A modern perspective of Arbuscular mycorrhizal fungi and their impact on plant disease management

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Abstract

Arbuscular mycorrhizal fungi (AMF) are essential for the health and growth of plants as they establish symbiotic relationships with most vascular plant species. In addition to their well-known roles in nutrient absorption and enhancing resilience to various stresses, AMF have demonstrated the ability to shield plants from attacks by phytopathogens, providing an ecological alternative to traditional pesticide methods. This review highlights recent progress in understanding the environmental and biological traits of AMF, emphasizing their multifunctional strategies for controlling phytopathogens. These strategies encompass competition with soil-borne pathogens, modulation of plant immune responses via induced systemic resistance (ISR), and alterations in the taxonomic and functional diversity and composition of both soil and root microbiomes. By enhancing plant defenses, generating antimicrobial compounds, and optimizing root structure, AMF significantly contribute to the protection of plants against a diverse array of fungal, bacterial, viral, and nematode phytopathogens. Additionally, this review examines the role of AMF in enhancing soil health, which is a crucial element in sustainable disease management, by affecting soil properties, nutrient cycling, and microbial activity. The incorporation of AMF into sustainable agricultural practices, including no-till farming, organic farming, and biological control inoculants, is also addressed. Nevertheless, challenges persist regarding their inconsistent effectiveness in the field and the expenses linked to the large-scale production and formulation of AMF-based products. A thorough understanding of the interactions among plants, AMF, microbiomes, and phytopathogens is essential for the advancement of sustainable and ecological agricultural systems.

Keywords: Arbuscular mycorrhizal fungi, Biocontrol methods, Mycorrhizal symbiosis, induced systemic resistance mechanisms, Soil microbiome dynamics, Sustainable agricultural practices.

Introduction

Sustainable agriculture continues to encounter ongoing challenges posed by phytopathogens, including nematodes, fungi, bacteria, viruses, and phytoplasmas. According to Savary et.al. (2019), plant diseases can lead to considerable global economic losses, representing about 30% of the production of commercial and food crops. The rising incidence of crop diseases is frequently associated with contemporary agricultural practices, such as crop intensification, the extensive use of genetically modified plant varieties, and management strategies that rely heavily on inputs (McDonald and Stukenbrock, 2016). Although traditional disease management techniques such as crop rotation, sanitation, and chemical pesticides have proven effective, they are increasingly under scrutiny for their environmental impact and their role in fostering pathogen resistance.

Chemical pesticides are effective against a variety of phytopathogens, yet they pose significant risks to ecosystems, human health, and soil biodiversity (Alengebawy et al., 2021). Furthermore, their excessive use has led to the development of resistance in numerous plant pathogens, including the multidrug-resistant Botrytis cinerea (Meena and Singh, 2022; Wu et al., 2024). Consequently, there is an increasing trend towards biological solutions or integrated phytopathogen management strategies that are rooted in sustainable agricultural practices. One of the most promising methods for tackling phytopathogens is the utilization of the rhizosphere microbiome, which contains a wide array of microorganisms, both beneficial and pathogenic. Various beneficial microorganisms can promote plant growth and bolster plant defense mechanisms, thus fostering a more conducive environment for plant development (Farhaoui et al., 2023; Tharanath et al., 2024).

In recent years, arbuscular mycorrhizal fungi (AMF) have garnered significant attention due to their capacity to shield plants from a range of phytopathogens while also enhancing nutrient absorption and stress resilience (Bhupenchandra et al., 2024; Farhaoui et al., 2025; Weng et al., 2022). AMF are classified under the subphylum Glomeromycotina (Spatafora et al., 2016) and establish symbiotic relationships with about 72% of vascular plants, including most cultivated crops (Brundrett and Tedersoo, 2018). As obligate symbionts, they form specialized structures like vesicles and arbuscules to facilitate nutrient exchange with their host plants, relying primarily on organic compounds derived from photosynthesis for their growth. AMF are widely acknowledged as biofertilizers due to their ability to enhance phosphorus uptake (Miyasaka and Habte, 2001) and improve the acquisition of other nutrients that are less mobile (Garg and Pandey, 2015; Read and Perez-Moreno, 2003).

AMF not only enhance plant nutrition but also increase tolerance to abiotic stresses like drought, salinity, and extreme temperatures (Duc et al., 2018; Lenoir et al., 2016; Püschel et al., 2020). In addition to improving nutrient uptake and abiotic stress resilience, AMF play crucial roles in biological control by influencing rhizosphere microbial communities (Basiru et al., 2025) and enhancing plant defenses against phytopathogens (Ismail et al., 2013; Ismail and Hijri,2012). Feng et al. (2023) showed that arbuscular mycorrhizal hyphal networks convey jasmonic acid (JA) signals that prepare adjacent Salvia miltiorrhiza to combat Fusarium root rot. Recent research indicates that AMF can actively inhibit pathogens by triggering systemic resistance and competing with them in the rhizosphere (Bao et al., 2022; Zhu et al., 2010). Furthermore, AMF generate bioactive metabolites, including the antibacterial agent polymyxin B and antifungal polyphenols, which assist in suppressing various phytopathogens (Bencherif et al., 2019; Kaur and Suseela, 2020). Inoculation with Rhizophagus irregularis has been proven to alleviate Zucchini yellow mosaic virus symptoms in cucumber by adjusting hormonal balance and antioxidant responses (Gaˇsi et al., 2025). AMF also influence plant root structure, enhancing root systems against pathogen invasions (Smith and Read, 2010). The protective benefits of AMF are closely associated with the “mycorrhizosphere,” a specialized root-related zone that develops during mycorrhizal colonization (Basiru et al., 2023; Shi et al., 2023). This distinct microenvironment curtails pathogenic activity while promoting beneficial microbial communities (P´erez-de-Luque et al., 2017; Raklami et al.,2019).

