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Arbuscular Mycorrhizal Fungi as Potential Agents in Augmenting Growth and Stress Tolerance in Plants

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ABSTRACT

Plants encounter a variety of difficulties when they are growing, many of which are exacerbated by increasing anthropogenic activities. Among such challenges, heavy metal accumulation in plants has raised serious concerns for the ecosystem and human health. Phytoremediation has emerged as a viable strategy to restore soil fertility without requiring expensive processes in order to solve the issue of heavy metal toxicity in an environmentally sustainable manner. However, several problems that lead to low plant growth rates due to metal toxicity in polluted soil limit the effectiveness of this technique. Arbuscular mycorrhizal fungi (AMF) effectively reduce heavy metal phytotoxicity and play a pivotal role in phytoremediation by augmenting plants' tolerance. AMF contributes to the successful remediation of contaminated sites, acts as a biofertilizer, promotes plant growth, enhances yield, and improves overall plant quality. This review summarized the potential of AMF in promoting plant development and addressing various challenges faced by plants exposed to heavy metals. It discussed the different roles that AMFs play and the mechanisms through which they contribute to phytoremediation. By understanding the beneficial effects of AMF, we can harness their potential to mitigate the detrimental impacts of anthropogenic activities and ensure the sustainable management of ecosystems.

Keywords: Mycorrhiza, Phytoremediation, Nutrient exchange, Soil fertility

INTRODUCTION

There are many biotic as well as abiotic challenges faced by plants. Phytoremediation is an eco-friendly measure to address these challenges. It is an approach in which plants are used to extract heavy metal pollutants from soil to regain soil fertility with cost-intensive methods (Yan *et al.*, 2020). Understanding the soil rhizosphere in plants exposed to stress is quite essential. The soil rhizosphere contains a variety of microorganisms that can be used in phytoremediation techniques, including bacteria, fungi, nematodes, microarthropods, and earthworms (Bhatnagar and Kumari, 2013; Balestrini *et al.*, 2015).

Arbuscular mycorrhizal fungi (AMF) are soil-borne microorganisms that are members of the subphylum Glomeromycotina and form a symbiotic association with 80% of terrestrial plants. The bidirectional exchange of resources is a hallmark and a functional necessity of mycorrhizal symbiosis. AMF colonizes plant roots and facilitates the uptake of nutrients from the soil (Campo *et al.*, 2020). They play a role in phytoremediation by mediating the interaction between plant and soil microbes, thereby enhancing nutrient uptake and heavy metal eradication from soil (Yang *et al.*, 2016). The symbiosis also helps effectively boost plant growth, yield, and quality. Thus, AMFs are also considered biofertilizers (Berruti *et al*., 2013; Kumari *et al*., 2022). The fungus spreads its mycelia as a network extending under plant roots and promotes the uptake of nutrients that are otherwise not available to plant roots (Smith and Read, 2008). AMF is distinct from other classes of fungi as it shows the formation of structures such as vesicles and arbuscles. Arbuscles are said to be the functional site of nutrient exchange (**Figure 1**) (Balestrini *et al.*, 2015).

Table 1: Effect of arbuscular mycorrhiza fungal species on host plants

Host Plants	AMF species	Functions	Reference
Cucumis sativus and *Robinia pseudoacacia*	*Funneliformis mosseae* *Rhizophagus intraradices*	It helps to increase nutrient quality, photosynthesis, and plant growth during drought	Yang *et al.,* 2016
Zea mays	*Rhizophagus intarardices*	The concentration of P, K, N, and Mg increases in roots and shoots, and plant dry weight increased	Gao *et al.,* 2020
Leymus chinensis	*Glomus mosseae*	Increased water content and seedling weight	Jiang *et al.,* 2017
Solanum lycopersicum	*Funneliformis mosseae* *Rhizophagus intraradices*	Improved root hydraulic conductance, photosynthetic rate, and stomatal conductance	Campo *et al.,* 2020
Glycine max	AMF	Proline content of leaf increases, leaf area index increased	Pavithra *et al.,* 2018
Ocimum basilicum	*Glomus deserticola*	Alleviates soil salinity	Elhindi *et al.,* 2017
Oryza sativa	*Claroideoglomus etunicatum*	Quantum yield of PSII photochemistry increased	Porcel *et al.,* 2015

