**Exploring the Mutualistic Relationship Between Plants and Arbuscular Mycorrhizal Fungi**

**Abstract**

Arbuscular mycorrhizal fungi (AMF) are a type of symbiotic fungi that form mutually beneficial relationships with the roots of most terrestrial plants. They belong to the phylum Glomeromycota and are known for their ability to penetrate plant root cells, forming tree-like structures called arbuscules, through which nutrient exchange between the fungus and the plant occurs. AMF play a crucial role in enhancing plant nutrient acquisition, particularly in the uptake of phosphorus, while also promoting plant growth and increasing stress tolerance. The developmental process of AMF includes stages such as spore germination, hyphal proliferation, root colonization, and the subsequent formation of arbuscules and vesicles within the plant root system. Apart from facilitating nutrient uptake, AMF also significantly contribute to improving soil structure and maintaining ecosystem balance. This review paper discusses the developmental stages and functions of arbuscular mycorrhizal fungi.

**Key words:** Arbuscular mycorrhizal fungi, plant, soil, symbiotic, nutrients.

1. **Introduction**

Arbuscular mycorrhizal (AM) fungi are essential for plant health, as they are associated with over 80% of current land plants. These fungi are commonly found in soil and form symbiotic relationships with most plants, providing benefits to the host plants during adverse conditions (Kumar et al., 2024a). The development of AM fungi in soil and plant roots varies due to changes in soil moisture, nutrients, and temperature, which also affects the benefits of the symbiosis (Bhardwaj, 2018). All AM fungi belong to the species Glomeromycota, a monophyletic group that diverged from the same common ancestor as Ascomycota and Basidiomycota (Chandra, 2015). Their widespread presence underscores their importance in supporting plant growth and ecosystem health (Schussler, 2001; Kumar et al., 2023a). The interplay between Glomeromycota and unculturableendobacteria introduces a new layer of complexity. Despite being a recent area of exploration, the inability to culture these endobacteria, their vertical transmission, and the compact genome of Candidatus Glomeribacter strongly indicate their ancient association with AM fungi, potentially influencing fungal speciation (Bhardwaj et al., 2023b). The presence of AM fungi is crucial for the survival and thriving of host plants in natural ecosystems. These fungi act as vital allies, significantly enhancing plant health and resilience (Chandra et al., 2021a). Research has demonstrated that AM fungi play a key role in nutrient uptake, boosting plant biomass, and fortifying plants against stress and pathogens (Smith and Read, 2008; Jamaluddin et al., 2001).

In contrast, attempts to cultivate AM fungi in the absence of host plants have proven unsuccessful. These fungi are obligate biotrophs, relying entirely on their host plants for growth and reproduction (Bennett, 2022; Ujjaini and Chandra, 2002). Despite this dependency, their ecological success underscores the substantial advantages of their close association with plants, outweighing any potential drawbacks from the loss of saprotrophic capabilities (Darro et al., 2022). Arbuscular mycorrhizal (AM) fungi play a crucial role as the primary mineral nutrient acquisition strategy for land plants. Fossilized intracellular fungi, identifiable as AMF, have been unearthed in the rhizomes of petrified early land plants from the Ordovician era, dating back 460 million years (Berbee, 2020; Bhardwaj et al., 2024)). This discovery indicates that arbuscular mycorrhiza predates vascular plants with roots and would have coexisted with the first green plants to colonize the land (Jamaluddin and Chandra, 1998). The association of plants with AM fungi can lead to a significant 20% net increase in photosynthesis, making a substantial contribution to the global carbon cycling budget of ecosystems (Parniske, 2008; Kumar et al., 2022b). Furthermore, the presence of AMF spores in all soil where plants grow underscores their ubiquitous importance. These spores, some as large as 0.5 mm in diameter, can be visibly separated from soil through sieving and filtration of soil suspensions (Srisom, 2020; Bhardwaj et al., 2023a). They possess thickened and resistant walls, colored white, yellow, orange, or brown with carotenoids, and contain reserves that support the growth of a short hypha upon germination (Chandra, 2013). The classification of arbuscular mycorrhizal fungi involves five distinct genera: Acaulospora, Entrophospora, Gigaspora, Glomus, and Scutellospora, which are differentiated based on their unique morphological characteristics (Bhardwaj and Chandra, 2017). Experts have the ability to distinguish approximately 230 morphospecies due to the subtle but significant morphological differences present within the fungi (Sarah, 2016; Tiwari et al., 2024).

