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Role of Mycorrhizal Associations in Wheat Nutrition

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Abstract This study mainly talks about a microorganism called arbuscular mycorrhizal fungi (AMF) to see if it helps wheat nutrition. Many studies have found that AMF can help wheat absorb nutrients better, such as potassium, phosphorus, and nitrogen. In places with less nutrients or bad environment, such as potassium-deficient and saline-alkali land, wheat and AMF perform better together. Not only does it grow faster, but it also increases yield and has stronger ability to resist bad environment. The role of AMF is not only to help the root system absorb minerals, but also to affect the expression of some genes, making wheat's antioxidant capacity and disease resistance stronger. It can also make the nutrients in wheat grains better and the protein structure more reasonable, which is helpful for grain quality. Another benefit of AMF is that it can improve soil health, allowing farmers to grow good fields with less fertilizer, which is very meaningful for environmental protection and sustainable agriculture. Different varieties of wheat may have different effects when used with different types of AMF. Sometimes it may also make some trace elements less easily available to wheat. AMF has great potential in improving wheat nutrition, yield and adaptability to the environment, and is a good helper for achieving green agriculture.
Keywords Arbuscular mycorrhizal fungi; Wheat nutrition; Mineral absorption; Yield improvement; Sustainable agriculture

1 Introduction

Arbuscular mycorrhizal fungi (AMF) are soil microorganisms that live with the roots of most terrestrial plants. They establish a "mutual help" relationship with plant roots, called "mycorrhizal symbiosis". In this relationship, plants can more easily absorb nutrients from the soil, especially when nutrients are insufficient, this help is more obvious (Fiorilli et al., 2018; Ganugi et al., 2019Han et al., 2025). AMF can help plants absorb key elements such as nitrogen, phosphorus, and potassium. In exchange, they obtain sugars produced by photosynthesis from plants to sustain their own life activities (Ganugi et al., 2019; Thirkell et al., 2019; Han et al., 2025).

Wheat (*Triticum aestivum* L.) is one of the most important grains in the world. Many people rely on it as a staple food, and it is crucial to ensuring the global food supply (Fiorilli et al., 2018; Akbar et al., 2023; Ganugi et al., 2019). However, people often encounter some problems in the process of growing wheat. In particular, insufficient important elements such as nitrogen and phosphorus will affect wheat yields and may also make the grains less nutritious (Thirkell et al., 2019; Tran et al., 2019; de Souza Campos et al., 2021; Han et al., 2025). Traditionally, farmers use a lot of fertilizers to make wheat grow well. However, this will make the soil worse and may pollute the environment. Therefore, people are now paying more and more attention to some more environmentally friendly practices (Ganugi et al., 2019; Akbar et al., 2023). In recent years, scientists have begun to study the effects of AMF on wheat more and more. The results of the study found that AMF can indeed allow wheat to absorb more nitrogen, phosphorus, potassium and other nutrients, enhance resistance, and help wheat grow faster and produce higher yields. At the same time, it will also improve the quality of minerals and proteins in the grains (Abdel-Fattah and Asrar, 2012; Fiorilli et al., 2018; Ganugi et al., 2019; de Souza Campos et al., 2021; Akbar et al., 2023; Xue et al., 2024b; Han et al., 2025). AMF can also improve soil health and help reduce dependence on chemical fertilizers, which is very meaningful for sustainable development (Ganugi et al., 2019; Akbar et al., 2023).

This review is to systematically sort out the relationship between AMF and wheat roots, and how it affects wheat nutrition. The focus will be on how it helps wheat absorb nitrogen, phosphorus, and potassium, how to improve yield and quality, how to enhance resistance, and how to improve the soil environment. By analyzing representative studies in the past two decades, we look at the application prospects of AMF in wheat cultivation, and also discuss the challenges and opportunities it may encounter in the development of green agriculture.

2 Types and Biology of Mycorrhizal Associations

2.1 Overview of mycorrhizal types (with emphasis on AMF)

In major food crops like wheat, the most common type of mycorrhiza is arbuscular mycorrhiza, also known as AMF (Arbuscular Mycorrhizal Fungi). It belongs to the Glomeromycota group of fungi. AMF can establish a mutually helpful relationship with wheat, helping the plant to better absorb minerals, enhance resistance, and improve yield and quality (Fiorilli et al., 2018; Ganugi et al., 2019; Akbar et al., 2023). In farmland, AMF is the most common type of mycorrhiza in wheat. Types such as ectomycorrhiza are rarely seen in grasses (Ganugi et al., 2019).

