Insights on the potentials of Arbuscular mycorrhizal fungi as a bio-control agent

Sadhana Rai, Rakhi Raj Maurya

Abstract— **Over the past few decades, interest has been grown in the variety of arbuscular mycorrhizal fungi in an environment and the plant communities. Majority of all known land plants have symbiotic relationships with arbuscular mycorrhizal fungi. It significantly promotes plant development, water uptake, mineral feeding and defence against abiotic and biotic stressors. This review reveals the basic mechanisms that are conclusively connected with plant-AMF interaction, phytochemical treatments, and its function in promoting human health. In addition, the AMF symbiosis aids in the survival and development of the plant's secondary metabolism. This review includes the properties of arbuscular mycorrhizal fungi linked to the host plant selection, quick adaptation to the biotic/abiotic stress, and the functional distinctions in host plant growth response. In most of the findings includes, AMF association aids the plant survival and application of phytochemicals as a bio-control agents showing nematocidal and larvicidal activities.**

Keywords: **AMF, biotic/abiotic stress, bio-control agent, nematocidal activity, larvicidal activity.**

I. Introduction

Given the fact that the term "fungus" and "root" are Greek in origin, "mycorrhiza" literally means "root fungus." In actuality, the word "mycorrhiza" is used to refer to a wide range of symbiotic relationships between fungus and plants. Arbuscular mycorrhizal fungi are soil microbes that colonize the majority of plant roots, forming a connection between the plant and its substrate, aid in the generation of plant growth hormones, boost nutrient availability, and also suppress root infections. Controlling different agricultural diseases requires an effective management system in order to supply enough food for the world's expanding population (Ayaz *et al*., 2021). The glomeromycotan fungi, often known as "Arbuscular mycorrhizal fungi" or AMF are well known for their significant ecological contributions. The bulk of land plants receive their inorganic nutrients, primarily phosphorus, but also nitrogen, trace elements, and water, from AM fungus. The quantity of AMF species is probably a determining factor in how well AMF provides ecological services (Sheng *et al*., 2022).

AMF have been present on the Earth for over 600 million year and they have lost their ability to exist independently due to long interactions with plants, and their life cycle can only be completed in the presence of host plant. Around 80% of terrestrial plant species form a mycorrhizal symbiosis with AMF (Wang & Qiu, 2006), and the arbuscular mycorrhizal symbiosis is the most common type of mycorrhizal symbiosis that does not have a host plant specialization (Klironomos, 2000). Arbuscular mycorrhizal fungi are obligatory symbionts that cannot survive without their host plant, colonizing plant roots through spores, hyphae, or infected root fragments (Klironomos & Hart, 2002). The majority of plants that develop in their natural environment have fungal relationships with their roots, which are referred to as "fungus-roots" or mycorrhizae.

Sadhana Rai, Research scholar of Botany, Nims University Rajasthan Jaipur, India, 8887866823.

Rakhi R Maurya, Research scholar of Botany, Nims University Rajasthan Jaipur, India, 9082285599.

The fast-expanding population is putting more and more demand for food as a result of industrialization, urbanization, and globalization, which are reducing the amount of arable land and decreasing agricultural productivity. Furthermore, the harsh weather brought on by changing climatic conditions has increased the frequency of droughts, heat waves, and floods, all of which have an impact on the food supply derived from agricultural systems (Kastner *et al*., 2021). By growing root systems, the AMF fungal mycelium influences plants and improves their ability to absorb water and minerals from the soil (Smith & Read, 1997). Numerous bacterial genera have shown considerable promises as a biocontrol agent for different kinds of plant diseases. It has been demonstrated that fungi are crucial in averting serious illnesses in vital crops (Zubair *et al*., 2022). Different strategies are used by biocontrol agents to shield plants from disease invasion. To lessen plant illness, they may interact with the pathogen directly or may be indirectly through one or more mechanisms (Ayaz *et al*., 2021).

As part of our study, a thorough review of the present state of knowledge on AMF and its potential use as a biocontrol agent in stressful circumstances will be given.

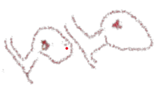
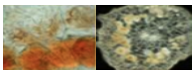
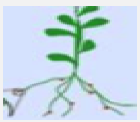
1.1 Introduction to symbiotic fungal association with plants

Most of the terrestrial plants have mutual interactions within their roots, with fungus. Pervasive symbioses called mycorrhizas facilitate the transfer of resources and energy between soils and the plants (Cardon *et al*, 2007). However, the word "mycorrhiza" suggests that fungi are associated with roots. Ectomycorrhizas and endomycorrhizas are the two primary types of mycorrhizas. They differ significantly in their structural makeup and physiological connections with mutualism. More than 6000 species of fungus that are classified as mycorrhizal include those in the Ascomycotina, Basidiomycotina, and Zygomycotina families. They are all found in close proximity to tree roots, which unites them despite their varied biodiversity. Their symbiotic relationships provide a steady flow of nutrients. On the other hand, the biology of mycorrhizal fungi in their pre-symbiotic stage has received minimal research. Propagules, which are asexual or sexual spores, and hyphae, which can grow independently of the host plant and can be solitary or bundled in highly structured bundles and rhizomorphs, are their pre- symbiotic structures. They are essential for nutrient mobilization, life cycle completion, and survival.

1.2 Fungal Mycorrhizal association with plants

Mycorrhizae are symbiotic relationships that occur between plant roots and fungus. Their main objective is to enhance the amount of nutrients and water that the host plant receives by utilizing more soil than can be achieved by roots alone. Mycorrhizae can take on a range of sizes and forms, contingent upon the taxonomy of fungus and the host plant. The distribution of these forms within ecosystems is influenced by both environmental conditions and the spread of host plants. The capacity of mycorrhizae to enhance the host plant nutrition and water intake, as well as to increase root pathogen and grazing protection, may have an effect on the host plant's performance. By differently modifying the performance of various species within the community, mycorrhizae can affect the makeup of plant communities, increase competition, and produce synergism through resource sharing. The comparison of different [lant and fungus interactions are showing in table 1.