Additionally, AM fungi can directly impact the environment by enhancing soil aggregation and structure (Riley et al., 2015; Kumar et al., 2023b) they can also influence plant community structure and productivity (Vander Heijden et al., 1998). There has been recent research on the impact of AM symbiosis on greenhouse gas (GHG) emissions (Bender et al., 2014; Lazcano et al., 2014). According to research by Bender et al., (2014), AM fungus can help reduce the production of N2O, a significant greenhouse gas, which raises the possibility that they could aid in the mitigation of climate change.

This review outlines the current understanding of the signals and mechanisms involved in the development of AM symbiosis, the molecular underpinnings of the nutrient exchange between AM fungi and host plants, the roles played by AM fungi in water uptake, nutrient acquisition, and various forms of abiotic stress, as well as the function of a novel plant hormone called strigolactone.

1. **Development of AMF**

The growth and development of arbuscular mycorrhizal fungi is dynamic and rapid.There are Six Development Stage of AMF. Which are Asymbiotic, Presymbiotic, Apressoria formation, Root Invasion, Arbuscule Formation and Ramification Of AMF (Huey, 2020). In the asymbiotic stage is the only phase in the organism's phenological development where there is clear evidence of limited saprophytic ability and is marked by the lowest level of metabolic activity (Willis, 2013; Chandra, 2014). A spore's germ-tube can grow to lengths of 20–30 mm; however, if it does not find a host root within 15–20 days, its growth may stop, resulting in septation as nutrients are exhausted. The spore can either produce another germ-tube or enter a dormant state until germination is triggered by the presence of a root (Delvian and Rambey, 2019). At the presymbiotic phase, AM fungi undergo multiple successive rounds of spore germination and retraction of nuclei and cytoplasm (Garg and Chandel, 2017; Chandra et al., 1997). This exploratory hyphal development undergoes remarkable transformations in response to plant-derived signals (Bonfante, 2010). An Extensive Study of the Complexities of Fungal Adhesion Mechanisms in Appressoria Formation (Vasselli & Shaw, 2022). The development of numerous adherence and invasion tactics by fungal infections has included the use of appressoria as a critical stage in this process. Fungal structures known as appressoria are designed to aid in adherence and penetration into host cells (Mapuranga, 2022; Kumar et al., 2022a). Creating effective antifungal treatments requires an understanding of the molecular mechanisms behind the development of appressoria. Fungal infections' adhesion to host tissues is one of the main elements in the creation of appressoria. At specific intracellular sites of contact with the root, appressoria are generated in response to signals derived from the fungal domain to construct prepenetration apparatuses (PPA) (Genre et al., 2005; Kamesh et al., 2023a), which facilitate penetration into the cortex. The pre-penetration apparatus (PPA), a tube-like intracellular infection structure that hosts AMF actively accommodates, is created by host plants through cellular reorganization and symbiosis-specific gene expression (Wang, 2021). In contrast to plant cells' papilla creation in reaction to pathogenic fungi's appressoria production, which obstructs the fungus's ability to enter cells, host cells prepare for fungal invasion in a very different way (Brown 2015). The endoplasmic reticulum (ER) and cytoskeleton material create an extensive network supporting the invaginated plasma membrane (PPA). It is believed that localized plant cell wall thinning at the contact location, following PPA production, permits AM fungal hyphae to proliferate within the apoplastic tunnel.

In a similar vein, when rhizobia colonize legume root hairs, an analogous structure known as the infection thread (IT) forms (De Carvalho-Niebel 2024). This reflects common molecular and cellular pathways, described by a collection of genes essential to both AM symbioses and nodulation, and coordinated to a significant degree by thecommon symbiosis signaling pathway( CSP) (Choi, 2018; Chandra et al., 2021b).