AMF serve as important biocontrol partners against bacterial, fungal, viral, and nematode pathogens, highlighting their vital function in sustainable disease management within various agricultural systems. To fully leverage the advantages of AMF symbiosis, it is crucial to implement an ecological strategy that encompasses effective soil management, appropriate fertilizer use, and the encouragement of beneficial soil microorganisms. This review consolidates existing knowledge on how AMF can act as a natural and efficient substitute for synthetic chemical controls in plant disease management. It explores the biological processes, practical uses, and future outlooks of AMF integration in sustainable agriculture.

Root colonization and symbiotic interactions

Development of AMF symbiosis

Arbuscular mycorrhizal symbiosis represents one of the oldest and most widespread mutualistic relationships, with origins tracing back over 400 million years. It is thought to have played a significant role in the early plants' colonization of terrestrial environments (Delaux and Schornack, 2021; Redecker et al., 2013). The formation of AMF symbiosis is a highly regulated process that involves a sophisticated molecular communication between the plant and the fungus. This interaction initiates even before any physical contact occurs when there is a deficiency of nutrients, particularly phosphorus, plant roots release strigolactones (SLs) that attract AMF spores and promote their germination and hyphal growth (Akiyama and Hayashi, 2006; Balasubramanian et al., 2020). These pre-symbiotic signals prompt AMF hyphae to grow towards the root (Boyno et al., 2023). As the hyphae near the root, the fungus releases lipo-chitooligosaccharide "Myc factors" that activate symbiotic responses in the plant. Notably, these Myc signals (such as CO_4 and CO_5 chitooligosaccharides) mimic pathogen-associated molecular patterns (MAMPs) but do not trigger plant immunity; rather, they commence symbiotic signaling (Shi et al., 2023). Plant receptors, including the rice LysM receptor kinase OsCERK1, detect these fungal signals and start a cascade that modifies root development and induces the formation of symbiotic structures, such as arbuscules within root cortical cells (Bao et al., 2022; Bisht et al., 2024). Another essential element is OsMYR1, the rice receptor for Myc factor 1, which collaborates with OsCERK1 to activate symbiotic signaling and enhance AMF colonization efficiency (Nasir et al., 2021). This complex exchange of signals (SLs, Myc factors, and their corresponding plant receptors) is vital for the establishment of mycorrhizal symbiosis and is fundamental to the improved nutrient absorption and pathogen resistance seen in mycorrhizal plants (Nasir et al., 2021).

The process of colonizing the root

The intricate and well-organized symbiotic relationship between arbuscular mycorrhizal fungi (AMF) and plant roots is multifaceted. It starts with the plant's ability to recognize the fungi and progresses through a series of carefully controlled stages that result in the formation of specialized structures. These structures play a crucial role in enhancing the health of the plant and its ability to withstand both biotic and abiotic stresses, in addition to promoting the circulation of nutrients.

Mycelium's advancement and establishment take place within cells

At the root surface, AMF hyphae attach to epidermal cells and differentiate into appressoria (Fig. 1), specialized structures that enable the fungus to penetrate root tissues—a critical step for establishing symbiosis (Pepe et al., 2020). The formation of appressoria is mediated by fungal adhesins binding to root surface receptors and is further stimulated by plant-derived signaling molecules (e.g., flavonoids and phytohormones) that promote hyphal growth towards the root cortex (Lone et al., 2024). Once the appressorium is established, the fungus exerts mechanical pressure and secretes cell wall–degrading enzymes (e.g., laccases, chitinases, glucanases) to breach the root epidermis and enter the cortex (Aparicio Chacon ´ et al., 2023). This process has been illustrated by Gutjahr et al. (2008), who showed that Medicago truncatula mutants defective in appressorium formation exhibited reduced root colonization, underscoring its essential role in symbiotic establishment. To contain the intruding hyphae, the plant forms a periarbuscular membrane around them, acting as a barrier that prevents excessive fungal invasion (Lone et al., 2024).

