

REVIEW

Potential of ectomycorrhizal and endomycorrhizal fungi in *Coffea* spp. plantationsAlexis Salazar-Navarro¹ , Victor Ruiz-Valdiviezo² , Jose Joya-Davila¹ , Daniel Gonzalez-Mendoza¹ ¹Instituto de Ciencias Agrícolas de la Universidad Autónoma de Baja California (ICA-UABC), Mexicali, Baja California, México²Tecnológico Nacional de México, Instituto Tecnológico de Tuxtla Gutierrez, Tuxtla Gutierrez, Chiapas, México

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ABSTRACT

The agroecosystem where coffee plantations are located can determine the longevity, health, and quality of coffee beans and plants. In this context, it is important to consider ectomycorrhizal and endomycorrhizal fungi to properly manage coffee plantations, especially in naturally shaded systems where several organisms interact with coffee plants. The microorganisms in the rhizosphere are determinant to achieve the proper nutrition in coffee plants. Endomycorrhizal or arbuscular mycorrhizal can complete a mutualistic symbiotic interaction directly with coffee plants, preparing the plants for future attacks of pathogens by maintaining their defense mechanisms alert. To date, ectomycorrhizal fungus has not been reported to establish a symbiotic interaction directly with coffee plants. Still, it is present in naturally shaded coffee plantations, probably due to their interaction with surrounding trees. Ectomycorrhizal fungi can also improve and alert the defense mechanism of plants, and Both ecto- and endomycorrhizal interactions can enhance the uptake of micro and macronutrients in coffee plants and improve the soil organic matter uptake, which can positively impact the coffee quality. This review establishes the importance of deepening research on mycorrhizal interaction with coffee plants.

Key words: Inorganic phosphorous deficiency; Myc factors; mycorrhizal-induced resistance; symbiotic interactions; systemic acquired resistance.

1 INTRODUCTION

The *Coffea* genus belongs to the *Rubiaceae* family and is cultivated in 80 countries. Within *Rubiaceae*, the *Coffea* genus has major economic importance. It comprises 124 species, but only *Coffea arabica*, *Coffea canephora*, *Coffea liberica*, and *Coffea excelsa* have the economic potential to be cultivated (Ferreira et al., 2021). Among these, *C. arabica* and *C. canephora* are the major economically important species responsible for 60-70% and 30-40% of global production, respectively. *C. canephora* is also known as robusta coffee due to its vigor, hardness, resistance to pathogen attacks, and higher caffeine content in comparison with *C. arabica* (Davis et al., 2006; Rojo Jiménez, 2014; Romero; Camili, 2019).

Coffee is native to the forest and tropical zones of Africa (Ethiopia, Sudan, Kenya, Guinea, and Mozambique) and was spread to Arabia, Yemen, and Egypt (Century XV). *C. arabica* is native to Ethiopia and Sudan and results from a natural hybridization between *Coffea eugenioides* and *C. canephora* (Batista et al., 2015; Rojo Jiménez, 2014; Romero; Camili, 2019; Scalabrin et al., 2020). These species have different contents of the alkaloid caffeine, one of the main bitter components in coffee cups: *C. eugenioides* has the lowest caffeine content, followed by *C. arabica* and *C. canephora* (Münchow et al., 2020; Ne Perrois et al., 2015; Vitzthum, 1999). The most common varieties are derived from the ancestral species in Yemen, for example, *C. arabica* var. *Typica* and *C. arabica* var. *Borbon* (Batista et al., 2015; Ne Perrois et al., 2015; Romero et al., 2010). Some *Coffea*

species result from natural hybridization between *C. arabica* and *C. canephora* and are known as Hybrids of Timor (HDT). HDT has resistance genes for Coffee Leaf Rust (CLR) caused by *Hemileia vastatrix*. Some *C. arabica* subspecies were developed by breeding, e.g. the hybrids of Catimor originated from crosses between *C. arabica* var. Caturra and HDT. Catimor hybrids were developed to produce *C. arabica* varieties resistant to CLR (Salazar-Navarro et al., 2024; Salojärvi et al., 2024).

Depending on the coffee fermentation process and roast profile, *C. arabica* beans have a variety of flavors overlapping with tea profiles (e.g., green tea, black tea, and jasmine tea), citrus fruits (the presence of citric acid and malic acid), tartaric fruits, and even acetic profiles due to the fragmentation of carbohydrates into aliphatic acids (Münchow et al., 2020; Sunarharum et al., 2014).

C. canephora is an autochthonous tree species from Uganda and South Sudan that can grow up to 10 m in height. Compared with other species, *C. canephora* has smaller cherries and beans with spherical morphology, whereas *C. arabica* beans have oval morphology. After the roasting process, *C. canephora* generally presents a bitter cup profile due to its higher caffeine and chlorogenic acid content (Nair, 2010; Ne Perrois et al., 2015; Rojo Jiménez, 2014; Romero; Camili, 2019).