There are several benefits that AMF provides to its host (**Table 1**). Colonization by AMF helps to improve nutritional quality by increasing the translocation and availability of nutrients, mainly inorganic phosphate (Campo *et al.,* 2020). AMF also produces a compound called glomalin, which maintains water content in soils and thus regulates water frequencies between soil and plants, and it triggers plant development (Wright and Upadhyaya 1998). Thus, AMF mediates host plants' growth promotion by improving the uptake of mineral nutrients and water. Increased photosynthetic rate and better stomatal conductance in mycorrhizal plants also support the idea that AM improves plant quality and yield (Campo *et al.,* 2020). Increased levels of secondary metabolites in mycorrhizal plants result in high antioxidant potential (Castellanos-Morales *et al.,* 2010). Hart *et al.* (2015) have highlighted that the dietary quality of *Solanum lycopersicum* has improved to a large degree. The study reported that colonization of *S. lycopersicum* by AMF augments the accumulation of sugars, organic acids, carotenoids, flavonoids, and ascorbate. AMF can also induce secondary metabolism in plants, leading to enhanced biosynthesis of health-promoting phytochemicals such as polyphenols, carotenoids, flavonoids, and phytoestrogens (Sbrana *et al.,* 2014). In addition, the mycobiont also forecasts other benefits, such as improved tolerance to abiotic stresses such as salinity, drought, and heavy metals (Evelin *et al.,* 2019; Gupta *et al.,* 2021; Sharma *et al.,* 2021). Subsequently, they show reduced N_2O emissions, an important greenhouse gas (Berruti *et al.*, 2013).

AM interacts with soil microbiota as bacteria, fungi, and nematodes help in plant development (Balestrini *et al.,* 2015). It contributes to disease resistance (Jacott *et al.,* 2017). The effectiveness of AM can be seen when colonization leads to soil anchorage to avoid soil erosion, which improves soil structure (Leifheit *et al.,* 2014). AM mycelium develops a matrix by cross-linking soil particles (Rillig and Mummey, 2006). Some of these methods help combat environmental pollution and broaden the scope of sustainable development (Begum *et al.,* 2019). This review focuses on the potential of AMF in plant development to maintain ecological stability and combat various challenges. The types of roles it can play and its mechanisms for contributing to phytoremediation are also being discussed.

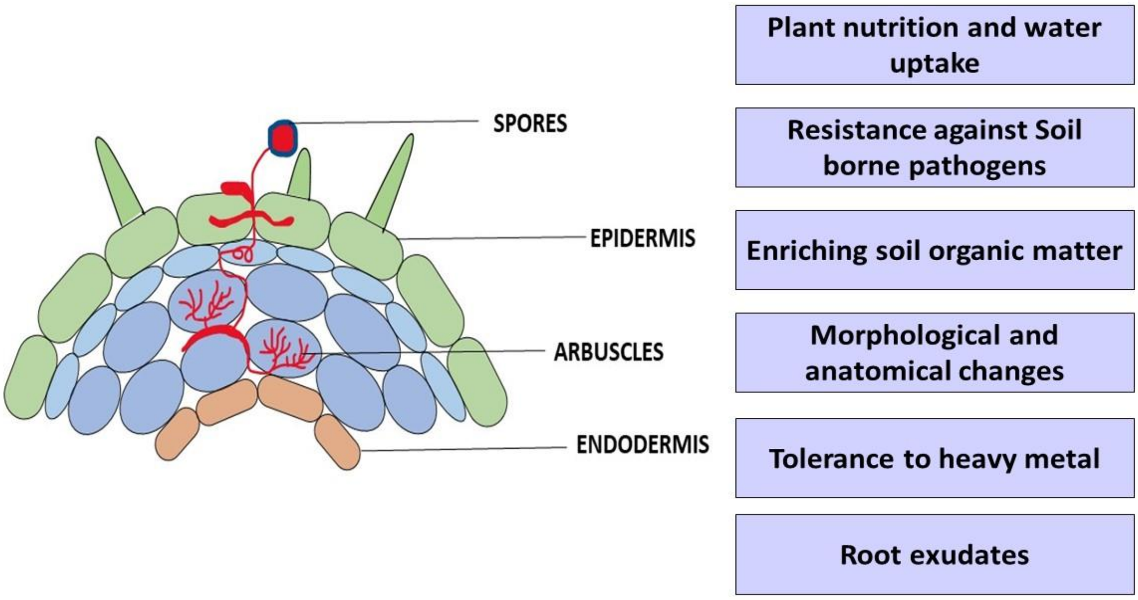

Figure 1: Formation of arbuscles in root cortex and different roles of AMF.

