchers observed that increased light intensities led to improved establishment and growth of mycorrhiza in lettuce plants [6] [Table 1]. This indicates that the presence of sufficient light is crucial for the establishment of this advantageous connection. Moreover, the study unveiled that heightened light intensities were linked to increased nutrient content in lettuce plants. This indicates that the strength of light positively influences plant nourishment by enhancing nutrient absorption through mycorrhizal partnerships. In a surprising discovery, researchers found that mycorrhiza-induced resistance to *Botrytis cinerea* can occur independently of its effect on plant nutrition [6]. This implies that plants can exhibit increased pathogen resistance even without significant nutrient changes from mycorrhizal associations. Generally, this study emphasizes the significance of light intensity in controlling mycorrhiza establishment, growth, and nutrient composition in lettuce plants. It also emphasizes the potential for separating mycorrhizal impacts on plant nutrition from its induced resistance against pathogens like *Botrytis cinerea*. However, a more exhaustive examination is needed to fully comprehend the intricate connections among light intensity, mycorrhizal associations, and plant health.

2.2. The role of AMF in the initiation of systemic defense responses

In a recent study conducted by Dreischhoff et al., it was revealed that chitin plays a crucial role in triggering local tissue defense mechanisms. Chitin, an intricate polysaccharide, is present in the cell walls of fungi and insects, and has demonstrated the ability to elicit immune reactions in plants. Additionally, the research indicates that aboveground tissues trigger an immune response through unidentified signals [23] [Table 1]. This signifies that there are still many areas of plant defense that necessitate additional investigation and understanding. The identification of these signals has the potential to lead to the development of innovative strategies for bolstering plant resistance to diseases. Another intriguing discovery from Dreischhoff et al.'s studies is the potential role of volatile organic compounds (VOCs) in intercommunication between below and aboveground tissues. VOCs are tiny molecules discharged by plants to establish communication with other organisms. Dreischhoff et al. state that gaining comprehension of how VOCs facilitate interactions among various components of the plant could yield valuable insights into plant defense mechanisms [23]. In addition to VOCs, Dreischhoff et al.'s research emphasizes the significance of jasmonate signaling in the leaves of EMF-colonized plants. Jasmonates belong to a group of plant hormones that play a role in diverse physiological processes, such as defense mechanisms. The activation of jasmonate signaling triggers changes in secondary and nitrogen-based defense metabolism, ultimately bolstering a plant's ability to fend off pathogens [23]. In general, Dreischhoff et al.'s studies have made substantial contributions to our comprehension of plant defense mechanisms. The identification of chitin as a catalyst for local tissue defenses and the exploration of unidentified triggers for immune responses offer innovative research possibilities. Exploring the involvement of VOCs in inter-tissue communication and understanding the impact of jasmonate signaling on metabolic alterations can advance our comprehension of plants' defense mechanisms against threats.

A study conducted by Cameron et al. has illuminated a captivating phenomenon called 'mycorrhiza-induced resistance' (MIR), demonstrating that plants establish a systemic defense against diverse assailants when infected by AMF [24] [Table 1]. Cameron et al. show that plants, upon being infected with AMF, display both direct responses to the fungal infection and indirect immune responses to ISR-eliciting rhizobacteria in the mycorrhizosphere. The integration of fungal stimulation and indirect immune responses plays a critical role in MIR development. Mycorrhizal fungi establish symbiotic associations with plant roots, thereby facilitating nutrient absorption and augmenting plant growth [24]. This study emphasizes an extra advantage of this connection, which is the plants' capability to fend off potential aggressors. The activation of MIR confers systemic protection to plants, enhancing their resistance against diverse pathogens and pests. This research unveils novel pathways for comprehending plant defense mechanisms and presents potential implications in agriculture. Through harnessing the potential of AMF-induced resistance, farmers can decrease their dependence on chemical pesticides and encourage sustainable farming practices [24]. In conclusion, Cameron et al.'s study unveils the captivating concept of mycorrhiza-induced resistance (MIR) in plants. This model incorporates direct plant responses to mycorrhizal infection as well as indirect immune responses to ISR-eliciting rhizobacteria in the mycorrhizosphere. The activation of MIR offers systemic protection against multiple attackers, presenting promising opportunities for sustainable agriculture practices. More extensive research is necessary to fully comprehend the mechanisms behind MIR and its potential applications in crop production.