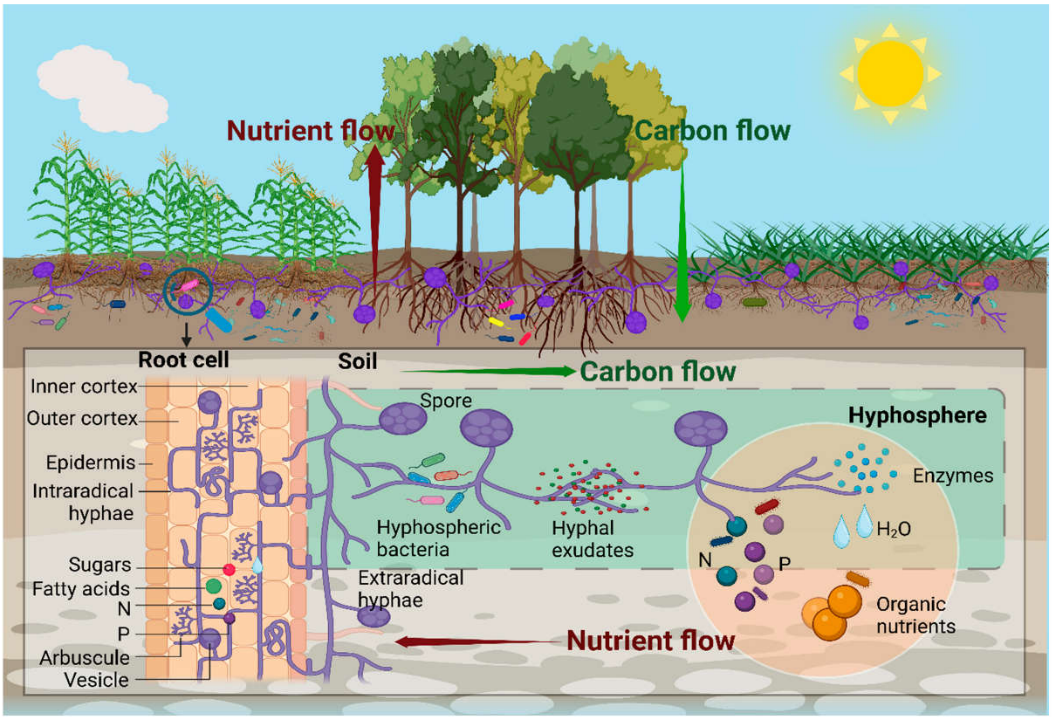

Fig 1. A diagram showcasing the symbiotic system of arbuscular mycorrhizal fungi (AMF) within the roots of host plants, highlighting the formation of vesicles, arbuscules, and extraradical hyphae.

Creation of mutually beneficial frameworks

Arbuscule function (nutrient exchange site): Within the root cortex, hyphae continue their intense branching process, creating highly branched structures called arbuscules (Fig. 1). These tree-like structures represent the main site of nutrient exchange. The high surface area of the surface of the arbuscules promotes efficient mutual nutrient exchange. The fungus provides P and other minerals to the plant, while the plant supplies carbon metabolites to the fungus (Tran et al., 2020). Arbuscules are extremely dynamic formations, frequently subject to renewal in response to the metabolic demands of the fungus and the plant at various stages of growth or under different environmental circumstances (Wipf et al., 2019). Their elaboration greatly favors the growth of the host plant, especially in conditions of nutrient deficiency. A study by Kobae and Hata (2010) using GFP-labeled AMF demonstrated the continuous turnover of arbuscules in rice roots, highlighting their dynamic nature and functional renewal during symbiosis. Vesicle role in reproduction and storage: In addition to arbuscules, several AMF species also generate vesicles (Fig. 1), which are structures rich in lipid molecules that fulfill various functions. These specific structures play a role as a reservoir, storing energy reserves in the form of lipid metabolites, which the fungus exploits during phases of nutrient shortage (Kameoka and Gutjahr, 2022). Vesicles can also play a role in the asexual reproduction of the fungus, thereby promoting the expansion of this organism within the roots. Their existence promotes the continuity and long-term balance of mycorrhizal symbiosis, especially in environments with fluctuating water availability(Kameoka and Gutjahr, 2022).

Elements that affect AMF root colonization

The colonization of roots by arbuscular mycorrhizal fungi (AMF) is influenced by various factors, which can be divided into abiotic, biotic, and host-related categories. Understanding these elements is essential for enhancing the symbiotic relationship with AMF and maximizing the advantages of this partnership, such as better nutrient uptake and increased resilience against both biotic and abiotic stressors.

Abiotic factors

Nutrient availability, soil type, and environmental constraints have a significant influence on the formation of mycorrhizal associations in plant roots. The physical conditions necessary for fungal hyphal growth and penetration are dictated by soil structure and texture. For instance, sandy soils, which possess a lower capacity for nutrient retention, might heighten the necessity for AMF colonization to enhance nutrient absorption (Wahab et al., 2023). Conversely, as noted by Torppa et al. (2023), compacted and poorly aerated soils can hinder the development of AMF mycelium. The establishment of symbiosis with AMF is heavily reliant on nutrient availability, especially phosphorus (P), which plays a crucial role in this symbiotic interaction. In fact, these fungi facilitate the uptake of poorly mobile nutrients in exchange for carbon derived from photosynthesis (Wahab et al., 2023). For instance, Huang et al. (2023) observed a 35% decrease in AMF colonization under salt stress in wheat, illustrating that salinity can greatly disrupt symbiotic establishment. Nevertheless, AMF-colonized plants in the same conditions showed improved growth and nutrient absorption, underscoring AMF's function in alleviating stress.