ROLE OF AMF IN MITIGATING STRESS IN PLANTS

Soil-borne pathogens

Arbuscular mycorrhizae protect plants against soil-borne pathogens, such as *Aphanomyces*, *Rhizoctonia*, nematodes, *Fusarium*, *Macrophomina*, *Phytophthora*, *Pythium*, and *Cylindricocladium* (**Table 2**). Changes in root morphology are due to AM colonization (de Vries *et al.*, 2021). A classic example is the protection of strawberries against *Phytophthora* infection when inoculated with *Glomus mossae* (Harrier and Watson, 2004; Weng *et al.*, 2022).

Gene expression plays a vital role in influencing plant defense responses. Genes such as phenylalanine ammonia lyase (*PAL5*) and chitinase (*Chib1*) regulate disease resistance in plants. *Glycine max* inoculated with AMF showed higher transcript levels of Chitinase (*Chib10)* and PAL aid in nematode resistance (Weng *et al.*, 2022).

Table 2: Disease resistance against soil-borne pathogens in plants inoculated with arbuscular mycorrhizal fungi

Fungal Species	Pathogen	Host plant	Reference
G. Asciculatum	*Pythium*	Barley	Aljawasim *et al*., 2020
G. etunicatum	*Phytopthora*	Peanut	Steinkellner *et al*., 2012
G. marcocarpum	*Fusarium*	Banana	Bubici *et al*., 2019
G. margarita	*Rhizoctonia*	Cotton	Aljawasim *et al*., 2020
G. heterogama	*Macrophomina*	Kidney bean	Eke *et al*., 2020

In tomato plants, *Funneliformis mossae* lowered the virus titer against the tomato yellow leaf curl Sardinia virus (Maffei *et al.*, 2014). Similar data have been collected with the cucumber green mottling virus and tobacco mosaic virus in tobacco and cucumber, respectively (Evelin *et al.*, 2023). Inoculation with *R. irregularis* increased resistance to these viruses (Hao *et al.*, 2019). Pea root rot caused by *Pythium ultimatum* is reduced (Poveda *et al.*, 2020). In order to prevent disease, some plants are known to produce anti-fungal (polyphenols) and anti-bacterial (polymyxin B) substances. *G. mossae* promotes callose deposition in the roots of cucumber protecting against *Colletrichum* *orbiculare* poisoning (Bais *et al.*, 2006). Flavanoid accumulation is increased at invasion sites of AMF leading to an increased infection rate (Gao *et al.*, 2006).

Soil organic matter

Soil organic matter (SOM) is intensively improved by exudates of extraradical hyphae, stabilizing soil structure and quality (Zhou *et al.*, 2020). Assuming enhanced C transport to microbial communities, AMF promotes litter breakdown and improves N collection (Fierer *et al.*, 2009; Brzostek *et al.*, 2015). Root exudates produce labile substrates that further lead to SOM turnover due to the increased growth of microorganisms. There is a synergistic relationship between AMF and microorganisms. They enhance nutrient acquisition, biogeochemical cycling efficiency, and organic matter solubilization (Gessner *et al.*, 2010). AMF inoculation creates an abundance of macroaggregates by binding agents such as glomalin-related proteins, enabling physically protected rhizodeposition of C against microbial degradation (Rillig and Mummey, 2006). Glomalin protects against soil erosion by chelating heavy metal ions, improving carbon sequestration, and stabilizing soil macroaggregates (Fall *et al.*, 2022).