In Gao et al.'s study, it was discovered that the spontaneous colonization of rhizobia and arbuscular mycorrhizal fungi (AMF) can exert a noteworthy influence on soybean red crown rot, particularly in the absence of phosphorus supplementation. The researchers observed that the inoculation of soybean plants with either rhizobia or AMF resulted in a significant reduction in disease severity and incidence [25] [Table 1]. It was noted that the most optimal outcomes were achieved with the simultaneous inoculation of rhizobia and AMF at minimal phosphorus levels. Moreover, the study also uncovered that root exudates played a pivotal role in suppressing pathogen proliferation and reproduction. Root exudates are chemical compounds that plants secrete from their roots into the soil, exerting a range of impacts on nearby microorganisms [25]. In this instance, it was discovered that these exudates exhibited inhibitory properties against the proliferation and propagation of pathogens accountable for inducing red crown rot. These findings carry substantial implications for soybean farmers as they propose potential tactics for red crown rot management that reduce dependence on phosphorus fertilizers. By actively promoting the natural inoculation of rhizobia and AMF and fostering root exudation, farmers may potentially mitigate disease severity and occurrence in their crops [25]. This not only brings economic advantages but also aids in sustainable agriculture practices by minimizing the use of chemicals. Overall, Gao et al.'s study underscores the significance of natural inoculation with rhizobia and AMF in the management of soybean red crown rot. The research highlights the significant decrease in disease severity through the co-inoculation of these beneficial microorganisms with low phosphorus levels. Moreover, root exudates were detected to hinder pathogen growth and reproduction to a greater extent. These findings offer valuable insights into potential strategies for disease management in soybean crops, while simultaneously promoting sustainable agricultural practices.

White rot is a significant garlic disease that poses a threat to the crop's productivity and quality. In order to combat this disease, researchers have delved into various methods of control. In a pot experiment conducted by Rashad et al., it was noted that the simultaneous application of *Bacillus amyloliquefaciens* GGA and AMF led to a more significant decrease in disease occurrence and intensity in comparison to individual treatments [26] [Table 1]. This implies that the combination of these two treatments exhibits a synergistic impact on the regulation of rot. Moreover, the combination treatment exhibited beneficial impacts on the growth of garlic plants. It was discovered that treated plants displayed heightened total phenol levels, recognized for their antimicrobial characteristics. The potential rise in phenol content might have played a role in decreasing the frequency and intensity of decay [26]. In addition, the dual treatment yielded enhanced overall plant growth. Garlic plants subjected to treatment with *Bacillus amyloliquefaciens* GGA and AMF displayed increased vigor and development when compared to untreated plants. This indicates that these treatments not only manage disease but also foster optimal plant development. In summary, the study conducted by Rashad et al. presents valuable insights into efficient methods for controlling garlic rot. The combination of *Bacillus amyloliquefaciens* GGA and Arbuscular Mycorrhizal Fungi demonstrates efficacy in mitigating disease occurrence and intensity while enhancing plant growth.

2.3. The mechanisms of tripartite interactions between AMF, plants, and pathogens

The study conducted by Wilkes et al. unveiled noteworthy disparities in wheat plant growth in arable soils, attributed to diverse inocula treatments and seedbed preparation methods. The research focused on the effects of *B. Amyloliquefaciens*, when used as a singular inoculant and blended with *R. Intraradices*, on wheat plant growth [27]. The findings of this study highlighted the utilization of *B. Amyloliquefaciens* as the only inoculant had a favorable impact on the growth of wheat plants. However, when mixed with *R. Intraradices*, the impact was even more pronounced. This indicates that the amalgamation of these two inoculation treatments has the ability to augment wheat plant growth in arable soils obtained from the field [27] [Table 1]. The study also investigated the impact of different seedbed preparation methods on the growth of wheat plants. Plant growth was discovered to be impacted by both traditional and zero tillage methods, with the precise influence varying depending on the type of inoculation treatment applied [27]. Overall, this research highlights the significance of using precise inoculation treatments and implementing suitable seedbed preparation methods to enhance wheat plant growth in arable soils acquired from the field. By understanding these factors and implementing them skillfully, farmers can boost crop yield and make a substantial contribution to the advancement of sustainable agricultural practices.