Plants are colonized by diverse microorganisms both above- (phyllosphere, including fruits, flowers, leaves, and stems) and belowground (rhizosphere) (Li et al., 2021). Plants can recruit beneficial microorganisms by photosynthetic exudates, e.g. Plant Growth Promoting Rhizobacteria (PGPB)

and Plant Growth Promoting Mycorrhizae Fungi (PGPF) as arbuscular and ectomycorrhizal fungi (Wang et al., 2022). The resultant plant-microorganism interactions and their impact on plant health depend on the genotype (Vishwanathan et al., 2020).

Rhizosphere microorganisms can promote plant growth (e.g., nitrogen fixer rhizobacterium and phosphorous solubilizer mycorrhiza) and protect the host from biotic (pathogens) and abiotic stresses. These interactions can result in an increment of plant biomass in roots, aerial organs, and induction of flowering (Anzueto-Herón et al., 2023; Li et al., 2021).

In this review, we focused on the interactions in the rhizosphere as the main colonization occurs in the near area of plant roots with a diameter of 5-7 mm. In this symbiotic interaction, mycorrhizal fungi receive photosynthetic carbon-fixed products in exchange for soluble mineral nutrients such as nitrogen and phosphorous (Genre et al., 2020). These interactions improve nutrient mobility at the rhizosphere and establish communication of the biogeochemical cycles between the rhizosphere and the phyllosphere (Kebert et al., 2022). The mycorrhizas establish mutualistic interactions exclusively with plants (85% of the plants) (Dreischhoff et al., 2020; Strullu-Derrien et al., 2018).

Mycorrhizal fungi are divided into two main categories or groups: endomycorrhiza and ectomycorrhiza (ECM). The fungal hyphae of endomycorrhiza grow and penetrate root cells, forming branched structures to establish an intracellular symbiosis. Most land plants associate with arbuscular mycorrhizal fungi (AMF) from the Mucoromycota subphylum Glomeromycotina (Dreischhoff et al., 2020; Mortier et al., 2020; Prates Júnior et al., 2021; Strullu-Derrien et al., 2018). AMF are obligate biotrophs, which means they can only live and grow through a symbiotic interaction with a living host (Bonfante; Genre, 2010). AMF has been well studied due to its influence on plant defense mechanisms through mycorrhizal-induced resistance (MIR) (Kebert et al., 2022). Other endomycorrhiza fungi exist, orchid mycorrhizal fungi and ericoid mycorrhizal fungi.

In ECM, the hyphae remain extracellular, forming a network (Hartig net) between the root cortical and epidermal cells that extend outward into the surrounding soil (Chot; Reddy, 2022; Dreischhoff et al., 2020; Strullu-Derrien et al., 2018). The Hartig net provides intimate cell contact between the symbiosis partners, increasing the surface area to exchange nutrients (Stuart; Plett, 2020). ECM increases soil N mobilization and the host uptake of macro- (P, K, Ca, Mg, S, and Fe) and micronutrients (Zn, Cu, and Mn) (Stuart; Plett, 2020). The colonization of ECM reduces the cell wall cohesion of the plant host by enzymatic degradation of pectin lamellas and the space occupancy of the growing fungal hyphae (Basso et al., 2020; Genre et al., 2020). Within Basidiomycota, exclusively Hymenomycetes, and within Ascomycota, exclusively Ascomycetes form ECM (Dreischhoff et al., 2020; Kebert et

al., 2022; Strullu-Derrien et al., 2018). Several species can alter or reprogram the root development by the secretion of auxins (AUX), which promote root colonization by activating lateral root (LR) initiation with ethylene (ET) (Basso et al., 2020; Genre et al., 2020; Yan et al., 2022). ECM is usually associated with woody plants (Chot; Reddy, 2022). AMF and ECM can trigger induced systemic resistance (ISR) responses through the common symbiotic pathway (CSP) (Vishwanathan et al., 2020).

The review's objective is to analyze the possibilities of applying AMF and ECM in the management of coffee plantations. Although only AMF can establish symbiotic interactions with coffee plants, ECM can improve nutrient availability in the agroecosystem. The application of AMF and ECM involves improving nutrient uptake and activating plant defense systems, thus as an alternative in the control of coffee phytopathogens.

2 MYCORRHIZAL INTERACTIONS IN COFFEE PLANTATIONS

Agroecosystems naturally benefit coffee plantations due to forest tree shading, and their proper management can enhance the quality of coffee beans. Microorganisms of the rhizosphere play a fundamental role in nutrient dynamics and the activation of defense mechanisms, including mycorrhizal fungi. From this perspective, it is fundamental to study the effects and possibilities of ecto- and endomycorrhizal fungi in coffee agroecosystems for a healthy organic culture (Hernández-Acosta et al., 2020; Livne-Luzon et al., 2022; Perea Rojas et al., 2019; Salazar-Navarro et al., 2024; Zarza et al., 2022).