Tolerance to heavy metals

Heavy metals have adverse effects on plant growth and yield. They are believed to cause inhibition in cell expansion, growth, absorption of mineral nutrients (Jian Zhou *et al.*, 2018; Adeyemi *et al.*, 2021), inhibition in photosynthesis, and mineral uptake (Abdelhameed *et al.*, 2019). AMFs are generally believed to support plant establishment in soils contaminated with heavy metals (Hildebrandt *et al.*, 1999; Audet and Charest, 2006). Owing to their potential for strengthening the defense system of AMF-colonized plants (Garg and Chandel, 2012; Sharma and Kayang, 2017). Tannery sludge-contaminated soil in Kanpur, UP, led to the discovery of many AMF species tolerant to heavy metals (Khade *et al.*, 2009). AMFs act as biofilters to limit the uptake of heavy metals (Dhalaria *et al.*, 2020). The strong effects of AMF on the plant defense system under severely stressful conditions are most often due to the ability of these fungi to increase morphological and physiological processes that increase plant biomass (Riaz *et al.*, 2021; Gupta *et al.*, 2022). AMF contributes to the immobilization of heavy metals such as Cd and Zn in the cell walls of mantle hyphae and cortical cells, further restricting their uptake (de Andrade *et al.*, 2008; Garg and Chandel, 2012). Heavy metals can also be fixed in the cell wall to store and chelate in the cytoplasm with some substances (Punamiya *et al.*, 2010; Begum *et al.*, 2019) and reduce metal toxicity in plants. By reducing the bioavailability of heavy metals in soil, mycorrhizae also interfere with the uptake of heavy metals by plants from the rhizosphere and their transfer from the root zone to the aerial portions. This is due to their ability to modulate soil pH and the complexation of heavy metals to glomalin (Gonzalez-Chavez et al., 2002; Evelin et al., 2023). Furthermore, colonization enhances leaf protection by retaining heavy metals, leading to phytostabilization (Dhalaria *et al.*, 2020). The phenomenon of metal dilution in plant tissues occurs when chelation is done in rhizospheric soil (Begum *et al.*, 2019; Kapoor *et al.*, 2013). It is believed that improved plant growth or the chelation of heavy metals in the rhizospheric soil can lead to a metal dilution in plant tissues (Zhang *et al.*, 2020).

Glycine max showed the retention of heavy metals in its roots (Adeyemi *et al.*, 2021). Inoculation with *Rhizophagus intaradices*, *Glomus versiforme*, and *Funneliformis mossae* decreased Pb concentrations in pakchoi plants (Wu *et al.*, 2016; Dhalaria *et al.*, 2020). Cd tolerance increased in *Aster tripolium* (Carvalho *et al.*, 2006; Dhalaria *et al.*, 2020). Extraradical mycelium of *Glomus* shows Cu accumulation (Gonzalez-Chavez *et al.*, 2002; Kumar and Saxena, 2019). *Trifolium* repens and *Festuca rubra* showed Zn tolerance because of *Glomus* sp. (Kumar and Saxena, 2019). *Festuca* and *Agropyron* showed Zn, Cd, As, and Se tolerance when colonized with *R. intraradices, F. mossae*, and *Gigaspora gigantea* (Riaz *et al.*, 2021). *Rhizophagus fasciculatus*, *Trichoderma pseudokoningii,* and *Helianthus annus* mutually decontaminated toxic metals from tannery sludge (Riaz *et al.*, 2021).

Overall, AMF aids plants in the alleviation of heavy metal toxicity in plants by immobilizing the metal compound, adsorbing it to the fungal cell wall or chelating it inside the fungus or with soil, and dilution of metal toxicity brought about by improved uptake of nutrient elements and consequently increasing plant biomass.

Root exudates

Plant roots secrete a myriad of valuable compounds such as mucilage, free oxygen, ions, enzymes, citric acid, oxalic acid, and malic acids that detoxify Al in soil (Bais *et al.,* 2006). Root exudates build the rhizosphere for AM and plant interactions. Fungal spore germination (Bucking *et al.,* 2012) and hyphal growth are indicators of its applicability (Nagata *et al.,* 2016). Flavanoid secreted by plant roots helps in fungal spore germination. These compounds present in root exudates, such as fatty acids, strigolactones, and isoflavonoids, directly affect fungal colonization (Tian *et al.,* 2021). The symbiotic relationship between plant microbes and root exudates could also be an important factor in plant growth. Due to the accumulation of phenolics, *Phytopthora parasitica* growth was reduced in tomato plants after colonization with *G. mosseae* (Monther *et al.*, 2012). Root exudates also suppress pathogen infections by releasing toxic secondary metabolites in the rhizosphere. Root exudates play the role of metal chelators to create an abundance of nutrients like iron, manganese, copper, zinc, etc. Metal chelators form complexes with soil to increase metal solubility and mobility (Dhalaria *et al.*, 2020).