Table 1- Comparison of different plant fungus interaction

Table 1- Comparison of different plant fungus interaction Association Types	Plant	Fungus
Mycorrhiza 	+	+
Myco-heterotrophic 	+	-
Antagonism 	-	-
Parasitism 	-	+
Endophytism 	+	+

+ = Beneficial; - = Harmful

1.3 Way of association supports the survival of plants

Mycorrhizae may be beneficial to crops cultivated in low-nutrient soils. Mycorrhizal linkages can lead to increased concentrations of nutrients in plant tissue, particularly those that need to diffuse towards roots in order to be absorbed (such as P and Zn). Because of this, mycorrhizal management is starting to show promise as a crop nutrient control method, even if there are still a lot of real-world obstacles to be solved. In addition to providing plants with nutrients through their mycorrhizal connections, mycorrhizae may also compete with fungal diseases for the infection of plant roots. Instead of creating a fungal mantle over the root, endotrophic or vesicular-arbuscular (VA) mycorrhizal fungi develop ovoid vesicles and branched arbuscules inside the plant root cells. Most people consider the interaction between plants and the arbuscular mycorrhizal fungus to be mutualistic. This beneficial effect could be eliminated, though, if the fungal-plant interaction's benefits change with colonization density. The interaction between AM fungus and host roots necessitates a constant flow of various signals that support the healthy growth of their symbiotic connection. Important signaling molecules known to control a variety of plant growth and developmental processes are called phytohormones. (Gutjahr, 2014).

We also investigated if plant performance and tolerance were similarly affected by a whole soil community gathered beneath a native congener. Midway along the inoculation gradient, plant performance peaked at an inoculum concentration, indicating the occurrence of an ideal level of AM fungal concentration that maximized arbuscular mycorrhizal fungus advantages. The colonization of roots by fungal hyphae increased linearly along the gradient of the experimental injection.

The site and the host plant's nutritional state have a significant impact on the mycelial development rate. Nutrient deficiencies, such as phosphate deficit, encourage mycorrhizal infection; whereas, well fertilized soil inhibits infection. Additionally, there is a connection between the quantity of bacteria and fungi on the root surface, which is directly linked to biomass, and the amount of nitrogen in the shoot. It is probably more that increasing nitrogen in plant produces higher microbial growth through the increased exudation, even if it is still possible for it to happen that way. This relationship is especially helpful in the forest system where site preparation, species competition, and spacing continue to affect site productivity.

1.4 – Relationship Between water and plants

Most of the compelling explanation for arbuscular mycorrhiza induced changes in plant water balance and drought resistance is most likely the indirect "little plant/big plant" effects connected with modifications in plant development and phenology brought on by better phosphorus and other nutrient acquisition. Plant size, which is often influenced by AM symbiosis, affects water relations. Plant size effects can sometimes be more pronounced in drier soils since larger plants might have more widespread access to the soil water storage because of their larger root systems. Even if diet is adjusted to take plant size into consideration, mycorrhizal impact is still evident. While most studies on AM fungi have concentrated on their impact on plant nutrition, mycorrhizal plants' resistance to drought is also gaining increasing attention (Allen and Boosalis, 1983).

1.5 Arbuscular mycorrhizal life cycle

The 450 million years old AMF is arguably the oldest and the most prevalent kinds of mutualism in the planet. With the advent of new mycocentric approaches to the mutualism, recent research has made great progress in understanding the life cycles of these seemingly enigmatic fungal symbionts. Once a suitable root is colonized by hyphae which is produced by arbuscular mycorrhizal fungal soil propagules, mycorrhizal roots or asexual spores, the arbuscular mycorrhizal symbiosis is established (Requena *et al*., 1996). Furthermore, one of the world's oldest and most pervasive mutualistic connections is the arbuscular mycorrhizal symbiosis. It involves a mutualistic relationship between a class of fungi called AMF and specific plant root.

Fungus enters the cortex by an appressorium to connect a hypha to the root surface. Once inside, it creates distinct morphologically specialized structures, including intracellular and intercellular hyphae, coils, and arbuscules. The amount that a plant benefits from an infestation with AM fungi depends largely on its surroundings. Thus, AM might promote intraspecific rivalry and give preference to mycorrhizal plants in particular. This may be the explanation for the persistence of arbuscular mycorrhizal fungus symbiosis over incredibly long evolutionary times in most land plant species. An issue arises because different types of plants may have different arbuscular mycorrhizal fungal partners, and because single fungal mycelium can infect multiple host plant. As a result, more research is done on the benefits of the complexity of mycorrhizal connections through common mycorrhizal networks (CMNs) (Jakobsen and Hammer, 2015).

1.6 Role of AMF in ecosystem

From bryophytes to tracheophytes, over 80% of land plant species establish mutualistic relationships with AMF (Smith, 2008). The development of this mutualistic relationship, which is considered to have occurred 460 million years ago, was essential for the emergence of terrestrial plants (Redecker, 2000). Within the host plant's root cortical cells, AMF creates highly branched fungal structures called arbuscules, which they use to trade inorganic minerals, particularly carbon and phosphorus atoms. An arbuscular mycorrhizal fungus is one of the most common rhizosphere organisms; connections with more than 200,000 different host plant species have been reported. Furthermore, substantial genetic diversity in arbuscular mycorrhizal fungi has been recorded between species even within one AMF spore. This have an effect on several key processes, including as colonization rates, hyphae production that is not radical, and phosphate uptake by AMF (Angelard, 2010). Through the facilitation of several complex communication procedures between fungus and the plants, AMF help to host plants for growing more vigorously under stress. This result was to improved water intake as well as enhanced properties relating to gas exchange and photosynthetic rate. Fungal symbiosis has been shown to increase resilience against a kind of stressors, including temperature, salinity, metals, herbivory and diseases. AM fungi have non nutritional effects such as stabilizing soil aggregates, preventing erosion, and reducing plant stresses which is caused by abiotic and biotic factors. As human needs and desires have grown, ecosystems are under more stress, there is a greater global demand for natural resources, and ecosystem services are being significantly reduced. As recompense for its symbiotic roles, the plant gives the AM fungus fixed carbon. Carbon transfer has been likened to interactions between plant pathogens, specifically hexoses, despite the long-held belief that it takes the form of carbohydrates. Numerous studies have actually demonstrated that AM fungus can actually absorb and use carbohydrates, but only in the roots' symbiotic environment (Roth and Paszkowski, 2017). AM fungi have been shown that fungus have a significant effect on soil nutrients uptake, plant biomass, and the plant resistance to diseases and stress in plants cultivated in artificial, non-symbiotic conditions. On the other hand, it has been demonstrated thus far that AM fungus cannot be cultured in absence of the host. Because such fungi cannot absorb carbohydrates from sources other than plant cells, they are mandatory biotrophs, meaning that their growth and reproduction are entirely dependent on their green hosts. According to evolutionary theory, the ecological success of AM fungi showed that the advantages of having such a strong bond with plants have exceeded the dangers associated with the lack of saprotrophic power. The role of AMF in an ecosystem are shown in table 2.