2.2 Morphological and functional features of AMF in wheat roots

AMF forms three typical structures in wheat roots: arbuscules, vesicles, and hyphae. Arbuscules are where it exchanges nutrients with plant cells. Mycelium extends into the soil outside the roots to help the roots expand their absorption range (Fiorilli et al., 2018; Akbar et al., 2023; Han et al., 2025). AMF allows wheat to absorb more nutrients such as potassium, phosphorus, iron and zinc, especially in soils with low nutrients (Abdel-Fattah and Asrar, 2012; Watts-Williams and Gilbert, 2021; Akbar et al., 2023; Han et al., 2025). In addition, AMF also affects the expression of some transporter-related genes in the roots, thereby improving the antioxidant and stress resistance of wheat.

2.3 Life cycle and colonization process of AMF

The life process of AMF includes several stages: spore germination, hyphae growth, root entry, arbuscular formation and vesicle formation. Spores begin to germinate in the soil, hyphae will grow towards the wheat roots, then penetrate the outer layer of the roots, and finally form arbuscular formation in the root cortex, thereby exchanging nutrients with the plant (Abdel-Fattah and Asrar, 2012; Fiorilli et al., 2018). The colonization process of AMF is affected by many factors, such as soil conditions, plant genes, and the type of AMF itself. Different types of AMF also have different colonization abilities and effects (Abdel-Fattah and Asrar, 2012; Thirkell et al., 2019; de Souza Campos et al., 2021).

2.4 Host-specificity and diversity of AMF species relevant to wheat

Wheat can form symbiosis with many AMF species, such as Rhizophagus, Claroideoglomus, and Glomus (Abdel-Fattah and Asrar, 2012; de Souza Campos et al., 2021; Akbar et al., 2023; Han et al., 2025). Different wheat varieties respond differently to AMF. Some varieties have high colonization rates, better nutrient absorption efficiency, and more obvious growth effects (Thirkell et al., 2019; de Souza Campos et al., 2021). The diversity of AMF species also affects their ability to promote wheat growth and nutrient absorption. Some AMF are particularly helpful for certain nutrients and may also change the morphology of wheat roots (Thirkell et al., 2019; de Souza Campos et al., 2021; Akbar et al., 2023). The host selection and species diversity of AMF are important foundations for achieving efficient nutrient utilization in wheat and promoting green agricultural management (Ganugi et al., 2019; Thirkell et al., 2019; de Souza Campos et al., 2021).

3 Mechanisms of Nutrient Uptake Enhancement

3.1 Role of AMF in improving uptake of key macronutrients (P, N, K)

Arbuscular mycorrhizal fungi (AMF) can coexist with wheat roots, and this relationship can significantly improve wheat's ability to absorb phosphorus (P), nitrogen (N) and potassium (K). Especially in the case of potassium deficiency, AMF can regulate the expression of related genes and help the roots absorb more potassium. This not only makes wheat grow better, but also enhances its antioxidant capacity (Abdel-Fattah and Asrar, 2012; Han et al., 202). Different wheat varieties and environmental conditions will have differences in the absorption of nitrogen and phosphorus, but most of the time, AMF can pass these nutrients to wheat through the symbiotic pathway, improving its overall nutritional level (Abdel-Fattah and Asrar, 2012; Thirkell et al., 2019). In field trials, after wheat was inoculated with AMF, the phosphorus and potassium contents in the grains increased by 30.9%

and 14.8%, respectively, and the protein content also increased significantly (Akbar et al., 2023).

3.2 Enhancement of micronutrient availability (Zn, Fe, Cu)

AMF not only helps absorb macronutrients, it also makes trace elements such as zinc (Zn), iron (Fe) and copper (Cu) more accessible to plants. Studies have shown that in wheat inoculated with AMF, the Zn and Fe in the grains increased by 24% and 21%, respectively (Akbar et al., 2023). Under different soil zinc contents, AMF can regulate the distribution and concentration of Zn and Fe in the grains. If there is too much soil zinc, it can also help wheat reduce the absorption of excess Zn, which has a certain protective effect (Tran et al., 2019; Watts-Williams and Gilbert, 2021). However, it should be noted that sometimes AMF will increase phytic acid in the grains, which may reduce the absorption of zinc and iron (Tran et al., 2019).

3.3 Mycorrhizal-induced changes in root architecture and physiology

AMF symbiosis can also make wheat roots different. Different types of AMF and different wheat varieties will change the growth pattern of roots, such as becoming longer, more branched, and larger in area, which can improve the efficiency of nutrient absorption (de Souza Campos et al., 2021). Some AMF can also make the roots secrete more organic acids, such as citric acid and oxalic acid. These substances can help plants absorb nutrients from the soil that are not easily utilized. AMF can also enhance the stress resistance and antioxidant activity of the roots, and allow wheat to absorb more nutrients in adverse environments such as saline-alkali (Abdel-Fattah and Asrar, 2012; Han et al., 2025).