AMF has been used in agriculture since the end of the 80s in organic plantations as an alternative to synthetic fertilizers (Hernández-Acosta et al., 2020). A total of 70 species of AMF have been reported to establish symbiotic interactions with *C. arabica* and *C. canephora* plants (Júnior et al., 2019). For example, *Acaulospora mellea*, *Glomus fugeianum*, *Acaulospora scrobiculata*, and *Glomus aggregatum* were present in *C. arabica* plantations (Prates Júnior et al., 2021).

AMF improves organic matter mineralization, the uptake of water and mineral elements (e.g., P, N, and Zn), and can translocate nutrients from the bulk soil to coffee plants (Hernández-Acosta et al., 2020; Júnior et al., 2019; Prates Júnior et al., 2021). Higher availability of P was found in *Coffea arabica* var *garnica* treated with a consortium of P-solubilizing fungi, and higher content of total leaf P was observed in plants treated with a consortium of arbuscular mycorrhizal fungi, indicating that AMF can work synergically with other beneficial microorganisms (Perea Rojas et al., 2019).

Hernández-Acosta et al (2020) reported the effects of two inoculums (*Rhizophagus aggregates* only and a consortium formed by *Glomus claroides*, *Rhizophagus diaphanous*, and

Paraglomus albidum) in different *Coffea arabica* varieties (garnica, catimor, caturra, and catuai). Inoculated coffee plants showed higher biomass (increments of 177% and 1701% of in plant height and dry matter, respectively, in the garnica variety compared to control) and P content (gain of 650% in the catimor variety compared to control). In addition, plants inoculated with the consortium were healthier.

Only a few reports on the impact of ECM in coffee plantations are available, focusing on the colonization of trees around the coffee plants in agroecosystems (Livne-Luzon et al., 2022; Zarza et al., 2022). These works have taxonomically identified the ECM fungi in naturally shaded coffee plantations and their role in helping the N acquisition of surrounding plants (Avila Bayona, 2020). Together, these findings highlight the importance and opportunities to study the impact of ECM in coffee agroecosystems more deeply.

3 COLONIZATION OF AMF

A complex set of reactions is necessary to establish the symbiotic interactions between AMF and the host plant, including spore germination, hypha differentiation, formation of appressorium, root penetration, intercellular growth, formation of arbuscules, and transport of nutrients (Mitra et al., 2021). AMF spores must first find colonizable roots and catabolize a lipid reservoir to form the germination hyphae. When the spore does not find a host, the germination hyphae is retracted to the cytoplasm, and the spore becomes dormant until it receives a signal to restart the germination (Riaz et al., 2021).

The presence of strigolactones (SLs) in the soil attracts the germination hyphae to the host root system in Pi deficiency conditions (Figure 1). SLs are phytohormones that regulate root growth and architecture (e.g., they inhibit lateral root growth) and are exuded by roots. SLs stimulate the metabolism and branching of AMF, increasing the possibility of finding and colonizing the root host. SLs in the rhizosphere promote the growth of beneficial microorganisms such as AMF and rhizobia (Bonfante; Genre, 2010; Ho-Plágaro; García-Garrido, 2022; Mitra et al., 2021).

Symbionts establish chemical communication via exudates (presymbiotic signaling). The plant secretes SLs under soil inorganic phosphorous (Pi) deficiency, and the AMF secretes Myc factors in response to SLs (Figure 1) (Ahmed; Hajiboland, 2024; Ho-Plágaro; García-Garrido, 2022; Robdrup et al., 2024). In host cells, this process is regulated by the transcription factor (PHRs) involved in Pi deficiency responses (Ahmed; Hajiboland, 2024). PHR1 regulates genes involved in the Phosphate Starvation Response (PSR) and helps in the symbiosis establishment by remodeling the lipid membrane and reducing pathogen defense, which reshapes the microbiome in the rhizosphere (Hajiboland; Ahmed, 2024; Isidra-Arellano et al., 2021;

Puga et al., 2024). PHR2 is involved in the biosynthesis of cutin monomers and SLs (Hajiboland; Ahmed, 2024).

Myc factors are involved in the common symbiosis pathway (SYM) and are exuded by AMF via diffusion to the rhizosphere. They are signaling molecules containing a chitin oligosaccharide backbone with an N-acyl group and can be recognized as lipochitooligosaccharides Myc-LCOs and as short-chain chitin oligomers Myc-Cos (Ho-Plágaro; García-Garrido, 2022; Wu et al., 2021). Myc factors are recognized by the lysin motif receptor-like kinases in the cell membrane of the root cells (Bonfante; Genre, 2010; Ho-Plágaro; García-Garrido, 2022; Wu et al., 2021).