Table 2 – The Role of AMF symbiosis as service provider in an ecosystem

Function of arbuscular mycorrhizal fungi	**service provided in an Ecosystem**
Changes in root shape and the emergence of a sophisticated, ramifying mycelial network in the soil	Increase soil stability and plant/soil adhesion (binding action and improvement of soil structure)
increasing plant absorption of water and minerals	increase plant growth while decreasing the need for fertiliser
Buffering effect against abiotic stresses	enhanced ability of plants to withstand drought, salt, heavy metal contamination, and loss of vital nutrients
"Glomalin" secretion into the soil	Improved water retention and soil stability
prevention of pathogen of root	improved plant tolerance to the biotic stressors and decreased reliance on phytochemicals
Altering physiology and metabolism of the plants	Biocontrol of the plant growth and improvement of plant quality for health of humans

Mycorrhizal fungi may affect the host plant's ability to fix atmospheric CO_2 by improving the sink effect and the movement of photo assimilates from aerial portions to roots.

In light of the significance of arbuscular mycorrhizal fungi and the developments in research pertaining to their applications in the agriculture, current review highlighted on the role of AMF as bio-fertilizers in the regulation of plant growth and development with improved nutrient uptake under stressful environments, as well as the extent to which arbuscular mycorrhizal fungi can increase plant growth under stressful environment. As public products, ecosystem services lack a formal market and are generally not included in society's balance sheet, despite the fact that many people believe they are unaffected, unlimited, and free. Many researchers have been fascinated by this very exchange because of its intricate physiological, biochemical, molecular, and ultrastructural characteristics. This is why work at the organismal level, such as the study of individual plant-fungal modules, is so popular.

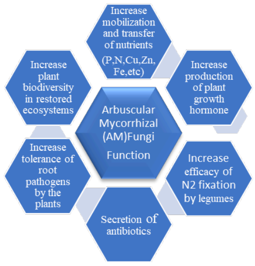


Fig 1- Overview of the diversity of AM symbiosis in terrestrial habitats

II. CROP PLANT TOLERANCE INCREASED BY AMF AGAINST ABIOTIC STRESSES

The interaction between the plants and arbuscular mycorrhizal fungi increases tolerance to the biotic challenges as well as abiotic issues like salinity and drought. Abiotic stresses affect broad misfortunes to agricultural crops. Mineral consumption, dry spell, saltiness, heavy metal or warm are genuine issues in numerous sections of the world, as in specific parched and semi bone-dry regions. Abiotic pressures on crop output have been made worse by climate change as well as agricultural malpractices such excessive use of pesticides and fertilizers. Abiotic stressors like drought, salt, and extremely high or low temperatures are related because they all make it harder for plant cells to access water and nutrients. Abiotic stresses, including salinity (Nadeem *et al*., 2007; Al-Khaliel, 2010), drought (Saleem *et al*., 2007), extreme heat (Canci and Toker, 2009), organic contaminants (Arshad *et al*., 2007), nutrient deficiency (Arevalo *et al*., 2005), and heavy metals (Kumar *et al*. 2008). AMF is also thought to provide resistance to a range of stressful circumstances, such as heat, salinity, drought, metals, and severe temperatures, when it is injected into host plants. Abiotic stressors obstruct the growth and productivity of plants. We desperately require environmentally friendly crop management techniques, such as the use of arbuscular mycorrhizal fungus as A "bio-fertilizer" is what AMF is referred to as.

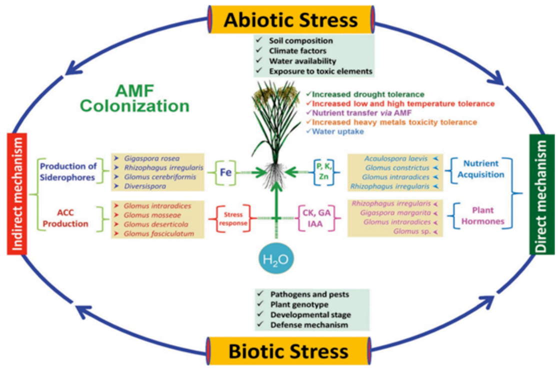


Fig 2- Schematic representation of AMF colonization and their potential position in plant growth management and promotion of abiotic and biotic stresses and uptake of various nutrients (Anand *et al*., 2022).

2.1 –Plant growth promoting organisms

Plant-growth-promoting microbes (PGPMs) activate host defense mechanisms against pathogens, aid in effective root colonization, engage in competition with other soil microorganisms, and support plant development through a variety of ways (Rabbee *et al*., 2023). Plant growth promoting rhizofungi and plant-growth promoting rhizobacteria which combat plant diseases, are examples of biocontrol agents (BCAs) found in PGPMs. Previous research revealed that many crop protection techniques have employed Bacillus, Pseudomonas, Actinobacteria, and Lactobacillus. By producing additional significant phytohormones including gibberellins and cytokinins, PGPR strains are also able to tolerate stress (Gu *et al*., 2022). Through many processes, biocontrol agents aid in the promotion of plant development. However, further research using contemporary methods for plant-microbiological interactions is still necessary.