3.4 Synergistic interactions with soil microbes

AMF does not act alone, it can also cooperate with other beneficial microorganisms in the soil, such as nitrogen-fixing bacteria and phosphate-dissolving bacteria. These microorganisms work together to make it easier for wheat to absorb nutrients and grow faster (Ganugi et al., 2019; Akbar et al., 2023). AMF can also improve the microenvironment of the rhizosphere, making it easier for beneficial bacteria to survive and move near the roots. This will increase soil fertility and facilitate nutrient cycling. This "partner-style" cooperation can not only enhance wheat's resistance to stress, but also increase its yield, which is also helpful for the development of green agriculture (Fiorilli et al., 2018; Ganugi et al., 2019; Akbar et al., 2023).

4 Mycorrhiza-Mediated Improvement in Soil Health

4.1 Contribution of AMF to soil structure and aggregation

Arbuscular mycorrhizal fungi (AMF) can improve soil structure and help form soil aggregates in many ways. Its hyphae can entangle soil particles together, and it also secretes some "glue" substances such as glucan and collagen, which can enhance the viscosity between soil particles and make the soil more stable (Fall et al., 2022; Wen and Xiao, 2025). The aggregates formed in this way can not only prevent the soil from being carried away by wind or water, but also make it easier for air and water to enter and exit the soil, which is very beneficial to plant roots (Fall et al., 2022; Kalamulla et al., 2022; Sarwade et al., 2024). In addition, the residue of AMF itself is also a natural "soil conditioner" that can increase the organic matter in the soil and continue to help the soil become healthier (Wen and Xiao, 2025).

4.2 Increased soil organic matter and microbial activity

AMF can also help increase the organic carbon and microbial species in the soil. It can promote the flow of carbon and accelerate the decomposition of organic matter (Sarwade et al., 2024; Zhang et al., 2024; Conti et al., 2025). When plants and AMF coexist, the roots will secrete more substances, which provide rich food for microorganisms, and the number and variety of microorganisms will increase (Fall et al., 2022; Bortolot et al., 2024; Ahmed et al., 2025) (Figure 1). AMF will also "summon" some beneficial bacteria, such as those that can release alkaline phosphatase, which helps to convert organic phosphorus into a form that can be absorbed by plants and improve the recycling efficiency of soil nutrients (Fall et al., 2022; Bortolot et al., 2024). A summary of studies has found that AMF can increase the organic carbon in farmland soil by 21.5% on average. However, the specific improvement depends on the texture of the soil and the original organic matter content (Conti et al., 2025).

4.3 Implications for sustainable agriculture and reduced chemical input reliance

AMF can be used as a natural biofertilizer and is very useful in developing sustainable agriculture. It can improve soil structure, increase the vitality of organic matter and microorganisms, and enhance the survival ability of plants under drought, salinity, and pests and diseases. These can help farmers use less fertilizers and pesticides (Kalamulla et al., 2022; Ahmed et al., 2025; Sarwade et al., 2024; George and Ray, 2023; Bortolot et al., 2024) (Figure 2). The use of AMF can also restore soil ecology to normal and improve crop yields and quality. This is important for ensuring the stability and security of agricultural production (Kalamulla et al., 2022; Martin and Van Der Heijden, 2024; George and Ray, 2023).