Initiating the development of arbuscules, hyphal branches are generated as the fungus develops through the apoplast and penetrates inner cortical cells. The plant's cortical cell wall is penetrated by fungi before any visible appressoriaemerge. The plant is actively involved in this process, as evidenced by the defective hyphae penetration into inner cortical cells in LjSYM4 and LjSYM15 mutants (Paszkowski, 2006). Development of arbuscules and nodulation is delayed in lotus plants that harbor weak mutant alleles of the LjSYM15 gene (.Timmers et.al., 2005; Chandra et al., 2024). Fungal hyphae proliferate and create the arbuscule, a structure like a tree, once they have penetrated the inner cortex cells. Mutants affecting the pea PsSYM36 gene are low and late nodulating, forming only stumpy branches instead of normal arbuscules. These host genes have been identified as necessary for the production of arbuscules (García-Garrido and Vierheilig, 2009). These primitive arbuscules are likely non-functional yet have enormous agricultural potential because the peri-arbuscular membrane in this interaction does not stain for the ATPase activity seen in the wild type (Wang et.al., 2014). Arbuscular mycorrhizal infections are mostly initiated by host plants (Corradi, and Bonfante, 2012) and it is logical to assume that comparable modifications take place when cortical cells colonize newly exposed surfaces. In general, molecular communication between the plant and the arbuscular mycorrhizae is necessary for these developmental processes. This communication includes the symbiotic partners' exchange and perception of signals.

1. **Function of Arbuscular Mycorrhizal fungi**

Arbuscular mycorrhizal fungi (AMF) establish symbiotic relationships with the majority of terrestrial plants, including crops and trees. These fungi are crucial for plant nutrition, especially in facilitating phosphorus uptake, and they enhance plant health and resilience to environmental stress (Wahab, et al., 2023). Role of ARB Discover the fascinating process of spore germination and hyphal growth in arbuscular mycorrhizal fungi (AMF). AMF begins as spores in the soil, staying dormant until they encounter a suitable host plant root or specific environmental triggers. Once conditions are favourable, the spores germinate, giving rise to thread-like structures called hyphae, which then grow toward the plant root( Brundrett 2009; Smith and Read, 2008) (figure 1). In the second step of AMF When AMF hyphae approach plant roots, a fascinating chemical exchange occurs between the plant and the fungus. The plant secretes powerful compounds known as strigolactones, which serve to actively stimulate AMF growth. In response, the AMF generate signals, including Myc factors, strategically preparing the plant for successful colonization. During penetration, the hyphae skill fully navigate through the root's epidermis (outer layer) and extend into the root cortex (the inner layer) without causing any harm. The fungal hyphae reach the plant cells while remaining external to the plasma membrane, demonstrating a remarkable symbiotic relationship (Bonfante and Genre, 2010). In the Third Step of root cortex, arbuscular mycorrhizal fungi (AMF) develop specialized structures known as arbuscules within plant cells. Arbuscules, which are highly branched hyphae, play a crucial role as the primary site for nutrient exchange between the plant and the fungus. These arbuscules form a symbiotic interface by being enclosed within a membrane, enabling the efficient transfer of nutrients, particularly phosphorus, from the fungus to the plant, while the plant reciprocates by providing sugars and carbon compounds to the fungus (Van der Heijden, 2015). In this fourth steps we studied that Arbuscular mycorrhizal fungi (AMF) play a crucial role in improving plant nutrition. AMF's ability to extend their hyphae beyond the nutrient-depleted zone around the plant root enables them to access phosphorus from distant soil areas, significantly boosting phosphorus uptake for the plant and AMF also facilitate the uptake of essential nutrients like nitrogen, potassium, zinc, and copper, particularly in soils with low nutrient levels, ensuring that the plant receives all the necessary micronutrients for healthy growth and In return for these vital nutrients, the plant supplies the fungus with carbohydrates, such as glucose or lipids, providing the necessary energy for the fungus's growth and spore production. This mutually beneficial exchange ensures the plant's enhanced nutrient uptake and overall well-being (Smith and Read, 2008; Gosling et al., 2006). In the five steps enhanced nutrient Availability with the presence of AMF, plant growth is significantly improved by boosting the accessibility of nutrients, particularly phosphorus, which is often a limiting factor in plant productivity and AMF hyphae play a crucial role in enhancing water uptake, particularly in drought conditions, by extending the plant’s root network and tapping into water from deeper soil layers and the secretion of glomalin by AMF hyphae promotes soil aggregation, resulting in improved soil structure that is more porous and adept at retaining water and nutrients (Salomon et al., 2022). In the next steps Arbuscular Mycorrhizal Fungi (AMF) play a vital role in boosting a plant's natural defense mechanisms, significantly increasing its resilience against soil-borne Pathogens and nematodes (figure 2). The dense network of fungal hyphae serves as a robust physical barrier, while the biochemical changes in the plant roots induced by the AMF make it significantly more challenging for pathogens to infiltrate and AMF has the remarkable capability to trigger Induced Systemic Resistance (ISR) in plants, effectively priming the plant to swiftly counter pathogen attacks by fortifying cell walls and promoting the production of defence-related compounds (Gosling et al., 2006).