The recognition of Myc factors starts several responses that modify the root epidermal cells (referred to as SYM) at different levels, not only in AMF but also in nitrogen-fixing rhizobia (Bonfante; Genre, 2010; Wu et al., 2021). The recognition of Myc factors (Figure 2) stimulates the influx of calcium ions in the cytoplasm by the expression of CCaMK/DML3 (Bonfante; Genre, 2010; Ho-Plágaro; García-Garrido, 2022; Wu et al., 2021). The influx of Ca^{2+} starts a signaling cascade mediated by Ca^{2+} /calmodulin-dependent protein kinases related to the expression of *NSP1* and *NSP2*, which form a heterodimer and promote the expression of *ENOD11* and *RAM1* (Wu et al., 2021). *ENOD11* gene expression is related to the region involved in hyphopodium (Bonfante; Genre, 2010). *RAM1* is induced under Pi deficiency and is related to the synthesis of apocarotenoids and other transcription factors (Ho-Plágaro; García-Garrido, 2022).

In addition to the Myc factors, AMF secrete effectors to establish colonization (Ho-Plágaro; García-Garrido, 2022). Effectors are small proteins synthesized by microorganisms to modify the host response and facilitate colonization. Microorganisms deliver effectors to avoid host immune system responses, such as pattern-triggered immunity (PTI) and effector-trigger immunity (ETI). This mechanism is called Effector-triggered susceptibility (ETS) (Salazar-Navarro et al., 2024). The effector secreted protein 7 (SP7) interacts with the ethylene response factor (ERF), whereas SIS1 promotes the formation of arbuscules and is promoted by SLs (Ho-Plágaro; García-Garrido, 2022).

After the symbionts enter into physical contact, the AMF differentiates a hyphal structure known as hyphopodium (Figure 1) that adheres to the root host surface where the AMF starts to penetrate the root epidermal cells (Ahmed; Hajiboland, 2024; Bonfante; Genre, 2010; Tominaga et al., 2020). When the hyphopodium is established, the expression of new genes produces the prepenetration apparatus (PPA). The PPA is composed of cytoskeletal and endoplasmic reticulum components (Ahmed; Hajiboland, 2024). The PPA divides the cytoplasm of the epidermal host cell and builds the route for the AMF hypha (Bonfante; Genre, 2010). The cytoplasm reorganization is directly coordinated by the symbionts;

hence, the AMF and root epidermal cells are actively involved (Bonfante; Genre, 2010; Robdrup et al., 2024).

Once the AMF hypha reaches the outer root cortical cells, it subsequently reaches the inner cortex cells by intercellular infiltration (Figure 1 and Figure 2). The AMF hypha forms highly branched hyphae inside the cortex cells known as arbuscules, which are at the heart of the AMF symbiosis (Ahammed; Hajiboland, 2024; Bonfante; Genre, 2010). During the cytoplasm restructuring, a periarbuscular membrane (PAM) is synthesized around the arbuscule and regulates the nutrient exchange (Bonfante; Genre, 2010; Robdrup et al., 2024). The formed arbuscules are dynamic and have a few days until their collapse, which is regulated by the symbionts (Ahammed; Hajiboland, 2024).

AMF can grow outside the root system in the rhizosphere surrounding the established symbiosis (Figure 3). The formed extraradical mycelium enables the AMF to uptake nutrients (e.g., P and N) and deliver them to the host plants in exchange for photosynthates (Ahammed; Hajiboland, 2024).

4 IMPACT OF AMF ON THE DEFENSE MECHANISMS OF COFFEE PLANTS

Systemic acquired resistance (SAR) and ISR are the main studied defense mechanisms that act systematically through hormone signaling and their activation depends on the pathogen. SAR is related to biotrophic or, more precisely, hemitrophic pathogens and is activated by salicylic acid (SA) (Dreischhoff et al., 2020; Kashyap et al., 2024). In contrast, SAR responses are more associated with systemic gene expression than ISR and depend on jasmonic acid (JA) signaling and NPR1 protein (Kashyap et al., 2024; Vishwanathan et al., 2020). The SAR pathway is activated by recognizing pathogen- or microbe-associated molecular patterns (PAMPs or MAMPs). These molecules are compounds associated with several microorganisms, such as flagellin, chitin, and lipopolysaccharides. SAR and ISR act antagonically; when SAR is active, ISR is suppressed.