2.2 - Increase soil stability-

A newly published meta-analysis emphasized the role of Arbuscular mycorrhizal fungi and plant symbiotic interactions in plant uptake of micronutrients. Similar to how AMF hyphae and plant roots recruit and work with certain microbial populations through their secretions to ensure effective phosphorus utilization (Zhou *et al*., 2022). The mycelial network can adhere to the soil and strengthen its structure. Additionally, AM fungus secrete hydrophobic, "sticky" proteinaceous compounds known as a glomalin (Rillig *et al*., 2002) which contributes to water retention and soil stability (Bedini *et al*., 2009). Amount of nutrients in the soil play an important role in the early stages of AMF colonization. In a glasshouse experiment, wheat was cultivated, and high soil phosphorus concentration was linked to reduced AMF colonization (Solaiman *et al*., 2019). In addition to nutrients, soil metabolites also influence AMF colonization.

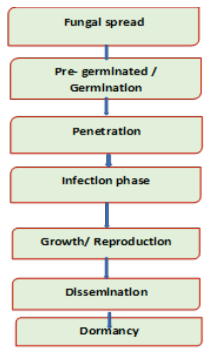


Fig 3- Stages of diseases caused by fungi

III. AMF SCAVENGING THE PLANTS FROM BIOTIC STRESSORS

Conventional agriculture has employed a lot of insecticides and plant breeding initiatives to create disease-resistant plants in an effort to stop the spread of pests that severely reduce crop yields. Considering that green plants provide the majority of other species with energy, it is not unexpected that plants have engaged in a variety of defense mechanism that can be constitutively activated in response to damage. AM protects host plants from a wide range of biotic stresses through functioning either alone or in conjunction with other related bacteria that live in locations that are directly impacted by the plant. AM-colonized plants develop more quickly and are more resistant to plant diseases. On the other hands, pesticides often provide only a limited level of protection against diseases spread through the soil. The use of many pesticides is being phased out due to its harmful results on human health and environment. Moreover, a single plant gene frequently results in the disease resistance that plant breeding programmes generate, and this gene can be easily circumvented by the evolutionary diversification of pathogenic organisms. To provide long-term disease resistance in plants, complementary techniques must be developed. By upregulating tolerance procedure and inhibiting the downregulation of significant metabolic pathways, arbuscular mycorrhizal fungus may benefit host plants.

Mycorrhizal plants benefit from arbuscular mycorrhizal symbiosis, a symbiotic interaction between plant roots and soil fungi that increases phosphorus and other scarcely transportable nutrient absorption. The onset of banana root rot symptoms was significantly influenced by the AM fungus. The higher development of mycorrhizal banana plant was linked with a decreased degree of illness. Because of this, the arbuscular mycorrhizal fungal mutually primarily affected the host pest connection by boosting Phosphorus nutrition and thus enhancing resistance to fungus that infect roots. In the recent years, research has identified significant variations in wheat genotypes with different ploidy numbers or origins in plant sensitivity and/or responsiveness to AMF (De vita *et al*., 2018).

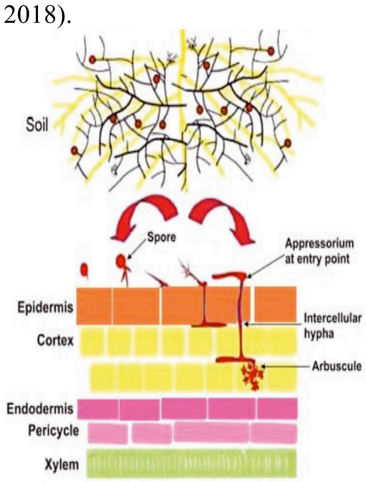


Fig 4 - Chain of events resulted to AM symbiosis development (Neera Garg *et al*., 2010)

3.1 - AMF in nutrient Connectivity and as Biofertilizer agent

Natural root symbionts called AMF help host plants grow and produce more in both stressed and unstressed settings by supplying them with vital inorganic plant nutrients. The action of AMF as a biofertilizer may improve crop's capacity to adapt to changing conditions. The organization of biological communities is shaped by multitrophic interactions, which are tremendous forces. Plants interact with a wide range of creatures in their environment; some are useful, such as symbiotic fungus and pollinators of insects. Even others are harmful, such as herbivore pests and pathogenic germs. For proper growth and development, plants need 16 various kinds of macro- and micronutrients, including N, P, K, aluminium, boron, copper, calcium, chlorine, iron, magnesium, nickel, molybdenum, selenium, and zinc. The inorganic or fixed form of those nutrients is typically absorbed from soil or air. Due to overuse and contamination, the amount of inorganic or fixed nutrients in soil has now been depleted, and chemically produced fertiliser has been used since the start of the green revolution to me*et al*l of the needs of plants (Khan *et al*., 2017). The usage of chemical goods in agricultural farms has led to issues with pollution and the degradation of soil quality. AMF utilization has recently been taken into consideration, along with other nutrient solubilizing or fixing microorganisms (Cozzolino *et al*., 2013). AMF are crucial in moving nutrients from the soil to the plants (Pfeffer *et al*., 1999).

Mycorrhizal hyphae, which connect the plant roots to the soil, are the conduits through which nutrients are transferred to the plants. AMF has been linked to increased nutrient mobilisation, including that of N, P, Zn, and Ca (Sadhana., 2014).

Mycorrhizal fungi are really valuable because they help plants, which are the main producers in ecosystems, get the irregularly distributed nutrients they need to develop. This facilitates the movement of high energy compounds required for the mobilization of nutrients and serves as a means of returning mobilized products to the hosts. One of the three essential mineral supplements linked to agriculture is phosphate, a basic mineral supplement for plant growth. Shake phosphate supplies are limited, and most phosphate mines will eventually run out of phosphate because to know global phosphate reserves.