Biotic factors

The rhizosphere microbial community plays a crucial role in the colonization of AMF roots. The formation of this symbiotic relationship can be either encouraged or hindered by the presence of various soilborne microorganisms, including nematodes, bacteria, and fungi (Duret et al., 2024). Different microorganisms may vie for root space or modify the plant's immune response, which could influence the success of AMF colonization. Certain soil bacteria have been found to produce compounds that enhance the growth of AMF mycelium (Wahab et al., 2023; Wang and Feng, 2021). Furthermore, the fungal microbiota in the rhizosphere can compete directly with AMF for water and nutrients, potentially impacting their efficiency in colonization (Wang and Feng, 2021).

Factors associated with the host plant

Colonization by AMF is significantly affected by the species of the host plant, its physiological condition, and its root secretions. Different plant species exhibit varying levels of susceptibility to AMF colonization, with some forming stronger symbiotic relationships than others (Berger and Gutjahr, 2021). The success of colonization is also determined by the plant's physiological condition, which includes aspects such as root vigor and metabolic processes. Consequently, depending on the type of stress faced, plants may release specific root exudates that either repel or attract AMF (Hashem et al., 2025). Root secretions, especially flavonoids and SLs, act as chemical signals that regulate the interaction between AMF and the host plant, affecting both mycelial growth and the formation of symbiotic structures. Additionally, these secretions can alter the rhizosphere microbiota, which subsequently impacts AMF colonization (Lone et al., 2024).

Interaction with soil microbial community

The AMF-plant symbiosis is greatly influenced by the interaction between the symbiotic partner (AMF or the host plant) and the surrounding soil microbiota. The soil microbial community, which comprises archaea, fungi, bacteria, and other microorganisms, plays a crucial role in the AMF colonization process. It significantly affects plant health, growth, and resilience to stress. This microbiota not only impacts the growth and establishment of AMF but also engages in complex feedback mechanisms that regulate nutrient cycling, control of phytopathogens, and plant defense responses (Svenningsen et al., 2018).

The processes involved in AMF's role in disease mitigation

Induced systemic resistance (ISR) AMF enhance plant disease resistance by triggering induced systemic resistance (ISR), a defense pathway predominantly regulated by jasmonic acid (JA) and ethylene (ET) signaling (Ismail and Hijri, 2010). ISR activation leads to the accumulation of pathogenesis-related (PR) proteins and antioxidant enzymes with antimicrobial properties (Fig. 2) (Upadhyay et al., 2025). Unlike systemic acquired resistance (SAR), which is initiated by pathogen infection and depends on salicylic acid (SA) signaling, ISR is elicited by beneficial microbe colonization and often functions independently of SA (Sood et al., 2021).