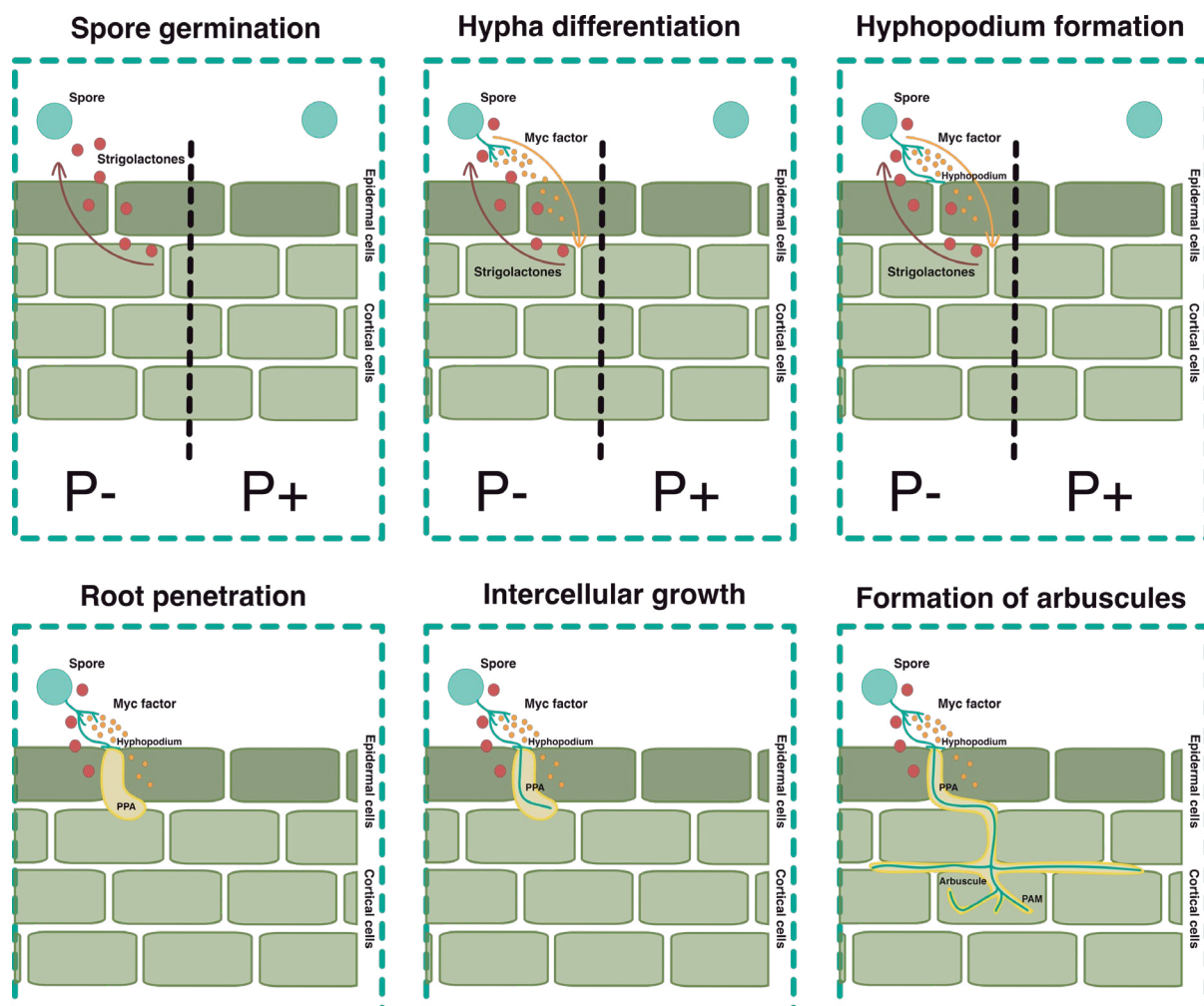


Figure 1: AMF colonization process. P- and P+ denote inorganic phosphorous deficiency and sufficiency, respectively, PPA is the prepenetration apparatus, and PAM is the periarbuscular membrane.

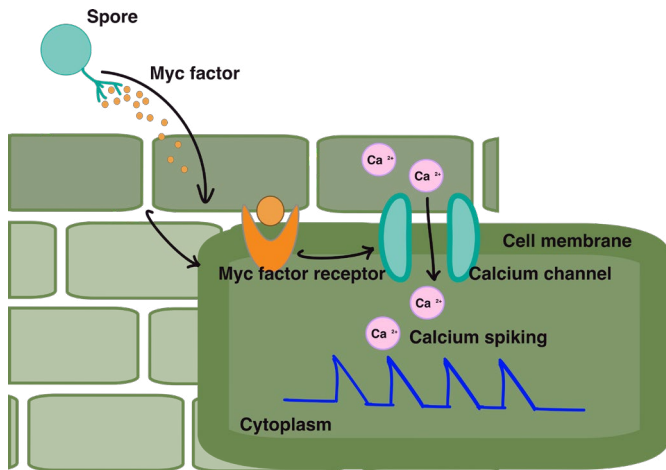


Figure 2: AMF Myc recognition and calcium spiking.