 **Figure 1: Development Stages of Arbuscular Mycorrhizal Fungi.**



**Figure 2: Arbuscular formation process in plant root.**

**4. Myc Factor (Fungal Signals & Plant Receptor)**

Arbuscular mycorrhizal (AM) fungi release chitooligosaccharides (COs) and lipochitooligosaccharides (LCOs), which are signaling molecules recognized at the plant plasma membrane (Luginbuehl & Oldroyd, 2016). The recognition of AM fungi triggers a series of signaling events, leading to significant changes in gene expression in the host cell and promoting fungal colonization of the root. This signaling process, known as the common symbiosis signaling pathway (CSSP or Sym pathway) (Bano & Uzair, 2021) is essential for both nodulation and mycorrhization. AM fungi are capable of producing a diverse range of signaling molecules that have the potential to activate the Sym pathway, known as Myc factors. Among the most promising candidates are LCOs, which share structural similarities with Nod factors produced by rhizobial bacteria (Kidaj et al., 2020).

**5. Calcium Spiking OrCa 2+Oscillations**

The recognition of rhizobial and fungal signals at the plasma membrane leads to calcium spiking, which is mainly associated with the perinuclear region of the cell. These rapid changes in nuclear calcium levels are among the earliest detectable responses in the plant and are crucial to symbiosis signaling (Downie, 2014). Symbiotic calcium spiking was initially observed in Alfalfa root hairs after treatment with Nod factors from rhizobial bacteria, occurring within minutes of Nod factor perception (Felle, 2013). Several genes, including those encoding the Nod factor receptor complex at the plasma membrane and various components associated with the nuclear envelope, have been shown to function upstream of the Nod factor-induced calcium response (Singh et al., 2021).

In accordance with genetic studies demonstrating common signaling, it is noteworthy that calcium oscillations are not confined to the rhizobial symbiosis. They have also been observed during a plant's response to AM fungi. These calcium oscillations occur in root cells in close proximity to the fungal hyphae, occurring before direct contact between the root cells and the fungus (Hata et al., 2010). Moreover, the activation of calcium oscillations in root cells by AMF spore exudates suggests that diffusible signals from AM fungi are accountable for eliciting the calcium response.

**6. Strigolactones, a novel class of Plant Hormones**

The most recently found plant hormones, known as strigolactones (SLs), may find use in agriculture. SL production occurs via the carlactone (CL) intermediate, and it can be a useful target for molecular research on plant signallingnet works, stress responses, and architectural development (Mashiguchi et al., 2021) (figure 3). In parasitic weeds like Orobanche and Striga, SL has been shown to aid in seed germination (Soto-Cruz et al., 2021). It has also been discovered to regulate the branching activity of AM fungus and influence plant architecture, all of which contribute to sustainable agriculture (Boyno et al., 2023). The ability of strigolactones to promote plant branching, promote the formation of symbiotic arbuscular mycorrhizal fungus (AMF) in the soil, prevent shoot branching, and initiate the germination of parasitic plant seeds are among their many vital roles (Naseer et al.,2024).