The study by Afkhami et al. emphasizes the critical role of diverse microbial communities in influencing plant health, productivity, and function. These mutually beneficial relationships have been discovered to augment nutrient absorption, bolster resistance against pathogens, enhance stress resilience, and foster overall development [28] [Table 1]. Through a comprehensive analysis of plant species in various environments, the researchers uncovered the context-specific nature of microbial mutualist influence. It was discovered that biotic factors, such as surrounding vegetation and herbivorous animals, can significantly impact these interactions. Furthermore, the study explored the molecular basis of tripartite interactions between plants and their associated microbes [28]. It discovered critical signaling pathways and genetic mechanisms that support communication between these organisms. Understanding these molecular processes creates a framework for designing tactics to improve agricultural productivity or minimize adverse effects on ecosystems. In general, this study highlights the crucial role of microbial mutualists in shaping plant performance. It elucidates the intricate relationship between diverse microbial communities and different aspects of plant health and productivity, encompassing biotic and abiotic factors.

In a groundbreaking study conducted by Mashabela et al., it was exposed that plant-microbe interactions unfold through chemical communications in the rhizosphere. The study revealed an intricate interplay among plants, pathogenic microbes, and plant-beneficial microbes [29] [Table 1]. The rhizosphere is the soil region encompassing plant roots that harbors a multitude of microorganisms. The study discovered that plants emit distinct chemical signals into the rhizosphere to attract advantageous microbes while repelling pathogens. These chemical signals play a role in facilitating communication between plants and microbes [29]. Furthermore, the research emphasized the significance of a three-way interaction mechanism in influencing plant health. Pathogenic microbes strive to colonize plant roots and inflict damage, whereas beneficial microbes engage in resource competition and offer protection against pathogens. This intricate balance dictates whether a plant thrives or succumbs to infection [29]. Gaining an understanding of these interactions unlocks fresh possibilities for sustainable agriculture practices. By utilizing chemical signaling in the rhizosphere, farmers can cultivate advantageous microbial populations surrounding their crops to augment growth and safeguard against diseases. Overall, Mashabela et al.'s study yields valuable insights into the communication dynamics between plants and microorganisms in their immediate surroundings. Through unraveling this complex network of interactions, it is feasible to develop innovative strategies to improve crop yield while reducing reliance on harmful practices.

3. Potential for Future Research

3.1. Investigating the precise mechanisms through which AMF colonization influences plant disease resistance

Table 1 Summary of results from previous studies on the interaction between AMF and plant pathogens

Interaction mechanism of AMF and plant pathogens	Effect of the interaction mechanism	Reference
Impact of AMF colonization on plant disease resistance	AMF result in a reduction of allelopathy indexes	[18]
	AMF suppress diseases through resource competition	[1]
	AMF enhance defense enzyme activities and defense-related genes	[19]
	AMF initiate a systemic defense response in tomato plants	[20]
	AMF bolster disease resilience in W. Trilobata	[21]
	AMF heighten resistance to *Neonectria ditissima*	[22]
	AMF induce resistance to *Botrytis cinerea* in lettuce plant	[6]
Impact of AMF in the initiation of systemic defense responses	AMF chitin play a crucial role in triggering local tissue defense mechanisms	[23]
	AMF activate MIR that offers systemic protection to plants	[24]
	AMF reduce the disease severity of soybean red crown rot	[25]
	AMF reduce the occurrence of white rot in garlic	[26]
Tripartite interactions between AMF, plants, and pathogens	AMF amalgamation enhance the growth of wheat plants	[27]
	Diverse AMF microbial communities influence plant health	[28]
	Plant-AMF microbe interactions repels pathogens	[29]

The link between arbuscular mycorrhizal fungi (AMF) and plant diseases has triggered considerable intrigue in the current age. Despite significant advancements in understanding the extensive impacts of AMF colonization on plant disease protection, further investigations are required in this field [30,31]. One aspect of research concentrates on the explicit ways in which AMF colonization impacts the safeguarding of plants against diseases. Different plant and pathogen species may display unique responses to AMF, requiring a thorough investigation of these interactions [32]. Through the examination of plant and pathogen reactions to AMF colonization, we can enhance our understanding of the fundamental mechanisms involved in disease resistance. Moreover, delving into a wide range of AMF species enables us to augment our comprehension of this interaction. There is a wide range of AMF species, each possessing unique traits and abilities. Studying the interaction between different AMF species, plants, and pathogens can yield valuable insights into the intricacies of this association.