3.2 - AMF as bio- control agent

By reducing pathogen populations and enhancing plant resistance to diseases, biocontrol of plant pathogens is a very effective way to increase plant production. These biocontrol agents may be imported from another country or may be derived from local soil microorganisms. In general, biocontrol agents offer a variety of advantages, including compatibility with sustainable agriculture, safety and risk-free use, and resistance to the development of chemical pesticide resistance. In the rhizosphere, BCA competes with pathogens for resources and space. It also hinders pathogens' pathogenicity by using a variety of compounds, including lipopeptides, enzymes, volatiles, bacteriocins and biosurfactants which have antimicrobial properties by inhibiting pathogen growth or metabolic activities. Because biocontrol agents suppress the synthesis of signal molecules that initiate infections, it may interfere with germs' ability to sense quorum. Making QS inhibitors, which are able to degrade QS signal molecules including lactonases, pectinases, and chitinases, is one example. These inhibitors lessen the symptoms of plant diseases by preventing pathogen invasion (Saeki *et al*., 2020).

Arbuscular Mycorrhizal (AM) fungi, which operate as a bio-protector of plants, are one type of such biocontrol agent. Considerable emphasis has also been paid to the study of fungal strains as a biocontrol agent for the prevention of crop diseases. Prospective biopesticides for field research or greenhouse studies, these fungus-based biocontrol agents show strong antagonistic action against wide range of airborne plant diseases and soil (Zubair *et al*., 2021). BCAs have the potential to indirectly protect plants in addition to directly interacting with them by inducing a defence response or encouraging plant development. The main reason for BCAs' decreased field efficiency is their capacity to adjust to the biotic and abiotic environmental variables in their area.

The main technique used in sustainable field which have aims to reduce the use of fungicides and utilise as an alternative management strategy to control soil borne pathogens, is biological control of plant pathogens. According to Azcon Aguilar and Barea (1997), biocontrol agents can be described as accurate management of the common components of the agricultural field of an ecosystem against diseases. Several agricultural practises, including crop rotation, the use of fungicides, resistant cultivar seed certification, and others, were used to combat soil-borne diseases. Due to challenges in lowering the pathogen inoculum, controlling diseases with long-term persistent living structures is fraught with difficulties. Numerous researchers have examined the defence function of mychorrhizal symbiosis against soil-borne pathogens. Erman (2011), Schonbeck (1979), Tahat (2008), etc. They came to the conclusion that arbuscular mycorrhizal associations can lessen negative effects of soil borne pathogens by the following mechanisms: plant damage compensation, competition for infection or colonisation sites, improve plant nutrition uptake, changes in the root system and rhizosphere.

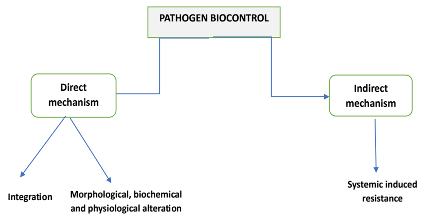


Fig 5- Biocontrol of pathogen (Kalamulla *et al*, 2022)

Enough information will be available from this assessment to understand the state of biocontrol techniques for sustainable agriculture both now and in the future. Table 3 lists a variety of fungal biocontrol agents and bacterial biocontrol agents against plant diseases.

Table 3. Fungal and bacterial biocontrol strains against various plant pathogens

Plant Species	**Pathogens**	**Biocontrol Agents**	**Mode of Action**	**Ref.**
	Bacterial strains			
Citrus fruit	Blue mold	*Bacillus megaterium*	In vitro antagonistic activity against post-harvest disease	Mohammadi *et al.*, 2017
Brassica campestris L	*Sclerotinia sclerotiorum*	*Bacillus thuringiensis*	Suppressing *S. sclerotiorum* growth by inducing systemic resistance	Wang *et al.*, 2020
Wheat	*Stagonospora nodorum* Berk	*Bacillus subtilis* 26DCryChS	Antimicrobial metabolites (surfactants showed antifungal activity against *S. nodorum* disease)	Maksimov *et al.*, 2020
Cotton/black root rot	*Thielaviopsis basicola*	*Paenibacillus alvei* K-165	K-165 inhibited *T. basicola* growth *invitro* through antibiosis and significantly reduced root discoloration and hypocotyl lesions on cotton seedlings	Schoina *et al.*, 2011
Rice	*Aphelenchoides besseyi*	*Bacillus* spp. GBSC56, SYST2, and FZB42	Antimicrobial VOCs of *Bacillus* spp. Showed the strongest nematicidal activity and accumulated ROS as well as promoted rice growth	Ali *et al.*, 2023
Rice	*Xanthomonas oryzae* pv. *Oryzae* (Xoo)	*Bacillus atrophaeus* FA12 and *B. cabrialesii* FA26	In vitro, antagonistic activity against various fungal pathogens significantly reduced Xoo lesions in greenhouse conditions	Rajer *et al.*, 2022
Rice	*Aphelenchoides besseyi*	*Bacillus thuringiensis* GBAC46	In vitro antagonistic activity through various proteins (Cry31Aa, Cry73Aa, and Cry40ORF) and in greenhouse conditions	Liang *et al.*,2022