**Figure 3: Function of Strigolactone**

Strigolactones (SLs) are derivatives of carotenoids found in various plants. They were first identified in 1966 as root exudates from cotton plants. The first naturally occurring SL identified was “Strigol” (Faizan et al., 2020). Strigolactones (SLs) are primarily synthesized in the roots and stems of plants and are transported through the xylem. Various monocots and dicots, such as sorghum, maize, cotton, cowpea, and red clover, have been identified as producers of SLs (Faizan*,* et al., 2020). To date, approximately twenty-five different SLs have been extracted from various plants. Some of these include strigol, orobanchol, sorgolactone, 20-epi-orobanchol, solanacol, and sorgomol (Samynathan et al., 2024). The most common naturally occurring SLs are characterized by a butenolide ring (D-ring) and a tricyclic ring (ABC-ring). These rings are connected by an enol-ether bridge in canonical SLs, while non-canonical SLs may have less conserved structures.

Strigolactones have the ability to induce spore germination in certain amyloid fungi Because of a labile ether bond that hydrolyzes spontaneously in water, strigolactones have a short lifespan in the rhizosphere (Schrey, 2014). It has been claimed that this transient compound's perception can serve as a trustworthy signal of the vicinity of a host root due to its sharp concentration gradient (Parniske, 2005). Remarkably, fifty years ago, the same family of chemicals was discovered to be a powerful inducer of germination for the seeds of the parasitic plant species Striga (Nelson, 2021).The finding that strigolactones function as signals for AM fungus has demonstrated that Striga species take advantage of an old and conserved communication mechanism between symbiotic fungi and their host plants (Parniske, 2005).

**7. Significance role of AMF**

***7.1 AMF in soil fertility***

AMF can improve nutrient acquisition and hence overcome nutritional limitation to plant growth, as demonstrated by tens of thousands of tests (Aggarwal, 2011). While P uptake has been the focus of most research, mycorrhizae have also been linked to the uptake of other vital minerals (smith et al., 2011). In comparison to uninfected roots, fungal hyphae offer a greater surface area for nutrient absorption to the external root surface, which accounts for the increase in inorganic nutrient intake in mycorrhizal plants (Kleinert, 2018). The fungus mycelium can come into touch with uninfected roots, occasionally those of different host species, as it spreads through the soil and scavenges for mineral nutrients (Karaman, 2012). Compared to roots, the small extra-radical mycelium can penetrate various crystalline minerals, aggregates, and organic substances because its holes are smaller than those that a root alone could. Furthermore, enzyme secretion can solubilize inaccessible forms of phosphate (Rawat et al., 2021).

***7.2 AMF in phosphorus absorption***

Phosphorus (P) is a necessary plant nutrient that is part of genetic material, building blocks, and plays a significant role in the transmission of energy. In the crust of the earth, it is the tenth most prevalent element (Bhatla et al., 2018). The majority of P is found in the inorganic fraction as organic and very little P is soluble, and the remainder is found in the primary (apatite) and secondary Pbearing minerals of Fe, Al, and Ca (Condron, and Newman, 2011). Crop P requirements are minimal in comparison to N and K. Nonetheless, due to plants' restricted access to P, crops require fertilization (Wang et al., 2008). Furthermore, applied P undergoes instantaneous transformation, fixes or precipitates as insoluble compounds, or is strongly adsorbed onto the soil's surface and/or Fe/Al hydroxides (Desouza Blaise, 2018). The main benefits of mycorrhizae include an increase in phosphorus uptake by plants. The process of phosphorus uptake involves three sub-processes (Bhatet al., 2017). (i) absorption from the soil by AMF hyphae, (ii) translocation along the hyphae from external to internal mycelia (root cortex), and (iii) the transfer of phosphate to cortical root cells . There are various mechanisms proposed to explain the enhanced nutrient uptake (Ortaş and Rafique, 2017) including: (i) increased exploration of soil; (ii) increased translocation of phosphorus into plants through arbuscules; (iii) modification of the root environment; (iv) efficient utilization of phosphorus within plants; (v) efficient transfer of phosphorus to plant roots; and (vi) increased storage of absorbed phosphorus. AMF phosphatases have the ability to convert organic phosphorus sources into minerals. Alkaline phosphatase activity is associated with the phosphate metabolism of fungi, as it is found within fungal vacuoles where polyphosphate granules are present. These polyphosphate granules in the fine branches of arbuscules are broken down by enzymatic activities, releasing inorganic phosphorus in the cytoplasm (Albi and Serrano, 2016).