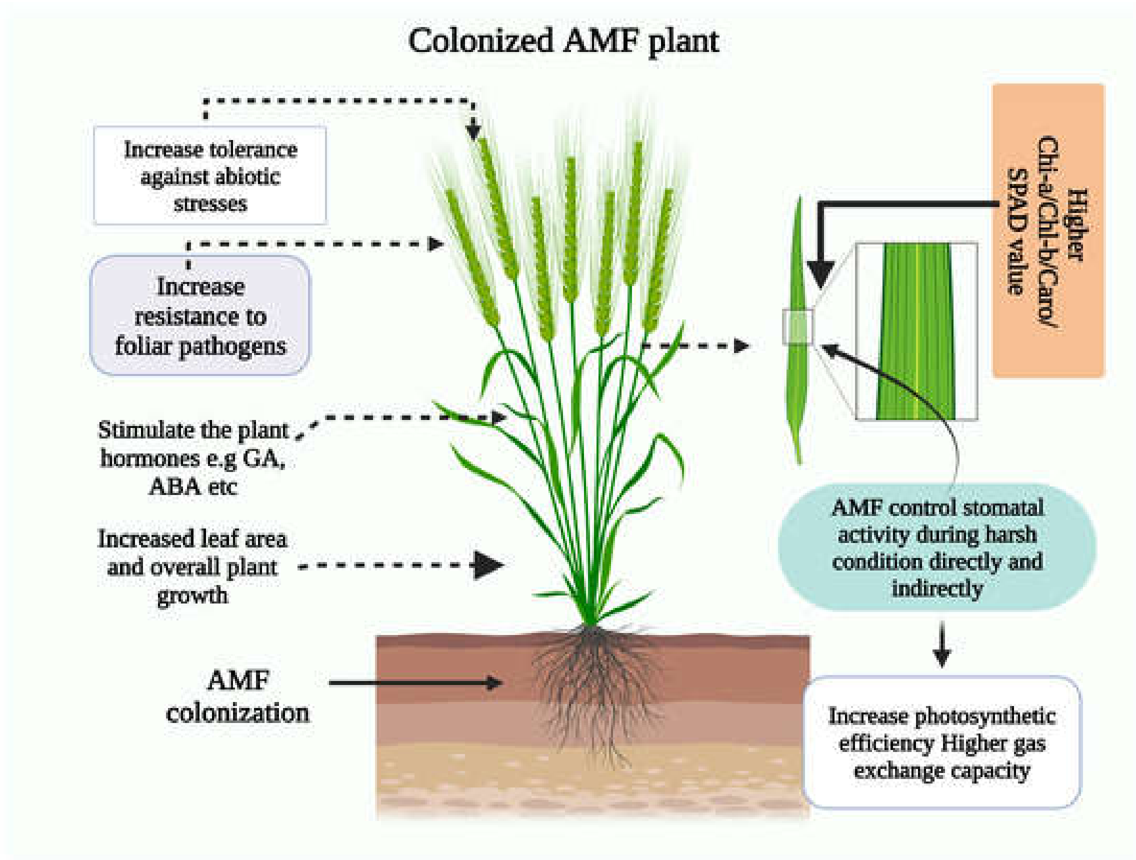

Fig 2. The general framework of how AMF leads to the induction of systemic resistance in plants.

These molecules aid in the recruitment of beneficial microorganisms and amplify systemic defense signaling within the plant, thereby confirming the presence of systemic defense signaling (Gough and B´ecard, 2016). Furthermore, the exudates not only promote microbial symbiosis but also stimulate the production of defense-related metabolites, including flavonoids, phenolics, and terpenoids, thereby boosting plant immunity (Lone et al., 2024). For example, tomato plants (Solanum lycopersicum) that are colonized by R. irregularis exhibit reduced susceptibility to Fusarium oxysporum, a result attributed to ISR-mediated lignin deposition and callose accumulation in root tissues, which collectively enhance structural defenses against pathogen invasion (Wang et al., 2022). ISR is involved in the transcriptional upregulation of genes that are critical for defense mechanisms (Romera et al., 2019). Research indicates that the colonization of AMF triggers the upregulation of WRKY transcription factors, which are essential in regulating defense-related genes and enhancing resistance to pathogens (Kashyap et al., 2024; Mierziak and Wojtasik, 2024). Additionally, the induction of ISR results in the synthesis of phytoalexins, antimicrobial peptides, and proteinase inhibitors that restrict pathogen proliferation (Simas et al., 2025). The effects of ISR extend beyond merely preventing pathogenic invasion. It also enhances resistance to abiotic stresses such as drought, salinity, and harmful concentrations of heavy metals, thereby further improving plant resilience (Al-Turki et al., 2023). Another significant feature of ISR is the generation of volatile organic compounds (VOCs) that deter herbivores and suppress pathogen growth (Sarkar and Sadhukhan, 2023). These VOCs (e.g., terpenes, green leaf volatiles, methyl jasmonate) serve as airborne signals that protect the host plant and prepare neighboring plants for heightened defenses (Ullah et al., 2024; Zhou and Jander, 2022).

The use of AMF is essential for effective plant disease control

AMF play a crucial role in safeguarding plants by boosting their resistance to a range of pathogens, including nematodes, fungi, bacteria, and viruses (see Table 1). By employing intricate mechanisms such as competing for nutrient absorption, triggering plant defense mechanisms, and altering root exudates, AMF contribute to disease suppression and enhance the overall health of plants.

Fungal disease-causing organisms

Since arbuscular mycorrhizal fungi (AMF) inhabit the soil and establish symbiotic relationships with plant roots, they are essential in managing soil-borne diseases (Filho et al., 2016; Weng et al., 2022). Various studies have highlighted their role as significant biocontrol agents, utilizing a range of mechanisms such as niche competition within the rhizosphere, systemic activation of plant defenses, and modulation of host biochemical pathways (Dowarah et al., 2022; Kashyap et al., 2024; Wahab et al., 2023). The colonization of the root system by

AMF allows them to compete with other pathogens, including Alternaria, Fusarium, and Phytophthora species, for space and nutrients, thereby restricting pathogen establishment (Li et al., 2013; Nasim et al., 2008; Spagnoletti et al., 2021). For instance, Funnelliformis mosseae enhances resistance to early blight caused by Alternaria solani in tomatoes and inhibits F. oxysporum infections in strawberries and cucumbers by upregulating defense-related genes and stress enzymes (Hu et al., 2010; Song et al., 2015). The synergistic effects were demonstrated through the combined use of F. mosseae and Glomus fasciculatum, which also mitigated the severity of Fusarium wilt in tomatoes by 40–60% through improved phosphorus metabolism and antioxidant activity (Devi et al., 2022).