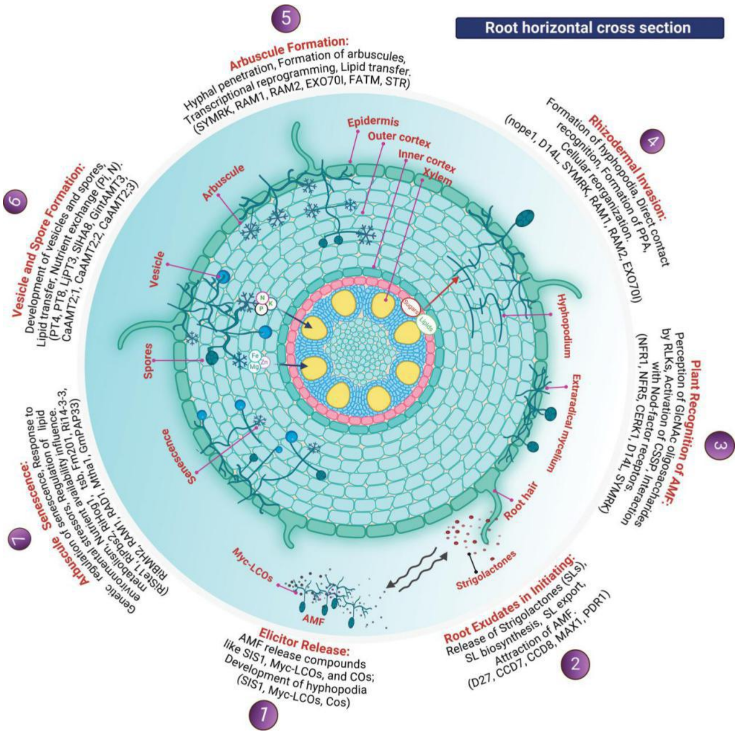

Figure 1 The sequential stages of symbiosis between plants and AM , starting from signal exchange with the release of strigolactones by the plant, to hyphal branching and colonization, leading to the establishment of arbuscules within root cortical cells for nutrient exchange (Adotped from Ahmed et al., 2025)

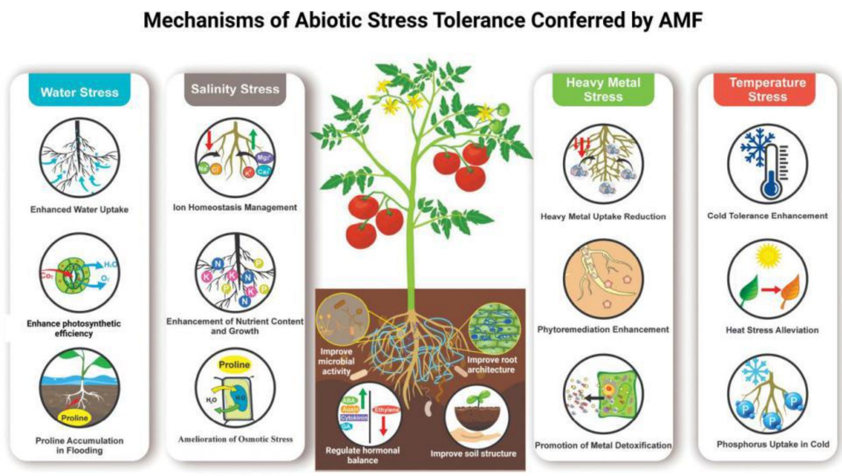

Figure 2 Schematic overview of AM -mediated key strategies to confer resistance to various abiotic stresses in host plants (Adotped from Ahmed et al., 2025)

5 Mycorrhizal Responses to Agronomic and Environmental Conditions

5.1 Influence of soil type, pH, and moisture on mycorrhizal colonization

Soil type, pH and water conditions directly affect the colonization ability of arbuscular mycorrhizal fungi (AMF) on wheat roots. Different soil and pH values will change the number and growth of AMF species, and will also affect the effect of wheat nutrient absorption and growth. If the soil is too acidic, too alkaline, too dry or too wet, it will make it more difficult for AMF to colonize and its function will be weakened. However, AMF itself has some adaptability, and they can cope with these harsh environments to a certain extent (Lenoir et al., 2016; Tedersoo and Bahram, 2019; Dhiman et al., 2022). The effect of water on mycorrhiza is particularly obvious. Appropriate humidity is conducive to the formation of mycorrhiza and helps it cooperate better with wheat (Lenoir et al., 2016; Dhiman et al., 2022).

5.2 Impact of fertilizer regimes and tillage practices

The amount and type of fertilization will affect the number and function of AMF. Generally speaking, too much nitrogen and phosphorus fertilizer will reduce the number of AMF and reduce the colonization ability. Studies have found that the number of mycorrhizae will decrease by about 32% after applying phosphorus fertilizer, and nitrogen fertilizer will decrease by 15% (Treseder, 2004). This is because when there are enough nutrients in the soil, plants are less "dependent" on AMF. This phenomenon is also called the "plant investment hypothesis." In addition to fertilization, the way of tillage also has an impact. If protective tillage methods are used, such as not deep plowing the land and planting perennial crops, it will be more conducive to the survival of beneficial bacteria and help AMF to better colonize and play a role (Jacott et al., 2017; McKenna et al., 2025). If crop varieties that are more responsive to AMF are selected in breeding, it may also help to increase crop yields and improve soil health (McKenna et al., 2025).