Strigolactones secreted out by plants such as maize, pearl millet, tomato, and red clover serve the purpose of AMF colonization under P-deficit conditions and parasite eradication. *Elymus repens* root exudates facilitate aphid repulsion in *Vicia faba* (Guerrieri *et al.,* 2002) and *Phaseoulus lunatus* (Bruin and Sabelis, 2001; Bais *et al.,* 2006) by producing volatile compounds or exudates, which are produced under normal conditions to attract aphids and predatory mites, respectively. This attraction of predators induces a plant signal to inform the plant of biotic stress and generate biocontrol efforts. This phenomenon is known as induced herbivore defense responses (Bais *et al.,* 2006).

MECHANISMS BY WHICH AM HELPS IN STRESS TOLERANCE IN PLANTS

Competition for colonization and infection sites

When a resource is limited by nature and is required by several organisms at once, competition develops. The soil microbiota consists of several microorganisms that possess almost the same phycological requirements in an ecological niche (Vos *et al*., 2013; Schouteden *et al*., 2015a). AMF and pathogens colonize the same host tissue and are known to develop in the same cortical cells. AMF competes with microorganisms for carbon supply (Vos *et al*., 2013).

There is a defined space within the soil matrix for growth. Thus, it seems plausible that competition for space also occurs between AMF-PPN (Plant Parasitic Nematode) in the roots (Jung *et al*., 2012; Schouteden *et al*., 2015). Mycorrhizal arbuscles occupy space in the cortex, which exerts a negative effect on the PPN since migratory endoparasitic nematodes also feed here (Bell *et al*., 2021). Feeding cells of nematodes extend into the cortex, and these cells are called syncytia. Syncytia is formed at the endodermis and hence, is not influenced much due to the presence of AMF. There are many other examples to quote, such as sedentary endoparasitic and ectoparasitic nematodes. *Meloidogyne incognita* reproduction rate decreases due to the production of spores by AMF, *Scutellospora heterogamy,* in sweet passion fruit (Anjos *et al*., 2010). AMF colonization has been reported to help coffee plants evade the attack of *Meloidogyne exigua* (Alban *et al*., 2013). It is proposed that arbuscules are formed before the nematode infestation, allowing coffee plants to regain the energy lost by the parasitic interaction. It becomes more difficult for nematodes to penetrate and enter plant roots as a result of AM's induction of lignification of the plant cuticle (Alguacil *et al.,* 2011). However, *Radopholus similis* and *P. coffae* in association with AMF and *R. irregularis* do not show a strong biocontrol effect (Schouteden *et al*., 2015). A similar case was observed in AM-colonized tomatoes where *M. incognitia* infection was lower in non-colonized tomato plants (Vos *et al*., 2012). *Glomus mosseae* and *Phytopthora nicotiana* variants parasitic in tomato lead to an increase in the AMF population at the root apex site (Steinkellner *et al*., 2012; Ahmad *et al*., 2020). Another example of completion for colonization and infection sites between AMF and the plant pathogen *Phytophthora* is tomatoes, where the pathogen does not enter the arbuscular-containing cells (Cordier *et al*., 1996).

Competition for host photosynthates

AMF and plant pathogens are known to acquire the same sites in host plant roots. This limits plant resources and increases competition between them. Plant roots serve the function of cycling and dividing nutrients to maintain a mutualistic relationship with AMF. When AMF provides plants with a sufficient amount of nutrition, photosynthates are secreted by host plants to maintain mutualism (Kiers *et al*., 2011; Bell *et al*., 2021). A similar pattern is followed for plant parasitic nematodes and AMF. Photosynthates are automatically allocated to AMF rather than nematodes, reducing nematode survival (Bell *et al*., 2021).

AMF- PPN symbiosis with plant hosts has three cases:

1. When PPN takes up all nutrition from the host plant, nutrient transfer from AMF halts, leading to a reduction in nutrition and plant carbon sink. This may affect AMF's relationship with the host severely (Bell *et al*., 2021).
2. Sometimes, while the carbon resource and plant nutrition are directed towards parasites, AMF still contributes to cycling nutrients to the host, which may get lost later to pathogens only. This creates an asymmetrical transfer of AMF to parasitic species. Due to limiting nutrients, AMF may acquire them from neighboring plants to fulfill the lack of it. So, even though a parasite invades the host plant, nutrient acquisition takes place under normal conditions (Whiteside *et al*., 2019).
3. Some host plants may have the ability to differentiate between beneficial and antagonistic symbiotic partners. When they identify such partners, they stop allocating nutrients and shut down their photosynthate mobilization. Photosynthates are directed towards AMF, and by shutting down the photosynthate mobilization, carbon waste is being stopped. Limitations in the nutrient supply create hindrance in the life cycle and survival of nematodes.