The effectiveness of AMF-mediated protection primarily relies on host-pathogen specificity, environmental factors, and symbiotic compatibility (Dey and Ghosh, 2022; Ullah et al., 2024). Increased atmospheric carbon dioxide (CO2), sufficient soil moisture, and favorable thermal conditions promote AMF colonization, which systematically activates defense cascades, including the phenylpropanoid and jasmonate pathways (Goicoechea, 2020; Kalamulla et al., 2022). For example, Glomus versiforme stimulates defense gene expression in Medicago truncatula, while R. irregularis in grapevines triggers stilbenoid biosynthesis, increasing resveratrol content by 2.5-fold to protect against Plasmopara viticola and B. cinerea (Cruz-Silva et al., 2021; Nair et al., 2015).

The effectiveness of AMF-mediated protection is primarily influenced by host-pathogen specificity, environmental factors, and the compatibility of symbiosis (Dey and Ghosh, 2022; Ullah et al., 2024). Increased levels of atmospheric carbon dioxide (CO2), sufficient soil moisture, and favorable thermal conditions promote AMF colonization, which in turn activates systematic defense cascades, including the phenylpropanoid and jasmonate pathways (Goicoechea, 2020; Kalamulla et al., 2022). For instance, Glomus versiforme stimulates the expression of defense genes in Medicago truncatula, whereas R. irregularis in grapevine enhances stilbenoid biosynthesis, resulting in a 2.5-fold increase in resveratrol content to protect against Plasmopara viticola and B. cinerea (Cruz-Silva et al., 2021; Nair et al., 2015).

Table 1. As biocontrol agents, arbuscular mycorrhizal fungi (AMF) combat different types of pathogens.

Pathogen	Species/disease	Mycorrhizal fungi	Crop	References
Fungi	*F. oxyspoum*	*F. mosseae*	Cucumber	Song et al., 2015
	F. oxyspoum	*F. mosseae*	Strawberry	Hu et al., 2010

	F. oxysporum f.sp.fragariae	*F. mosseae*	Strawberry	Duan et al., 2021
	P. viticola	*R. fasciculatum*	Grapevine	Cruz-Silva et al., 2021
	A. alternate	*R. fasciculatum*	Tomato	Nair et al., 2015
	P. fragariae	*G. etunicatum*	Strawberry	Norman and Hooker, 2000
	A. mellea	*R. intraradices*	Grapevine	Nogales et al., 2009
	P. aphanidermatum	*G. deserticola + F. mossae*	Carica papaya	Olawuyi et al., 2014
	Verticillium Wilt	*G. deserticola + F. mossae*	Cotton	Zhang et al., 2018
	F. oxysporum f. sp. ciceris	*G. deserticola + F. mossae*	Chikpea	Shukla et al., 2015
Bacteria	*P. lacrymans*	*G. macrocarpum*	Eggplant	Kapoor et al., 2002
	P. syringae	*F. mosseae*	Soybean	Mohammad, 2019
	R. solanacearum	*R. irregularis*	Tomato	Chave et al., 2017
Virus	*Cucumber green mosaic virus and Tobacco mosaic virus*	*R. irregularis*	Cucumber and Tobacco	Stolyarchuk et al., 2009
	Potato virus Y	*R. irregularis*	Potato	Thiem et al., 2014
	Tomato yellow leaf curl Sardinia virus	*R. irregularis*	Tomato	Maffei et al., 2014
Nematode	*M. incognita*	*F. mosseae*	soybean	Bamigboye et al., 2020
	M. incognita	*G. fasciculatum + G. versiforme*	Grapevine	Li et al., 2006
	S. bradys	*F. mosseae*	Yam	Tchabi et al., 2016
	N. aberrans	*F. mosseae*	Tomato	Marro et al., 2018
	X. index	*R. irregularis*	Grapevine	Hao et al., 2012
	H. glycine	*C. clarioddeum*	Soyabean	Vallejos-Torres et al., 2021

Schonbeck and Dehne (1977) found that mycorrhizal fungi in cotton plants significantly enhanced their resistance to Thielaviopsis basicola infection when compared to non-mycorrhizal plants. Additionally, later studies have shown that higher levels of mycorrhizal colonization correlate with a reduction in the production of T. basicola chlamydospores, suggesting that mycorrhizal symbiosis plays a crucial role in curbing pathogen development (Harrier and Watson, 2004). In their study, Chou and Schmitthenner (1992) illustrated that the co-inoculation of AMF with Rhizobium led to a synergistic effect, reducing legume mortality caused by P. ultimum and Phytophthora megasperma by 30–50%. Moreover, inoculation with Glomus rhizogenes and G. mosseae showed significant decreases in the disease index and incidence of R. solanacearum in solanaceous crops, with reductions of 9.7% and 49.8%, respectively, likely due to changes in root exudation profiles (Aguk et al., 2018). The impact of Claroideoglomus etunicatum and Glomus macrocarpum on regulating the activities of Macrophomina phaseolina and R. solani in peanut and soybean is particularly significant, highlighting their beneficial roles in various agroecosystems (Aljawasim et al., 2020; Guzman et al., 2021).