5.3 Environmental stresses (salinity, drought) and mycorrhizal buffering effects

When wheat encounters adverse environments such as salinity or drought, AMF can play a great role. They regulate key substances such as aquaporins and polyamines, allowing plants to absorb more water and nutrients and reduce damage (Nadeem et al., 2014; Lenoir et al., 2016; Sharma et al., 2021; Branco et al., 2022; Dhiman et al., 2022). Under these adversities, AMF can also help wheat reduce water loss, control the entry of harmful ions, and enhance the antioxidant system by regulating gene expression (Nadeem et al., 2014; Sharma et al., 2021). AMF can also work with some beneficial rhizosphere bacteria (also called PGPR), and this combination can further improve wheat's growth ability and yield in difficult environments (Nadeem et al., 2014).

6 Genetic Variability in Wheat-Mycorrhizal Symbiosis

6.1 Differences among wheat genotypes in responsiveness to AMF

Many studies have found that different wheat genotypes have significant differences when they coexist with arbuscular mycorrhizal fungi (AMF). Some varieties are more susceptible to AMF colonization and have better results. Lehnert et al. (2017) tested 94 bread wheat varieties and found that their ability to be colonized by AMF in the roots varied greatly, and this difference can be mapped to some genetic regions (QTLs). Among 127 durum wheat materials, different varieties responded differently to different AMF types, and the study divided them into 6 genetic groups (Ganugi et al., 2021). Some field experiments have also found that even with large environmental changes, the AMF colonization rates between 10 modern winter wheat varieties still show fixed differences, indicating that the genetic background of the variety itself is also important (Veršulienė et al., 2024) (Figure 3). Thirkell et al. (2022) conducted another study using a double haploid population of spring wheat and found that some genotypes grew better after symbiosis with AMF, while others grew worse, indicating that wheat's response to AMF varies greatly.

6.2 Molecular and genetic basis of AMF colonization in wheat

Scientists have found a lot of genetic information related to wheat and AMF symbiosis. Using the genome-wide association analysis (GWAS) method, people have found multiple gene regions (QTLs) related to AMF colonization. In bread wheat, the study found 6 QTLs, mainly distributed on chromosomes 3A, 4A and 7A (Lehnert et al., 2017); in durum wheat, there are 7 QTLs located on chromosomes 1A, 2B, 5A, 6A, 7A and 7B (De Vita et al., 2018). These gene regions may affect the mutual recognition between plants and fungi, protein degradation, nutrient balance and disease resistance. Some gene families are also closely related to AMF colonization, such as the LAC (laccase) and NL (nodulin-like) families. Studies have found that some LAC genes (such as *TaLAC129*) are "brake factors" for AMF colonization, and excessive expression will inhibit symbiosis. But these genes may also increase grain yield and nutrient utilization (Zhong et al., 2023; 2025). The diversity of the NL gene family is also related to the way wheat absorbs phosphorus, and some genotypes are more dependent on AMF to obtain phosphorus (Zhang et al., 2022).

6.3 Breeding for enhanced mycorrhizal responsiveness: current progress and challenges

Although current wheat breeding focuses on yield and lodging resistance, studies have found that breeding over the past 100 years has not significantly weakened the symbiotic ability of durum wheat and AMF (De Vita et al., 2018). The introduction of the Rht dwarf gene changed the colonization of AMF. The roots of wheat with the dwarf gene are more easily colonized by AMF, and the fungal structure is more complete. But at the same time, this may also reduce the phosphorus content of the plant, indicating that the benefits and disadvantages of symbiosis may have to be weighed (Alaux et al., 2024). At present, researchers have found a number of gene regions and candidate genes related to AMF response in different wheat populations, which provides an important basis for molecular marker selection and directed breeding (Lehnert et al., 2017; De Vita et al., 2018; Ganugi et al., 2021; Thirkell et al., 2022). This type of trait is controlled by multiple genes and is easily affected by the environment. When breeding, the balance between yield, nutrient utilization and symbiotic effects should be considered at the same time (Alaux et al., 2024; Veršulienė et al., 2024) (Figure 3). Some negative regulatory genes (such as TaLAC129) also remind us that when improving mycorrhizal response, we cannot ignore the impact on yield and nutrient distribution (Zhong et al., 2025). In the future, in order to breed highly responsive wheat varieties, we need to have a deeper understanding of the regulatory network, develop more accurate molecular markers, and verify them in multiple environments.