***7.3 AMF in nitrogen uptake***

Nitrogen (N) is one of the most important macronutrients that significantly affect plant growth and yield production. There are different ways to supply nitrogen to plants, including the use of chemical and biological fertilization. (Barłog et al., 2022). When using chemical fertilization, it's important to supply the proper amounts of nitrogen while considering the economic and environmental aspects of nitrogen compounds (Miransari and Mackenzie, 2010a, b, c). Biological fertilization can be achieved by utilizing soil microbes such as plant growth-promoting rhizobacteria (PGPR), including nitrogen-fixing bacteria like rhizobium (Zabihi et al., 2010).

Additionally, arbuscular mycorrhizal (AM) fungi can be used as a source of biological fertilization. AM fungi are soil fungi that form symbiotic associations with most terrestrial plants (Sadhana, 2014). In this symbiosis, the fungi provide the host plant with water and nutrients in exchange for carbon (Smith and Read, 2008). Arbuscular mycorrhizal (AM) fungi can also influence the uptake of other nutrients necessary for plant growth and yield production, including nitrogen (N). McFarland et al. (2010) indicated that more than 50% of the plant's nitrogen requirement was supplied by the mycorrhizal association. Since nitrogen is one of the most important macro-nutrients significantly affecting plant growth and yield production, it is important to determine the contribution of AM fungi to nitrogen uptake by the host plant.AM fungi have the capability to utilize inorganic nitrogen released from organic sources as well as amino acids (Miransari, 2011). The presence of AM fungi on some plant tissues during the mineralization process indicates that AM fungi are able to enter the tissues through the vascular bundle and utilize the inorganic nitrogen released by soil microbes (El Amerany, 2020). The ability of AM fungi to use soil organic matter as a source of inorganic nitrogen has yet to be fully understood (Talbot et al., 2008). However, even if AM fungi are not effective in such a process, their influence on the activity of soil mineralizing microbes may indirectly indicate their role in soil nitrogen dynamics and uptake by plants indicated that the AM fungi, can enhance the mineralization process of soil organic matter while acquiring mineral nitrogen (Miransari, 2011).

***7.4 AMF in water uptake***

Plant water relations are positively impacted by arbuscular mycorrhizal (AM) fungi, and the benefits of AM symbiosis are frequently mentioned in relation to the ability of host plants to withstand drought stress. Studies have shown that AM fungi have beneficial effects on plants during drought (Mathimaran, et al., 2017). The presence of AM fungi can significantly impact the way plants absorb water, actively or passively (Puschel et al., 2020). This is closely related to the physical traits of the plants and the intricacy of the soil environment. In a single cubic centimeter of soil, AM fungi hyphae can exceed 100 meters in length. These absorbing networks, branching dichotomously, can extend over 10 centimeters away from the roots (Püschelet al., 2020). When considering the efficiency of nutrient absorption, mycorrhizal hyphae dramatically outperform plant roots alone, enhancing the surface area available for absorption by as much as 100 times (Willis et al., 2013). Additionally, mycorrhizal hyphae, typically about 2 μm in diameter can penetrate soil pores with diameters of less than 30 μm, which are not accessible to the roots allowing them to access resources in these areas (Wang, et al., 2022). These highly branched hyphae can significantly enhance plant water uptake as roots grow through moist soil and the hyphae acquire water from small pores that are physically inaccessible to the roots (Puschel et al.,2020). Moreover, the "runner" or "arterial" hyphae act as highly efficient channels for water transport, enabling plants to access remote water sources even in challenging environments. This remarkable adaptation not only enhances their survival but also promotes robust growth in areas where water is scarce (Püschel et al., 2020). Additionally, under drought stress conditions, arbuscular mycorrhizal fungi (AMF) can influence plants by increasing transpiration rate, reducing stomatal resistance, and altering the balance of plant hormones (Hameed et al., 2014). The change in leaf elasticity due to AMF inoculation improves water and turgor potential of leaves, increases root length and depth and may also influence water relations and the drought resistance of the plants. Mycorrhizal plants have enhanced water and nutrient uptake rates, which can be attributed to better distribution of absorbing hyphal network, more favorable geometry of hyphae compared to roots, greater surface area and faster extension rate, increased functional longevity, chemical alteration in the soil rhizosphere, altered rhizosphere microbial population, uptake kinetics, greater hydraulic conductivities, lower transportation rates per unit leaf area, extraction of water from soil to lower water potentials, and more rapid recovery from water stress (Bitterlich et al., 2018).