3.2. Elucidate the signaling pathways and biochemical factors involved in the induction of systemic defense responses by AMF

Another area that necessitates attention is clarifying the signaling pathways implicated in the induction of systemic defense responses by AMF. It is widely acknowledged that AMF has the ability to activate multiple genes associated with plant defense, resulting in an augmented immunity against detrimental microorganisms [33]. However, the precise mechanisms underlying this initiation are still not fully comprehended. Through the examination of these signaling pathways, we can acquire a more profound comprehension of how AMF regulate plant defense responses. Moreover, delving into the biochemical factors implicated in this process can offer valuable insights into the intricate interaction between AMF and plant pathogens. For example, recent research has proposed that particular metabolites synthesized by AMF could have an essential role in initiating plants' defense mechanisms against pathogens. Acquiring knowledge about these biochemical factors can facilitate the creation of new tactics for disease management and crop preservation.

3.3. Exploring the role of AMF in modulating plant immune responses and understanding the interactions between AMF and specific pathogen species

Arbuscular mycorrhizal fungi (AMF) establish mutualistic relationships with plant roots, exchanging nutrients for carbohydrates. Nevertheless, their role in modulating plant immune responses and their interactions with specific pathogen species remain largely unexplored [34]. Investigating the relationship between AMF and plant immune responses can contribute to a more comprehensive understanding of both plant defense mechanisms and fungal biology. It is widely acknowledged that AMF can bolster a plant’s resistance to pathogens, however, the underlying mechanisms remain poorly comprehended [35,36]. Through the investigation of the molecular pathways implicated in this interaction, researchers can gain fresh insights into plant defense mechanisms against pathogens. Additionally, investigating the interactions between AMF and particular pathogenic species can yield valuable insights for devising sustainable approaches to manage plant diseases. In some studies, it has been demonstrated that particular AMF species can suppress the growth of pathogens or stimulate systemic resistance in plants [37]. By identifying the key factors responsible for these effects, scientists may be able to develop novel biocontrol methods or enhance crop resistance through targeted manipulation of AMF communities.

3.4. Investigating the potential of using AMF as biocontrol agents to manage plant diseases sustainably

AMF have been recognized for their ability to enhance plant resistance against diverse pathogens by triggering systemic defense responses [38]. Nevertheless, the mechanisms that drive this phenomenon remain incompletely comprehended. Additional research can illuminate the precise signaling pathways implicated in AMF-induced disease suppression, offering valuable insights into the formulation of efficient biocontrol tactics. Exploring the potential of AMF as biocontrol agents can enhance our comprehension of their interactions with plants and pathogens. By examining their impacts on various pathogen species, scientists can pinpoint specific AMF strains that display robust antagonistic activity against important plant diseases. This knowledge can subsequently be employed to cultivate precise biocontrol strategies that are both eco-friendly and enduring. Likewise, researching on the utilization of AMF as biocontrol agents can enrich our understanding of their ecological roles in indigenous environments. Acquiring an in-depth knowledge of the intricate correlation between these fungi, other soil microorganisms, and their integral role in preserving ecosystem health is vital for designing sustainable agricultural tactics.

3.5. Evaluating the impact of different ecological components, such as soil conditions and nutrient availability, on the interaction between AMF, plants, and pathogens

Studies have indicated that certain plant pathogens can leverage this symbiotic association to their benefit by manipulating AMF colonization or suppressing their advantageous impacts [39,40]. A comprehensive understanding of how different environmental factors modulate the interaction between AMF, plants, and pathogens is pivotal in the formulation of sustainable agricultural practices. For example, soil conditions such as pH levels or organic matter content can have a substantial impact on the abundance and diversity of AMF communities. Through studying the influence of these factors on pathogen infection rates or disease severity in plants colonized by AMF, it is possible to discover approaches to bolster plant resistance against detrimental pathogens. Additionally, the availability of nutrients is another pivotal factor that affects this tripartite interplay. Nutrient deficiencies or imbalances have the potential to compromise plant defenses against pathogens or modify the composition of AMF communities. Studying the impact of nutrient availability on disease development in mycorrhizal plants will offer valuable insights for optimizing fertilizer management to enhance plant growth and disease resistance.

4. Conclusion

The intricate interplay among AMF, plants, and pathogens is an intriguing and ever-evolving area of study. Assessing the influence of AMF colonization on plant disease resistance, exploring their involvement in systemic defense responses, and examining the mechanisms of tripartite interactions are crucial for the development of sustainable disease management strategies and the enhancement of crop health. By conducting more extensive research and gaining a deeper understanding, we can tap into the advantages of the AMF-plant-pathogen relationship to mitigate crop diseases and enhance agricultural productivity.

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