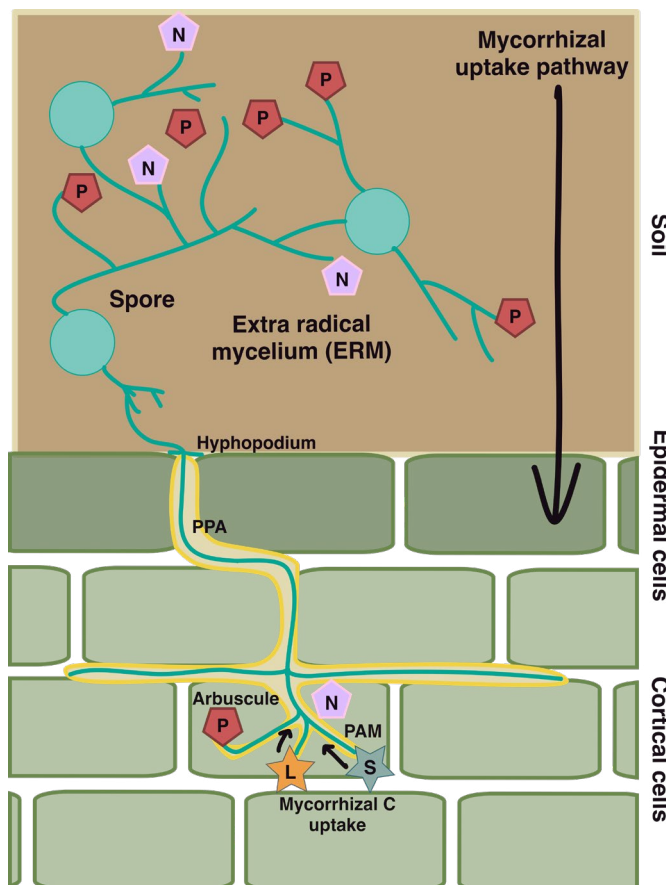


Figure 3: Nutrient exchange between root host cells and AMF. N denotes nitrogen, P phosphorous, S sugar, and L lipid.

AMF and ECM possess MAMPs on the surface of the infection structures, which are recognized by the host defense mechanism (Dowarah et al., 2022). MAMPs are recognized by transmembrane proteins known as pattern recognition receptors (PRRs) related to the activation of PTI responses (Figure 4). PTI responses include MAMP/DAMP/

PAMP triggered immunity responses (Dey; Ghosh, 2022; Dowarah et al., 2022). PRR proteins can belong to receptor-like proteins (RLP) or receptor-like kinases, which bind or release a protein to activate the immune signaling pathway (Salazar-Navarro et al., 2024).

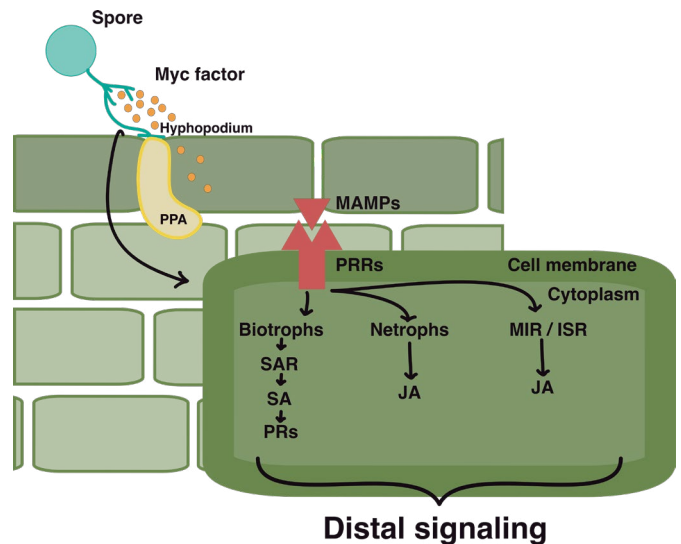


Figure 4: Signaling events during the AMF colonization.

Activation of ISR can be related to rhizosphere-dwelling microorganisms such as beneficial microorganisms (e.g., agrobacterium and mycorrhizal fungi), and their signaling pathway is less clear than SAR (Dowarah et al., 2022; Dreischhoff et al., 2020). The activation of ISR works systemically, protecting the aerial and distal parts of the plant roots (Dowarah et al., 2022). As ISR, MIR is conducted by JA (Dowarah et al., 2022). This represents an opportunity for necrotic pathogens (Dreischhoff et al., 2020). The activation of ISR mechanisms by MIR is related to cell wall thickening, accumulation of PR proteins, and callose deposition (Dowarah et al., 2022).

Besides MAMPs, R proteinase can recognize effector molecules produced by microorganisms during colonization, activating effector-trigger immunity (ETI) (Dowarah et al., 2022). The effectors are produced by microorganisms to alter the cell wall integrity and the host metabolism to avoid or suppress their defenses (Dowarah et al., 2022; Salazar-Navarro et al., 2024). The activation of ETI responses induces similar but faster, stronger, and longer effects of PTI; thus, they include hypersensitive responses (HR) characterized by the necrosis of the zone of invasion (Dowarah et al., 2022; Salazar-Navarro et al., 2024).