Rice	*Magnaporthe oryzae*	*Pseudomonas putida* BP25	BP25 showed strong biocontrol activity against blasts caused by *M. oryzae*	Patel *et al.*, 2021
Wheat and Maize	*Fusarium graminearum* and *Fusarium verticillioides*	*Bacillus Subtilis* ATCC6633	Antimicrobial mycosubtilin showed a strong antagonistic activity against *F. graminearum* and *F. verticillioides* in vitro and in vivo	Yu *et al.*, 2021
Tomato	*Meloidogyne incognita*	*Bacillus atrophaeus* GBSC56	Antimicrobial VOCs showed nematicidal activity and also produced ROS in nematodes	Ayaz *et al.*, 2021
Tomato and Soybean	*Phytophthora sojae* and *Ralstonia solanacearum*	*Bacillus velezensis* DMW1	Antimicrobial metabolites (fengycin, iturin, and bacillomycin) demonstrated antagonistic activity in vitro and in pot experiments	Yu *et al.*, 2023
Soybean and Rice	*Xanthomonas axonopodis* pv. *Glycines*, and *Burkholderia glumae*	*Pseudomonas parafulva* JBCS1880	Strong antagonism and antibacterial activity against *Xanthomonas axonopodis* pv. *Glycines* and *Burkholderia glumae*	Kakembo *et al.*, 2019
Maize	*Pantoea ananatis* DZ-12	*Pseudomonas protegens* Pf-5	Antimicrobial pyoluteorin showed strong antagonistic activity against *P. ananatis* in vitro and in vivo	Gu *et al.*, 2022
Pepper	*Phytophthora capsici*	*Bacillus licheniformis* BL06	BL06 effectively reduced pepper *Phytophthora* blight severity in vitro and pot experiments	Li *et al.*, 2020
Wheat	*Fusarium graminearum*	*Bacillus atrophaeus strain* TS1	TS1 was found as a potential biocontrol agent to inhibit *F. graminearum* under low temperatures	Zubair *et al.*, 2021
Rape Seed and Tabaco	*Sclerotinia sclerotiorum*	*Bacillus amyloliquefaciens* EZ1509	*Bacillus* strain EZ1509 showed a strong antifungal activity against *S. sclerotiorum* and also led to the development of new biopesticides	Farzand *et al.*, 2019
Tomato	*Sclerotinia sclerotiorum*	*Bacillus amyloliquefaciens* FZB42	Antimicrobial potential (fengycin-induced systemic resistance in tomatoes against *S. sclerotiorum*)	Farzand *et al.*, 2019
Tomato	*Ralstonia solanacearum* and *Xanthomonas euvesicatoria*	*Streptomyces* sp. AN090126	*Streptomyces* sp. AN090126 can combine with antibiotics effectively control different bacterial plant diseases	Le *et al.*, 2022
	Fungal strains			
Pineapple	*Meloidogyne javanica*	*Purpureocillium lilacinum*	The application of *P. lilacinum* significantly reduced nematode egg and egg mass production, reducing root galling damage in pineapple	Kiriga *et al.*, 2018
Tomato	*Meloidogyne javanica*	*Paecilomyces lilacinus*	*P. lilacinum* is used as a biocontrol agent to control *M. incognita* and as a better alternative against chemical nematicides	Hanawi 2016
Cabbage	*Sclerotinia sclerotiorum*	*Trichoderma hamatum*	*T. hamatum* LU593 reduced apothecial	Jones *et al.*,

			production, decreased disease severity index, and could potentially control *S. sclerotiorum* disease in cabbage	2014
Mango	*Colletrotrichum gloeosporiodes*	*Trichoderma asperellum T8a*	*T. asperellum* T8a plays a role in biological control against *C. gloeosporioides* and controlling anthracnose disease in mangoes	De los Santos *et al*., 2013
Carrot	*Meloidogyne incognita*	*Pochonia chlamydosporia*	*P. chlamydosporia* reduced nematode galls and also decreased juvenile 2 nematodes in vitro and pot experiment methods	Bontempo *et al*., 2017
Okra	*Meloidogyne incognita*	*Trichoderma virens*	*T. virens* observed a reduction in second-stage juveniles' hatching periods tested in vitro	Tariq *et al*., 2018
Beans	*Sclerotinia sclerotiorum*	*Trichoderma asperellum*	*T. asperellum* the reduced disease severity index and antagonistic activity against *S. sclerotiorum* in field trials of beans	Geraldine*et al*., 2013
Onion	*Sclerotium cepivorum*	*Trichoderma asperellum*	*T. asperellum* BCC1 exerts efficient biocontrol against *S. cepivorum* and activates onion systemic defenses against *S. cepivorum* under greenhouse conditions	Rivera *et al*., 2020

The host responds to this by going through a variety of molecular and the biochemical mechanisms which works as a barrier against different infections. Useful microorganisms can also increase plant development by improving the absorption of nutrients and water or by generating compounds like hormones that keep plants fit. When there is an ideal relationship, the biocontrol agent's effectiveness increases. Consequently, timing the application of BCAs is essential for efficient biocontrol. Biocontrol works best when the antagonist is used prior to the infection being entrenched.

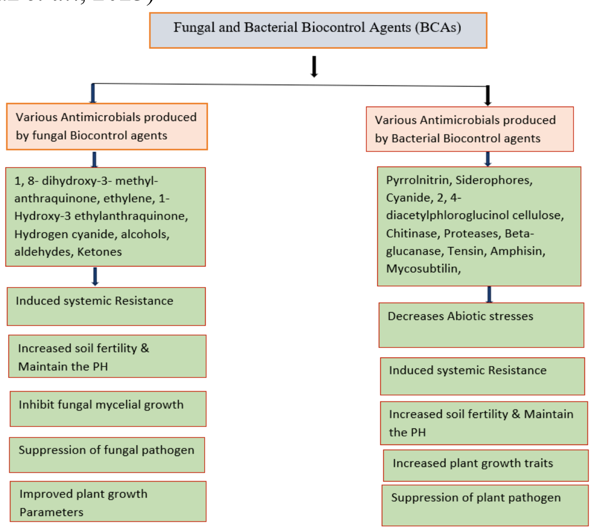
3.2.1- Biocontrol of Phytopathogenic Fungi by AM Fungi

AMF have the greatest impact on illnesses that are transmitted through the soil because they dwell there and infect plant roots (Li *et al*., 2021). Plant pathogenic bacteria and viruses come in second place in terms of their contribution to the overall loss in crop output. The use of agrochemicals, which are administered to different plant areas, has long been used to manage phytopathogens. According to Bodker *et al*., (2002), the continuous uses of these chemicals that have harmful impacts on the environment, that harm water bodies, soil, plants, animals, and human health. AMF is frequently employed as a biological control technique to eradicate several phytopathogenic fungus (Lin *et al*., 2021). Peas were infected with Aphanomyces euteiches by Slezack *et al*., who discovered that complete AMF symbiosis is necessary for plant defence against pathogens. AMF-mediated plant disease control has frequently employed the model pathogenic fungus Phytophthora (Krzyzaniak *et al*., 2021).