The significance of AMF in promoting soil health within the context of disease management

Influence over the changes in soil microbiome activity

AMF play a crucial role in establishing soil microbial communities through intricate ecological and biochemical processes that bolster plant resistance to soilborne diseases. By infecting plant roots and extending their hyphae into the surrounding soil, AMF form a network that not only structures the soil but also selectively alters the composition of microbial communities (Li et al., 2025). AMF can influence plant physiology, particularly in root exudation, which subsequently affects the microbial community in the rhizosphere (Solís-Domínguez et al., 2011). Results indicated that AMF inoculation significantly impacted the recovery of microbial communities involved in the nitrogen cycle, thereby enhancing nutrient cycling within the agroecosystem (Wang et al., 2021). Additionally, a study has found that mycorrhizal plants exhibit higher levels of microbial biomass carbon (Cmic), indicating that AMF improve soil microbes' access to carbon (Mahmoudi et al., 2020). The presence of AMF not only diversifies microbial populations but also boosts microbial respiration (Mahmoud et al., 2021), illustrating that AMF can stimulate microbial metabolic processes.

Contribution to enhancing soil structure and fertility

AMF contribute to the stabilization and enrichment of soil through a complex network of interrelated physical and biochemical processes that promote plant health and disease management. One of the key soil stabilization mechanisms facilitated by AMF is the release of glomalin, a glycoprotein produced by extraradical hyphae. This compound binds soil particles together, aiding in the creation of stable macro-aggregates that improve soil structure and resilience (Liu et al., 2024). This structural reinforcement enhances soil porosity, aeration, and water retention, making it a more conducive environment for root development (Singh et al., 2022). In addition to structural advantages, AMF symbiosis greatly enhances nutrient bioavailability, especially phosphorus (P), which is often a limiting nutrient for plant defense responses (Lee et al., 2014; Majewska et al., 2017). By accessing and mobilizing inorganic P through their extensive hyphal networks, AMF improve P uptake by host plants, resulting in increased production of defense metabolites such as phenolic compounds and phytoalexins, which bolster plant resistance against pathogen attacks (Lone et al., 2024). This advantageous nutritional environment is also linked to improved growth and vigor of the root system, thereby enhancing the resilience of host plants (Ain et al., 2025). Beyond their direct advantages, AMF also play a role in indirectly suppressing soil-borne pathogens by fostering a more resilient and competitive beneficial microbial community. In fact, AMF inhibit pathogens through niche exclusion, competitively displacing them from the rhizosphere and nutrient resources. By colonizing roots, AMF prevent soil-borne pathogens from accessing infection sites, thus hindering their establishment and growth on or within the root system (Bennett et al., 2006).

Difficulties and constraints in practical applications of the field

Genetic diversity of host plants is a crucial factor influencing incompatibility with specific AMF lines, leading to inconsistent success in forming plant-AMF symbiosis across various crop species (Berger and Gutjahr, 2021; Kokkoris et al., 2020). Beyond these limitations, the mass production of AMF is hindered by their obligate symbiotic nature, which precludes their growth in axenic environments. This necessitates intricate methods, such as in vitro culture on transformed roots, which are labor-intensive and susceptible to contamination (Tiwari and Adholeya, 2003). Issues related to formulation, like preserving spore viability during storage and transport, further limit the accessibility of effective commercial inocula (Mang'erere Nyamwange and Njeru, 2024). The method of application also poses a challenge. In field trials, the establishment of microscopic fungi can be affected by soil characteristics such as pH and texture, along with biotic factors like the presence of pathogenic microorganisms (Vo et al., 2015).

For instance, a review article on the biological control of soil-borne diseases using AMF emphasized that inoculation strategies need to be aligned with crop management to achieve optimal success rates (Kamore et al., 2024). Another issue with AMF application is the competition between introduced AMF strains and the native AMF populations already found in the soil. Native AMF tend to outcompete introduced strains, reducing their benefits as they are already adapted to the existing environmental conditions (Ghosh and Verma, 2024). Crop rotation involving non-mycorrhizal crops and certain tillage practices can disrupt AMF activity and diversity, negatively impacting their capacity to enhance plant growth and biotic stress tolerance (Kuila and Ghosh, 2022). Additionally, a significant limitation of utilizing AMF to boost plant resilience against biotic stress is the difficulty in predicting the outcomes of AMF inoculations in real-world settings. The performance of AMF can fluctuate considerably depending on the types of crops cultivated.

Upcoming possibilities

Numerous studies have underscored the positive impact of AMF on enhancing plant growth in challenging environments, including salinity, drought, nutritional deficiencies, and extreme temperatures. By facilitating nutrient absorption and mitigating environmental pressures, AMF can boost crop yields while decreasing reliance on synthetic fertilizers, thereby fostering sustainable agricultural practices. The symbiotic interaction between AMF and plants is essential for enhancing plant resilience and productivity, especially when paired with PGPRs. These beneficial bacteria, particularly those that produce ACC deaminase, enhance salt stress tolerance by lowering ethylene levels and promoting increased plant biomass. AMF contributes to improved plant growth, yield, and soil health through various mechanisms. Nonetheless, their implementation in practical settings encounters obstacles such as variability in performance and possible effects on soil health.