DAMPs/PAMPs can be represented by elicitor as exogenous molecules from microorganisms' surfaces or microorganisms' secretions (e.g. chitosan, chitosan oligosaccharides, peptides, proteins, and fatty acids derivatives). Endogenous elicitors are more related to the delivery of molecules due to damage in the cell host, such

as the enzymatic activity of the microorganism, or defense mechanisms such as HR. When the elicitor is a product of wound tissue, it is known as a damage-associated molecular pattern (DAMP) and works similarly to MAMPs/PAMPs as a systemic defense mechanism (Salazar-Navarro et al., 2024).

AMF has been studied to promote tolerance of foliar and root diseases in various plants. Root colonization by AMF can induce some structural and chemical changes at a systemic level. These changes can include structure modifications in host roots, secondary metabolite profile, modulation of phytohormones related to plant defense signaling, and expression of genes related to defense mechanisms such as the synthesis of defense enzymes and antioxidant enzymes. The modifications in the root structure can create a barrier to several phytopathogens due to thickening and lignification. Moreover, increased lignin synthesis also creates barriers in distal areas such as in leaves, xylem, and roots (Kashyap et al., 2024).

Besides the lignin barriers, plants in symbiosis with AMF increase the synthesis of glycoproteins rich in hydroxyproline (HRGP), which protects the cell wall from degradation by pathogen-secreted enzymes (Kashyap et al., 2024). The symbiosis with AMF can also induce the activation of the shikimic acid pathway, related to the production of antimicrobial compounds such as defense enzymes, phytoalexins, and phenolic compounds (Costa et al., 2023; Kashyap et al., 2024; Santos-Sánchez et al., 2019).

The induced modifications by AMF symbiosis also affect the interactions of root-knot nematodes (*Meloidogyne* nematodes) by different mechanisms. For example, reduction in quantity and quality of root exudates to nematodes and the possible interference of phenols accumulation. Lignin accumulation in host roots and the competition for space and nutrients reduce the colonization and severity of root-knot nematodes (Da Silva Campos, 2024).

5 COFFEA SPP. MAIN PHYTOPATHOGENS AND POSSIBLE INTERACTIONS WITH AMF

Coffea arabica species growth is favored in tropical, subtropical zones and equatorial regions between the Cancer and Capricorn tropics. The countries in these regions are usually called coffee belt. Regularly *Coffea* genera are cultivated at altitudes close to the sea level and up to 2,100 meters above the sea level, in a temperature range from 18°C to 22°C, and relative humidity of 60% and 80% (Patay; Bencsik; Papp, 2016). Unfortunately, the growth conditions of some coffee species favor the spread of pathogens as fungal infections, such as the case of coffee leaf rust (CLR) infection produced by *Hemileia vastatrix* fungus (Patay; Bencsik; Papp, 2016; Talhinhos et al., 2014).

CLR is one of the most severe diseases in coffee plantations. *H. vastatrix* is a biotrophic obligate parasite

and depends on its live host to germinate and reproduce. The severity of CLR can affect the coffee cup quality and productivity (reduction of up to 30%) of coffee plantations (Salazar-Navarro et al., 2024).

Besides *H. vastatrix*, other pathogens can affect coffee cultivars. The most significant are the female specimens of the insect coffee berry borer (CBB) (*Hypothenemus hampei*), which attack the developing coffee berries, making a hole in the outer skin to reach the seed where they reproduce eventually. The larvae then feed from the endosperm coffee seed, so the CBB proliferation significantly affects the yield and quality of produced coffee worldwide (more than 20 million rural families) (Damon, 2000; Jaramillo et al., 2006; Johnson et al., 2020).

Coffee leaf miner (CLM) (*Leucoptera coffeella*) is a monophagous pest considered the principal coffee pest with production losses of up to 87% depending on coffee cultivars and environmental conditions (*L. coffeella* activity and damage increase in dry seasons). *L. coffeella* penetrates the palisade parenchyma for larvae feed, forming tunnels or mines inside the coffee tree leaves. This reduces the photosynthetic area and fruit production, with eventually necrosis and defoliation (Dantas et al., 2021; Filho, 2006; Motta et al., 2021).

Coffee stem borers (CSB) are several pests that damage coffee crops, especially *C. arabica* varieties (crop losses can reach up to 93.6%) (Pandey et al., 2022; Venkatesha; Dinesh, 2012). CSB eggs are deposited into the bark, and the larvae enter, making tunnels and feeding from the cadmium and wood, making it difficult to manage the pests due to the depth of the tunnels (Pandey et al., 2022; Rajus et al., 2021; Vega et al., 2006; Venkatesha; Dinesh, 2012). CSB can delay plant growth and development or even cause the death of the host, as reported for *Plagiohammus* sp. in America (Abigail Funlayo et al., 2017; Romero; Camili, 2019; Vega et al., 2006). *Xylotrechus quadripes*, commonly known as coffee white stem borer (CWSB), can be found mainly in coffee-growing countries in South Asia (Pandey et al., 2022; Rajus et al., 2021; Vega et al., 2006; Venkatesha; Dinesh, 2012).