***7.5 AMF in Carbon Sequestration***

AM fungi affect the exchange of carbon (C) between plants and the atmosphere. The plant trades soil nutrients, particularly phosphorus (P), for carbon through photosynthesis (Parihar, et al., 2020). Carbon is then transferred from the host plant to the fungal hyphae inside the roots and further into the soil environment. Estimating the quantity of fungal hyphae turnover in the soil, which is related to the hyphal network inside the roots, is challenging (Figueiredo, et al.,2021). Additionally, the generation of soil aggregates by the fungal hyphae, known as rhizodeposition, may aid in carbon sequestration in the soil (Solaiman, 2024). Glomalin, a glycoprotein containing 30–40% carbon (C), is incredibly stable and persistent in soil. Its high carbon and aggregate stability allow it to sequester more carbon in the soil. Glomalin related soil protein (GRSP) is exclusively produced by arbuscular mycorrhizal fungi (AMF) such as Acaulosporamorroaiae, Glomus luteum, Glomus verruculosum, and Glomus versiforme (Hossain, 2021). Factors such as mixed primary forest, tropical rainforest, soil organic matter, clay soil, no tillage, quality and quantity of fertilizers, crop rotation, and water-stable aggregates can significantly increase glomalinproduction (Singh et al., 2017). Glomalin can sequester 0.24 Mg C ha-1 in soil when present at 1.10±0.04 mg g-1. Under elevated CO2 (700 µmol mol-1) levels, easily extractable glomalin (EEG) and total glomalin (TG) were found to be 2.76 and 5.67% SOC in the surface soil layer over ambient carbon dioxide (CO2) levels, indicating the effective function of GRSP C sequestration in soil under global environmental change scenarios (Hossain, 2021). Additionally, glomalin can protect labile carbon, helping to regulate nutrient supply to plants. GRSP proves to be an essential tool for carbon storage in deep soils, mediating soil aggregates, improving soil quality, increasing carbon sequestration and crop production, and mitigating climate change (Sonet al., 2024).

**Conclusion**

In conclusion, this review offers a thorough investigation into the developmental stages and functions of arbuscular mycorrhizal fungi (AMF), emphasizing their pivotal role in enhancing plant nutrient acquisition, especially phosphorus uptake, while also promoting robust plant growth and resilience to stress. The symbiosis between AMF and plant roots is inherently advantageous; AMF not only supports nutrient absorption but also improves soil structure and fosters a balanced ecosystem.A deep understanding of AMF's developmental journey, from spore germination to the establishment of arbuscules and vesicles, is vital for unlocking their full potential in sustainable agriculture and ecosystem management. This knowledge paves the way for innovative strategies aimed at boosting plant productivity, alleviating environmental stresses, and maintaining ecosystem health.Ultimately, this review accentuates the critical importance of AMF in terrestrial ecosystems and calls for ongoing research into their biology and applications, ensuring we maximize their benefits for future generations.

**Disclaimer (Artificial Intelligence)**

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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**Competing Interests**

Authors have declared that no competing interests exist.

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