3.2.2- Biocontrol of Phytopathogenic Bacteria by AM Fungi

Observations of interactions between the AM fungus and other rhizosphere inhabitants, biological insecticides, and diazotrophic bacteria have been made (Nemec, 1994), and these interactions often result in discernible alterations in plant growth and development. The incidence of P. syringae pv. mori bacterial blights were significantly decrease in mulberry plant inoculated with Glomus fasciculatum or G. mosseae and phosphate, according to Sharma *et al*., 1995.

Table 4- Different antimicrobial products produced by fungus and bacteria and their effects on the plant pathogens (Ayaz *et al*., 2023)



3.2.3 - - Biocontrol of Nematicidal and larvicidal by AM Fungi

Siddiqui and Akhtar (2009) found that P. Chrysogenum can be used either by itself or in combination with Arbuscular mycorrhizal fungus, Aspergillus niger, and rhizobacteria that promote plant growth to decrease nematode infection. According to Cooper and Grandison's 1986 study, the majority of studies on Arbuscular mycorrhizal fungi and plant parasitic nematodes discovered that the root colonization of AM fungi inlarge the host's tolerance to Meloidogyne species, such as tomato to Meloidogyne hapla. Plant roots are a source of food and shelter for both plant parasitic nematodes and arbuscular mycorrhizal fungi. A few plants parasitic nematodes are important commercial agricultural pests. The most powerful nematodes must be replaced with nematode management techniques that don't negatively impact non-target organisms since they don't fit the needs of the current environmental circumstances. Tenuzanoic acid, phytotoxic mycotoxin of several species of Alternaria, demonstrated larvicidal properties against first instar larvae of L. sericata (LD50 120 g/mL): Aphids, T. urticae, Sitophilus granarius, and D. melanogaster (La Croix *et al*., 1995). This is in contrast to other studied insects and mites from various orders as well. Endophytic fungi are expected to create bioactive chemicals that will aid in their survival in this dynamic environment, as they are a part of a complex web of interactions including the plant host, endophyte, and phytopathogen. Numerous extracts of plants and the isolated compounds from various plant groups have their potential larvicidal effects studied (Markauk *et al*., 2000). Manimaran *et al*. investigated larvicidal activity of Mentha piperita, Myrtus caryophyllus and Acorus calamus, reporting low LC50 and LC90 rate with 95 percent confidence upper and lower limits. The low effective larvicidal agent against Anopheles stephensi was eucalyptus oil, with LC50 and LC90 values. When used against the Aedes aegypti, menthol, clove oils and citronella demonstrated strongest larvicidal effects, yielding the value of LC50 and LC90 along with confidence intervals of 95% between the upper and lower bounds. According to Manimaran *et al*., 2012, eucalyptus oil has less effective larvicidal action with LC50 and LC90 value.

Current theory suggests that by postponing nematode development, AMF may increase resistance and enhance host tolerance. The end outcome is affected by nematode species, fungus isolates, plant genotype, and environment. It is feasible to classify nematode species based on the sort of parasitism they display, and this could have an impact on nature and the result of interactions with arbuscular mycorrhizal fungi.

Most of the researches on the relationship between arbuscular mycorrhizal fungi and nematodes have been done on two different kinds of nematodes that is Pratylenchus spp. and Meloidogyne species or root-knot worms. Significant pests include nematodes with unique feeding habits, such as Longidorus species on maize, Xiphinema species on the fruits, and Tylenchorhynchus species on grasses (Barker *et al*., 1998). Among these endoparasites are important nematodes for the economy. The majority of reviews that focus on the relationship between AMF and nematodes only discuss sedentary nematodes as a group or solely on root-knot nematodes. Since sedentary cyst nematode (Heterodera, Globodera and Punctodera species) have substantially least information available as comparison to Meloidogyne, this is most likely the result of practical factors. While both cyst nematodes alter plant cells and consume them, their methods of invasion and the types of cells they consume differ. The feeding cells that root-knot and cyst nematodes form inside the vascular cylinder may break the endodermis, allowing them to spread into the cortex and may directly compete with AMF for available space. By parasitizing soybean cyst nematode cysts, AMF can decrease different nematode diseases of soybeans, cotton, oats, cucumbers, kidney beans, tomatoes, alfalfa, peaches and citrus to differing degrees (De *et al*., 2020). AMF mutualism can boost crop resistance to the nematodes, but they are unable to totally mitigate the damage that nematodes can cause, according to Shrinkhala 2011, At high doses, its effect turns inhibitory.

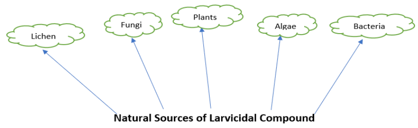


Fig 6. Natural sources of larvicidal compound

IV. FUTURE ECOSYSTEMS OF AMF

Future ecosystems may include ones that are off-planet since it may become economically and technically feasible to visit and live on the other parts in the solar system in generation (Musk, 2017). Even if early ecosystem could be very simple, it could be important to consider however AM fungal communities belong there. It could be instructive for mycorrhizoologists to think about whether these symbionts are necessary for totally working and sustainable ecosystems built from scratch, and if so, what characteristics would be required to support AM fungi's growth and survival while also producing the best outcomes for plant nutrition and survival. Mycorrhizal research is smoothly placing a present and future priority on recognize the key role of arbuscular mycorrhizal fungal communities in an ecosystem functioning, given the effects of many changes in global and the need to manage agroecosystems sustainably.