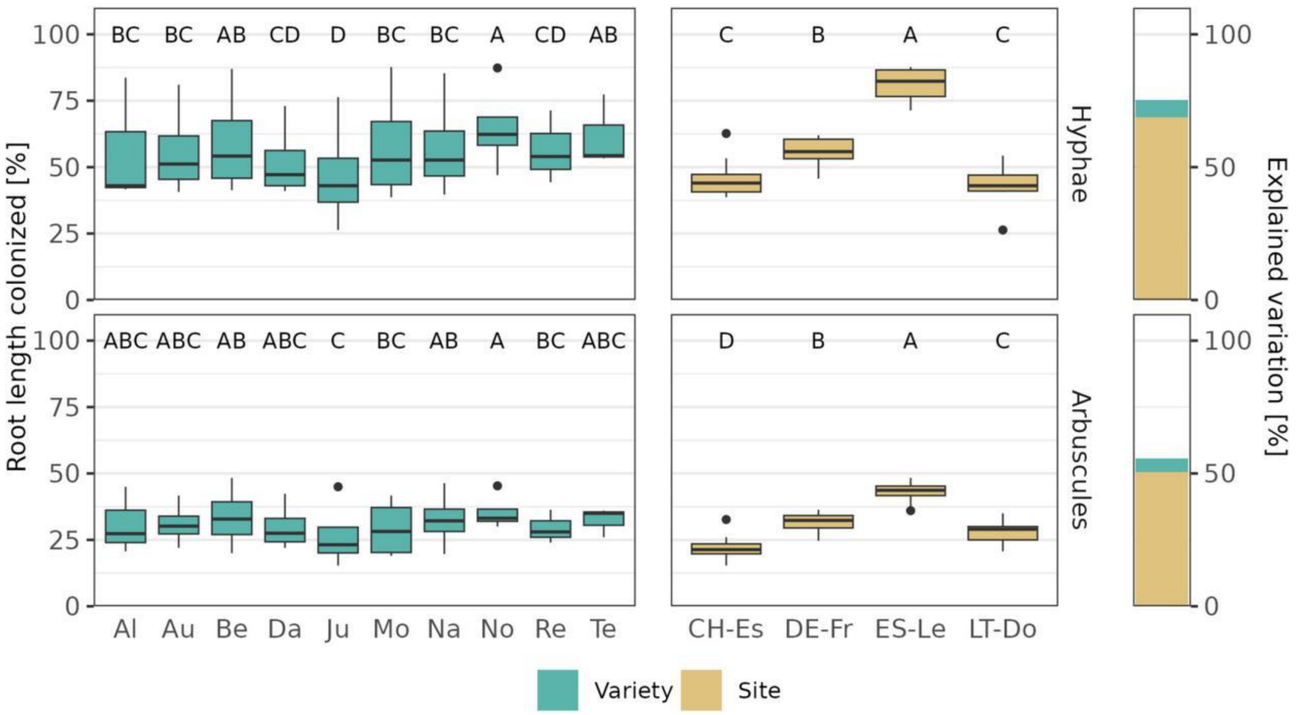

Figure 3 Hyphal and arbuscular abundance in roots of 10 winter wheat varieties grown at four European sites grouped by variety (left) or site (middle) and explained variation (LMG scores) in hyphal and arbuscular root colonization by variety and site (right). The boxplots are based on average values of three field replicates per variety: N = 3 or 4 sites per variety (left) and n = 9 or 10 varieties per site (middle). Al, Altigo; Au, Aurelius; Be, Bernstein; Da, Dagmar; Ju, Julie; Mo, Montalbano; Na, MV Nador; No, Nogal; Re, RGT Reform; Te, Tenor (Adopted from Veršulienė et al., 2024)

7 Integration of Mycorrhizal Technology in Wheat Production

7.1 Commercial AMF inoculants: strains, formulations, and field application methods

There are many commercial arbuscular mycorrhizal fungi (AMF) inoculants on the market. Common strains include Rhizophagus irregularis, Funneliformis mosseae, and some dominant strains from local sources (Oliveira et al., 2016; Duan et al., 2021; Marrassini et al., 2024). These inoculants have different forms, such as granules, powders and liquids. There are many ways to use them, such as mixing them in the soil, treating the seedbed, or coating the seeds. Seed coating is a very effective method, which not only saves dosage and cost, but also has the same effect as direct mixing with soil (Oliveira et al., 2016). After using AMF inoculants in the field, the mycorrhizal colonization rate of wheat roots will be significantly improved, and the plants can absorb more nutrients. This effect is particularly evident in fields with low fertility or water shortage (Duan et al., 2021; Elliott et al., 2021; Akbar et al., 2023; Marrassini et al., 2024; Xue et al., 2024a).

7.2 Compatibility with conventional and organic farming systems

AMF technology can be used with conventional and organic farming. In conventional farming, AMF inoculation can reduce the use of chemical fertilizers and improve fertilizer utilization efficiency, especially for the absorption of key nutrients such as nitrogen and phosphorus (Oliveira et al., 2016; ; Xue et al., 2024a). In organic farming, AMF can be used together with organic fertilizers, straw return to the field, and biochar. These combinations can make the soil have more organic carbon, more active microorganisms, and more resistant crops (Ndiate et al., 2022; Mason et al., 2025). Different wheat varieties respond differently to AMF. Choosing the right strain and inoculation method suitable for local soil and varieties will make it easier to improve yield and quality (Marrassini et al., 2024).