Rhizosphere deposition

Soil pores contain many bacteria and microorganisms that feed on sloughed-off plant cells, and this phenomenon is known as rhizodeposition. Any material lost from plant root cells, including water-soluble exudates, secretions of insoluble materials, lysates, dead fine roots, and gases like CO_2 and ethylene, can also be referred to as root loss. AMF colonization increases root exudation (Schouteden *et al.,* 2015). It subsequently helps in events such as hatching, chemotaxis, and host localization of PPN. Root exudates of AMF symbionts are imperative when compared to non-symbionts such as sugars, organic acids (Gupta, 2003; Schouteden *et al.,* 2015), amino acids (Harrier and Watson, 2004), phenolic compounds (Mcarthur *et al.,*1992), flavonoids (Steinkellner *et al.,* 2007), and strigolactones (López-Ráez *et al.,* 2011). The nutrition requirement of microbes is also fulfilled by AMF. It is widely reported by Lioussanne *et al.* (2008) that *Phytopthora nicotianae* zoospores were attracted to *R. irregularis*. However, the colonized root exudates switched suddenly to repellency depending on the maturity stage of AMF colonization (Vos *et al.,* 2013).

Meloidogyne incognitia root penetration was negatively affected due to AMF root exudate application (Vos *et al.,* 2013). In the second stage, infected juveniles were temporally paralyzed in the presence of tomato root exudates. This made colonized plants unsurpassed when compared to non-colonized banana plants (Vos *et al.,* 2013). *Pseudomonas fluroscens is* a type of plant-growth-promoting bacteria that gets attracted to mycorrhizal plants. They also tend to elicit *Trichoderma spp.,* which can affect them (Dong *et al.,* 2006). Host root exudates can induce spores to germinate and the mycelium growth of ectomycorrhizal fungi (Jones *et al.,* 2004). Mycorrhizal helper bacteria produce substrate-stimulating mycorrhizal growth either by direct or indirect detoxification of harmful substances. AMF secretes glycoproteins and glomalin into the soil environment (Wright and Upadhyaya, 1998). Sometimes exuded compounds are reabsorbed. Rapid turnover of extraradical hyphae, measured to be 5-6 days in the case of AM hyphae, represents a large input of carbon into the soil environment.

Damage compensation

Soil pathogens are antagonistic toward host plants. They are known to severely affect plant functionality and biomass production (Ahmad *et al.,* 2020). AMF is substantially helpful in compensating for this loss caused by several fungi and nematodes (Cordier *et al.,* 1996). They increased the tolerance of host plants to pathogens (Hildebrandt *et al.,* 2007). Root function is hampered by pathogen activity. AMF promote plant growth by boosting nutrient uptake as their extra-matrical hyphae penetrate deeper realms of soil nutrient reservoirs and acquire nutrients that are otherwise not accessible to the plant (Smith and Read, 2008), which helps the plant rejuvenate the damage caused by pathogens (Ahmad *et al.*, 2020).

Soil microbial population

Many benefits are shared by the host plant due to mycorrhizal association, which enhances microbial activity. Microbial activity promotes phytohormone production, specific enzymatic activity, and plant protection from diseases by producing antibiotic and pathogen-depressing subsets such as siderophores (Kamnev and van der Lelie, 2000; Khan, 2005). Microbes detect the signal molecules, which further initiate the multiplication of the microbial population and spread over the root surface as a biofilm layer. In turn, this elicits systematic actions whenever a certain population density is attained (Harrier and Watson, 2004). Quorum sensing combines with various other regulatory systems. This enhances the environmental signal range. It targets gene expression beyond population density (Daniels *et al.,* 2004; Khan, 2005). The N-acyl homoserine reaction is an example of a quorum-sensing signal molecule that helps regulate the expression and regulation of symbol genes (Daniels *et al.,* 2004).