Cercospora coffeicola is another fungus causing coffee leaf spot disease and brown eye spot on coffee, with yield losses up to 50% (Funlayo et al., 2017; Romero; Camili, 2019; Souza et al., 2011). *C. coffeicola* can attack leaves and coffee fruits and is considered a hemibiotroph pathogen because it behaves as a biotrophic pathogen in its initial and sporulation phases and later as a necrotrophic pathogen (Andrade et al., 2021; Mukasa, 2009; Souza et al., 2011).

Mycena citricolor (American leaf spot disease) causes a severe disease with up to 56% production losses. *M. citricolor* is difficult to control mainly because it is not a specific disease of coffee and has no historical coevolution (Funlayo et al., 2017; Caitlin, 2008; Granados-Montero et al., 2020; Romero; Camili, 2019).

Nematodes also represent important damage and concern for coffee plantations and producers. *Meloidogyne exigua* and *Meloidogyne incognita* cause the most damage to coffee plantations. These nematodes cause mineral deficiency and affect the uptake of water and nutrients from the soil by the formation of giant cells and root galls (Da Silva Campos, 2024; Vallejos-Torres et al., 2021).

Symbiosis interaction between AMF and *Coffea* spp plants offers an alternative to control several diseases in coffee plantations as it improves the tolerance of coffee plants to diseases. However, this symbiosis does not confer immunity to the pathogen colonization. Just a few works reported the application of AMF in coffee plantations to control the main coffee plant pathogens. The available and recent works are focused on the interaction of AMF to induce tolerance to coffee plants against root nematodes and CLR.

A study conducted in 2022 by Vallejos-Torres and coworkers analyzed the inoculation of *C. arabica* varieties as Caturra and Pache with three different AMF consortiums. Moyobamba was composed of *Acaulospora mellea*, *A. sp.1*, *Glomus geosporum*, *G. sp.1*, and *G. sp.2*. El Dorado was composed of *A. rugosa*, *A. spinosissima*, *A. lacunosa*, *G. sp.1*, and *Ambispora appendicula*. The consortium Huallaga was composed of *A. mellea*, *A. sp.1*, *A. sp.2*, *G. macrocarpum*, and *G. sp.2*. They showed a reduction of CLR incidence in comparison to non-inoculated coffee from 43.7% to 22.1% (Moyobamba), 22.7% (El Dorado), and 13.2% (Huallaga). CLR severity was reduced in comparison to non-inoculated plants from 34.8% to 21.1% (Moyobamba), 20.4% (El Dorado), and 12% (Huallaga). The AMF consortium Huallaga had the best results for reducing CLR incidence and severity (Vallejos-Torres et al., 2023).

Besides the effects of AMF as PGPF, they also protect the inoculated host. When *C. arabica* plants were inoculated with the AMF isolates *Acaulospora longula* (Aca1) and *Gigaspora margarita* (Gig2, Gig3), they showed a reduction in infection rate against *Fusarium oxysporum* from 15% to 5% after 3 months of inoculation. Also, the Gig2 inoculated *C. arabica* plants showed an increment in plant height and leaf number from 25.7 cm and 8.3 leaves (control) to 26.9 and 9.0, respectively respectively (Trai et al., 2023).

The application of AMF against *Meloidogyne* spp. was reported by (Vallejos-Torres et al., 2021). They report a reduction of root infection severity from 7.10% to 3.37%, 4.37% and 4.38% in *C. arabica* plants inoculated with AMF consortiums denominated as Huall-pache (*A. mellea*, *A. rhemii*, *A. foveate*, *G. macrocarpum*, and *Glomus sp2*), Do-cat (*Acaulospora rugosa*, *A. spinosissima*, *A. lacunosa*, *Glomus trimurales*, *G. sinuosum*, *Paraglomus occultum*, and *Ambispora appendicula*), and Mo-cat (*A. mellea*, *A. tuberculata*, *A. rhemii*, *A. foveate*, and *Glomus sp1*), respectively. Also, the inoculated plants showed an increment in plant height, number

of branches, number of leaves, and stem diameter compared to the control plants (Vallejos-Torres et al., 2021).

6 CONCLUSIONS

As exemplified in this review, ectomycorrhizal and endomycorrhizal fungi can increase the health and quality of coffee plantations. This could be an alternative to counteract the negative impact of climate change on coffee production. Symbioses with AMF could be a stronger alternative to commercial fertilizers and commercial fungicides due to their influence on preparing the coffee plantations for the invasion of future pathogens such as biotrophic fungi (e.g. *Hemileia vastatrix*), nematodes, and others. Thus, establishing symbiosis between AMF and coffee plants can open a window of opportunities for coffee plantation management. We must continue to develop new biotechnological technologies focused on the preservation of the environment.

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8 AUTHORS' CONTRIBUTION

Conceptual idea: Salazar-Navarro, A.; Data analysis and interpretation: Valdiviezo-Ruiz, V; Joya-Davila, J.; and Writing and editing: Gonzalez-Mendoza, D.

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