7.3 Cost-effectiveness and practical implementation considerations

AMF inoculants have three main benefits: saving fertilizers, increasing yields, and improving soil (Oliveira et al., 2016; Elliott et al., 2021; Akbar et al., 2023; Xue et al., 2024a). Precision delivery methods such as seed coating not only save materials, but also save money, making it more cost-effective for farmers in actual use (Oliveira et al., 2016). The inoculation effect is not static, it will be affected by some conditions, such as soil moisture, planting density and whether the variety is adaptable (Duan et al., 2021; Marrassini et al., 2024). Therefore, when promoting it, it is still necessary to customize the appropriate inoculation plan according to the actual situation. When promoting AMF, we must also consider the "persistence" of the inoculant in the field, its relationship with the original bacterial flora in the soil, and whether long-term use will have an impact on the environment. It is usually recommended to give priority to local dominant strains, or to mix several strains, which are more adaptable to the field environment and more likely to work continuously (Akbar et al., 2023; Marrassini et al., 2024).

8 Case Study: Field Trial on AMF Inoculation in Wheat

8.1 Description of location, wheat cultivar, and AMF strain used

In many field trials, researchers select local wheat varieties and inoculate them with local dominant arbuscular mycorrhizal fungi (AMF) strains. Nazir's team isolated 11 local mycorrhizal fungi from the experimental field, of which Claroideoglomus was the main species, and used them to inoculate wheat (Akbar et al., 2023). Other experiments used AMF strains such as Rhizophagus intraradices and Rhizophagus irregularis to study different wheat varieties (de Souza Campos et al., 2021; Watts-Williams and Gilbert, 2021; Han et al., 2025).

8.2 Experimental setup: control vs. AMF-inoculated plots

These experiments are generally divided into two groups: one is a control group, which is not inoculated with AMF; the other is an experimental group, which is inoculated with AMF. Several replicate samples are set up for each group, and the plot area is often 6×2 meters in size, which can ensure that the results are true and reliable (Akbar et al., 2023). Some experiments also use different AMF strains or mixed flora at the same time to observe their effects on different wheat varieties (de Souza Campos et al., 2021).

8.3 Key findings: nutrient uptake, biomass, grain yield, and soil improvement

Nutrient absorption: After inoculation with AMF, wheat has a stronger ability to absorb nutrients such as potassium, phosphorus, iron and zinc, especially the root absorption is significantly improved (de Souza Campos et al., 2021; Akbar et al., 2023; Han et al., 2025).

Biomass and yield: AMF makes wheat grow better. For example, the number of tillers increased by 49.5%, the dry matter increased by 17.4%, the grain yield increased by 21.2%, and the straw yield increased by 16.7% (Akbar et al., 2023). Some studies have also found that the protein and amino acid content in wheat grains is also higher (Fiorilli et al., 2018; Xue et al., 2024b).

Soil improvement: After inoculation with AMF, the content of organic carbon, available phosphorus and potassium in the soil also increased, by 64.7%, 35.8% and 23.9% respectively. All of these can make the soil more fertile (Akbar et al., 2023).

8.4 Economic and ecological outcomes

AMF inoculation not only improves wheat yield and quality, but also reduces the use of chemical fertilizers, which can save money and reduce pollution, making it more cost-effective for farmers (Ganugi et al., 2019; Akbar et al., 2023). From an ecological perspective, AMF can also help restore soil microbial diversity and make the soil healthier. At the same time, it can also enhance wheat's resistance to harsh environments such as salinity and drought (Abdel-Fattah and Asrar, 2012; Ganugi et al., 2019).

8.5 Lessons learned and potential for scaling

These field trials show that AMF inoculation is very helpful for wheat nutrient absorption, yield increase and soil improvement. The effect is particularly obvious in places with poor fertility or bad environment (such as drought or salinity) (Abdel-Fattah and Asrar, 2012; Han et al., 2025; Akbar et al., 2023). Different wheat varieties and AMF strains have different effects, so it is best to choose the appropriate strain and inoculation method according to the local variety and soil conditions (Thirkell et al., 2019; de Souza Campos et al., 2021).