PGPR, in combination with AMF, increases the efficiency of plants to tolerate stress. Fermicutes (*Clostridia* and *Bacillus*) show a gradual increase in abundance with AMF inoculation (Nanjundappa *et al.,* 2019). Actinobacteria and certain bacteriocytes are also reported to decrease in number in the presence of AMF (Nuccio *et al.*, 2013). While Fermiculates and Bacterodetes display their decomposer activity, members of Clostridia produce a multienzyme cellulosome complex that aids in the effective degradation of cellulose (Bayer *et al.,* 1998; Nuccio *et al.,* 2013).

Activation of plant defense response

AMF contributes to regulating plant defense responses and thus protecting them from biotic and abiotic stresses. The first step in defense responses involves the recognition of the foreign invader by plant cells. In the initial stages, beneficial organisms are identified as putative pathogens because of microbe-associated molecular patterns (MAMPs). Some sequences are conserved between pathogenic fungi and beneficial organisms (Pieterse *et al.,* 2009; Zamioudis *et al.,* 2012). Then MAMPs are recognized, and a MAMP-triggered response is activated. This readily leads to hormonal and transcriptional changes in host plants (Schouteden *et al.,* 2015). Also, some molecules are known as elicitors and are secreted by microbes or obtained because of plant cell wall damage (Garcia-Garrido and Ocmpo, 2002). Changes in cells were observed, such as the ion permeability of plasma membrane-bound enzymes, the activation of kinases, phosphatases, and phospholipases, and the production of signal molecules, including oxygen species. As a result of this, transcriptional activation of defense-related genes occurs (Somissich and Hahlbrock, 1998; Garcia-Garrido and Ocmpo, 2002). AMF also secretes certain compounds, such as chitin, which is known to be an inducer of defense responses. AMF also helps in improving tolerance against biotic and abiotic stress (Dowarah *et al.,* 2022; Kumari *et al.,* 2022). *G. intraradices* induce phytoalexin synthesis in soybean cotyledons (Garcia-Garrido and Ocmpo, 2002).

Another mechanism for defense response could be developed during AMF development. Carbohydrate levels have a positive relationship with AMF. Cells with arbuscles are greater sucrose sinks than cortical cells without arbuscles (Luginbuehl and Oldroyd, 2017). This leads to the efficient transcriptional activation of the defense gene (Blee and Anderson, 1998). However, the role of defense mechanisms that are activated as a result of stress during the interaction with AMF is unclear.

Oxidative bursts or the production of reactive oxygen species may be indicators of the activation of defense responses. It is depicted in *G. intararadices* which attempted to penetrate the cortical cell of *Medicago truncatula.* Cell death and necrosis are reported in *Gigaspora margarita* infections of *Medicago sativa* roots. Defense responses are characterized by callose deposition, PR-1 protein, phenolics, etc. and are observed in some plants (Garcia-Garrido and Ocmpo, 2002).

CONCLUSION AND FUTURE PERSPECTIVES

Arbuscular mycorrhizal fungi are essential to ecosystem health and sustainable development. The potential applications of AMF in biocontrol, biofertilizer, stress response, activation of plant defenses, etc. are the main emphasis of this paper. AMF forms symbiotic, mutualistic relationships with its hosts to efficiently contribute to the development of nutrient-rich soil reservoirs. Numerous studies also emphasized the significance of AMF in modifying plant anatomy, root morphology, and vesicle formation, all of which improve crop quality and productivity. Networks of mycelial cells help to mitigate the harmful effects of soil-borne diseases. AMF increases the activity of plant root exudation. There are lots of secondary metabolites that can be used in industry. AMF's strong competitive ability allows plants to utilize more photosynthates. Mycorrhiza blocks infection sites, making it challenging for pathogens to attack and spread disease. Plants frequently experience stress conditions and parasitic infections. Such a succession of actions compromises the health of the plant. These fungi replenish and rejuvenate through damage-compensating mechanisms. AMF triggers stress-responsive factors. The secretion of various compounds by AMF develops signals for enzymes, receptors, and other members that exhibit stress-regulating mechanisms. AMF has favourable effects on plant development. These instances demonstrate how AMF promotes plant health and improves and replenishes the environment around it. The use of AMF in agriculture can improve agricultural yield, crop quality, and resilience beneficial to the economy. The analysis of AMF using more plant species is better suited to understand its interactions and impacts. Extensive metabolomic, transcriptomic, and genomic research can provide a clear picture of the processes causing these impacts. Products based on AMF can create a sizable market in the near future.

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