Agricultural production can be enhanced by comprehending how AMF influence tolerance mechanisms and how crosstalk is initiated to regulate plant performance. To gain a deeper insight into their natural role as biofertilizers for sustainable agricultural production, AMF need to be examined at all levels. Future investigations should concentrate on unraveling the genetic and molecular mechanisms that underpin these symbiotic interactions to maximize their application in agriculture, especially in addressing biotic stresses and fostering sustainable agricultural practices.

Promoting the utilization of AMF is essential for the enduring viability of modern global agricultural systems. Their application to enhance agriculture could certainly lead to a significant decrease in dependence on synthetic fertilizers and other chemicals, thus encouraging bio-healthy agricultural methods. Future research should mainly aim at pinpointing genes and gene products that govern AMF-induced growth and development in reaction to biotic stressors. Subsequent studies in this domain could emphasize identifying crucial physiological and metabolic processes influenced by various biotic factors, along with host-specific protein components and AMF that play a role in managing the symbiotic relationship.

Table 2

Issues and resolutions for the successful application of arbuscular mycorrhizal fungi in the field

Challenge	Mechanistic consequences	Strategies	Reference
Outcome predictability	. Existing monitoring techniques (destructive sampling, microscopy) are time-consuming and limit their useful application.	Conduct extensive field tests to create predictive models of AMF responses.	Ji et al., 2022; Wang et al., 2018; Yadav et al., 2022
Environmental heterogeneity (climate, soil, nutrient levels)	Plants can reduce their investment in AMF in nutrient- rich soils, thereby minimizing colonization and benefits.	Inoculate with native or site adapted strains of AMF.	Thirkell et al., 2017; Yan et al., 2025
Host plant genetic differences	Symbiosis can enhance nutrient acquisition and stress tolerance in fertilizer-poor or dry soils, but variation leads to inconsistent field performance.	Adapt inoculation procedures to specific soil, climate, and crop conditions.	Berger and Gutjahr, 2021; Kokkoris et al., 2020
Large-scale production obstacles	Genetic diversity of host plants is associated with differences in host plant compatibility with certain AMF taxa and thus with varied performance for various crops.	with AMF. Combination of AMF strains with compatible host cultivars.	Tiwari and Adholeya, 2003
Formulation challenges (spore viability maintenance)	The symbiotic nature of AMF makes axenic culture difficult, requiring sophisticated and time-consuming procedures such as root organ culture, which is prone to multiple contaminations.	Standardize and optimize sophisticated production technologies. Improve formulation procedures to preserve spore viability during storage and transport. Formulate robust, cost-effective inocula with	Mang'erere Nyamwange and Njeru, 2024

Application method problems	Spore viability loss in storage and transport reduces commercial inocula efficacy.	preserved spore viability.- Enhance packaging and distribution quality control.	Kamore et al., 2024; Vo et al., 2015
Competition from native AMF	Soil physical characteristics (texture, pH) and biotic factors (presence of a pathogen) can hinder the establishment of AMF.	Apply standardized inoculation and crop management procedures adapted to specific field conditions.	Ghosh and Verma, 2024

AMF: arbuscular mycorrhizal fungi.

Conclusion

Arbuscular mycorrhizal fungi are essential for the health of plants and serve as a natural, sustainable approach to managing diseases. They facilitate nutrient absorption in plants, enhance their resilience to various stresses, and modulate defense mechanisms, making them a crucial element in agricultural production systems. This review outlines the various ways in which AMF mitigate plant diseases, including the induction of induced systemic resistance (ISR), competition with pathogens, the production of antimicrobial compounds, and the overall enhancement of plant immunity. Additionally, AMF affect the soil microbiome's ecology, improve soil fertility and structure, and contribute to biocontrol efforts; thus, they are integral to integrated disease management strategies. Despite their significant potential, transitioning from laboratory and greenhouse settings to field applications poses challenges due to the inconsistent performance of AMF in varying environmental conditions. Research and technological advancements must focus on scaling up AMF bioproducts, ensuring compatibility with other biocontrol agents, and achieving consistency across diverse cropping systems. Innovations in precision agriculture, genomics, and metabolomics offer new opportunities to deepen our understanding of AMF interactions with plants and pathogens, facilitating their incorporation into disease management frameworks. As the agricultural sector moves towards more sustainable and eco-friendly practices, utilizing AMF in plant health management presents a practical solution for reducing chemical pesticide usage while fostering long-term sustainability for crops and soil. With increased research efforts and the implementation of strategies to overcome existing challenges, AMF-based technologies could become foundational to future agricultural systems, promoting food security and environmental sustainability.

Acknowledgements

The authors would like to thank **Department of Botany, KRT Arts, BH Commerce & AM Science (KTHM) College, Nashik** for providing all necessary infrastructural support to carry out the study and thanks to **Chhatrapati Shahu Maharaj Research, Training and Human Development Institute (Sarthi)** for financial support.

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