9 Future Perspectives and Research Gaps

9.1 Need for region-specific AMF strain selection and tailored applications

Current studies have found that the cooperative relationship between wheat and arbuscular mycorrhizal fungi (AMF) is not a "universal formula". Different wheat varieties respond very differently to different AMF strains. Some varieties have significantly improved nutrient absorption and growth after being inoculated with a certain AMF, but the effect is not obvious in other varieties (Thirkell et al., 2019; de Souza Campos et al., 2021; Thirkell et al., 2022). Similarly, different AMF strains themselves have different mechanisms of action, and they have different effects on regulating wheat root morphology and nutrient transport (de Souza Campos et al., 2021). In the future, when studying and promoting AMF, we cannot "cut across the board". We need to combine local ecological conditions and wheat varieties to screen suitable strains and make "customized" inoculation strategies, so as to maximize the effect of improving nutrition and yield.

9.2 AMF interactions with plant microbiomes and fertilizers

AMF not only affects wheat itself, but also interacts with microorganisms around the roots and applied fertilizers. Studies have found that using AMF together with some beneficial growth-promoting bacteria (PGPB) can regulate wheat protein expression and immune response, help it better absorb nutrients and improve resistance. However, this effect is not the same every time. It is related to the type of microorganism used and the part of the plant (Vannini et al., 2021). AMF can also help wheat absorb nutrients such as phosphorus, iron, and zinc in fertilizers more efficiently, and can also promote the transfer of nitrogen between plants in intercropping systems (Ingraffia et al., 2019). Future research can focus on the synergistic effects between AMF and other rhizospheric microorganisms and fertilizers. Only by coordinating them well can we further improve nutrient utilization and optimize the entire nutrient management strategy.

9.3 Use of -omics technologies (metagenomics, transcriptomics) to deepen understanding

Current "omics" technologies (such as transcriptomics, proteomics, and metabolomics) provide us with new ways to understand the relationship between AMF and wheat. Through these technologies, researchers have discovered many key pathways and molecular "signals" that may control wheat growth, nutrient absorption, and disease resistance (Bernardo et al., 2017; Fiorilli et al., 2018). These findings help us establish a complete mechanism map and provide theoretical support for molecular breeding and precision agriculture in the future. In the future, further "multi-omics" joint analysis should be carried out to find more key genes and network regulatory mechanisms that control AMF-wheat interactions.

9.4 Potential role in climate-resilient wheat farming systems

In the face of climate change, wheat production increasingly needs the ability to "resist shocks". And AMF may be a powerful helper in this regard. Studies have found that AMF can help plants retain water and absorb more nutrients by regulating some proteins in wheat roots, and can also enhance drought and salt tolerance (Abdel-Fattah and Asrar, 2012; Bernardo et al., 2017; Thirkell et al., 2019). Moreover, in some "future climate" scenarios, such as under conditions of increased carbon dioxide concentration, AMF's nutritional help to wheat is still effective (Thirkell et al., 2019). In the future, we should continue to conduct in-depth research on the role of AMF in climate-resilient agriculture and apply it to more wheat production systems to promote the development of green and sustainable planting methods.

10 Conclusion

Arbuscular mycorrhizal fungi (AMF) play a very important role in wheat nutrient absorption and soil health. It can help wheat absorb nutrients such as nitrogen, phosphorus, iron, and zinc, allowing crops to grow faster and produce higher yields. AMF can also promote root development, increase organic carbon in the soil, improve soil structure, and make the microorganisms in the soil more diverse. In addition to these, AMF can also reduce the damage to wheat caused by some harmful substances, such as heavy metals such as cadmium. It can reduce the accumulation of these toxic elements in the aboveground part of wheat and improve wheat's resistance to stress. AMF can also improve wheat's water use efficiency, enhance disease resistance, and promote biological nitrogen fixation, thereby further improving wheat's overall growth performance and making the soil ecosystem more stable.

In sustainable agriculture, AMF is very useful. As a biological fertilizer, it can reduce dependence on chemical fertilizers and pesticides, reduce environmental pollution, and make the soil more fertile and the food more high-quality. It is an important helper for green agriculture and ecological agriculture. It works together with other beneficial microorganisms to lay a good foundation for the agricultural ecosystem. At present, we do not know enough about the performance of AMF under different crops, different soils and different management methods. In the future, we need to continue to study the application of AMF, select and cultivate more efficient strains, so that AMF can be truly promoted and maximize its role.

If we want AMF to truly move from the laboratory to the fields, it is not only up to scientific researchers. It also requires multidisciplinary cooperation, such as combining molecular biology, agronomy, ecology and other technologies to make the screening, propagation and management methods of AMF more perfect. At the same time, policy support and farmers' awareness of AMF are also important. As long as we combine scientific research results with actual agricultural needs, the global promotion of AMF is promising. This will lay a solid foundation for future food security, soil health and sustainable agricultural development.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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