As there is growing interest in and consensus on the need to promote sustainable development, mycorrhiza have a significant role to play in reducing the negative effects of agricultural inputs like fertilizers for improving plant growth and pesticides, fungicides, and insecticides for controlling various diseases. We can look into a variety of ways that AMF can offer a more thorough approach to addressing many environmental issues, including disease control, ecologically sustainable land management, "carbon-neutral" electricity, and CO2 sequestration (Aggarwal *et al*., 2011). The paucity of research on cation proton antiporters and the absence of research on CNGCs in relation to arbuscular mycorrhizal symbiosis are remarkable (Ouziad *et al*., 2006).

V. APPLICATION OF PHYTOCHEMICALS EXTRACTED FROM THE SYMBIOTIC ASSOCIATION OF MYCORRHIZAL FUNGUS

The amount and quality of phytochemicals can be assessed using a variety of analytical techniques, which provide correct identification and quantification of each individual molecule and their respective molecular arrangements. Metabolome analyses of plant-based diets are also made possible by these techniques. The well-being of soil and its biological fertility play an important role in the cultivation of safe plant feeds, primarily due to the influence of useful soil microorganisms, especially arbuscular mycorrhizal fungi that form mutualistic relationships with plant roots. In addition to improving the nutrition and health of plants, they also alter secondary metabolism, which boosts the production of phytochemicals which promote health including, carotenoids, polyphenols, flavonoids, and phytoestrogens and increases the properties of antioxidant enzymes.

Numerous abiotic and biotic stresses, in addition to factors related to agronomy like genetic makeup of the plant, timing of harvest, nutrient availability, and light conditions, pesticide uses, irrigation, soil quality, fertilisers, and organic management, can affect the amount and characteristics of phytochemicals. Nonetheless, numerous research teams worldwide have contributed information on the amount and antioxidant properties of phytochemicals found in vegetables and fruits (Lee *et al*., 2013).

Specifically, research has shown that a class of symbiotic organisms associated with plants called arbuscular mycorrhizal fungi, which are found in close proximity to the roots of the majority of plant species globally not only enhance plant nutrition and well-being but also alter secondary metabolism, resulting in an increase in the activity and biosynthesis of phytochemicals that promote health like carotenoids, polyphenols, flavonoids, and phytoestrogens. The primary phytochemicals that are extracted from the mycorrhizal fungus's symbiotic relationship and are known to improve health will be covered in this review, along with the analytical methods that have been employed to detect and measure them in plants. We'll also discuss how AMF might be used in the food chain to create fruits and vegetables that are rich in nutrients and nutraceuticals.

5.1 – Health promoting phytochemicals in mycorrhizal plants

The development of arbuscular mycorrhizal symbiosis causes several transcriptional alterations that alter plant metabolism and physiology. The nitrogen, protein, and carbohydrate pathways and the secondary metabolites of AM tomato plants were discovered to be regulated differently by AM symbiosis. The deoxy-D-xylulose phosphate pathway's key enzymes, 1-deoxy-D-xylulose 5-phosphate synthase and 1-deoxy-D-xylulose 5-phosphate reductoisomerase demonstrated a robust increase in transcript levels in some mycorrhizal plants from the Graminaceae family, which resulted in an accumulation of blumenin and mycorradicin. The primary structure of glycosylated cyclohexenone derivatives has been determined to be the yellow-hued compound known as mycorradicin, which is formed in the roots of mycorrhizal gramineous plants Rosopsida and Liliopsida (Klingner *et al*., 1995). Since the exogenous treatments of blumenin diminish arbuscular mycorrhizal fungal growth in the barley plant, the cyclohexanone derivatives found in the mycorrhizal roots like result from carotenoid breakdown and may be involved in fungus control. Concerns about the safety of their usage for human consumption have grown as a result of breeding, genetic selection and metabolic engineering producing types of plant with significant elevations in phytochemical levels. Phytochemicals don't have much efficacy compared to medication molecules, yet regular consumption could have major lasting physiological impacts. Furthermore, most of the phytochemicals don't have any negative side effects and may influence a disease's course in a way that is helpful rather than just symptomatic. Numerous phytochemicals that are alkaloids, carotenoids, or organosulfur compounds can also interact with pathological and physiological processes. The ability of phenolic acids to scavenge free radicals makes them abundantly present in plants. Furthermore, low density lipoprotein oxidation was strongly inhibited by chlorogenic acid (Rodrigues *et al*., 2022).

5.2 – Health promoting phytochemicals in plant products

The majority of phytochemicals, which are non-nutritive plant compounds having therapeutic, disease-preventing, or health-promoting qualities, are found in plant-based foods (Table 6). Phytochemicals don't have much efficacy compared to medication molecules, yet regular consumption could have major long-term physiological impacts. Furthermore, the majority of phytochemicals don't have any negative side effects and may influence a disease's course in a way that is beneficial rather than just symptomatic.

Table 5- phytochemicals containing plant food showing health-promoting activities (Sbrana *et al*., 2014).

Phytochemical	Plant food	Health promoting activity
Baicalein, curcumin, quercetin, lutein, baicalin	Fruits, vegetables	Antiproliferative action on leukemia, hepatoma, melanoma, breast, lung, colon, bladder, pancreas, ovary, brain, kidney, and stomach carcinoma cells
Luteolin	Vegetables	Hypocholesterolemic activity
Theaflavins and thearubigins	Black teas	Antiproliferative action
Luteolin, kaempferol, apigenin, myricetin	Fruits, berries, vegetables	Anti-inflammatory and antibacterial activities

Epicatechin, epigallocatechin, epicatechin-3-gallate, epigallocatechin-3-gallate	Grapes, berries, cocoa, green tea	Reduce dysregulations and degenerative phenomena, anticarcinogenic effects
Gamma-carotene, lycopene, lutein	Vegetables	Protect against uterine, prostate, breast, colorectal, lung, and digestive tract cancers
Isothiocyanates, dithioelthiones, and sulforaphanes	Brassicaceae	Inhibit carcinogenesis by modulating carcinogens metabolism and detoxification
Beta-sitosterol and its glycosides	Vegetables, wheat germ	Antioxidant activity and ability to lower the serum cholesterol levels in humans, antineoplastic, antipyretic, exhibited anti-inflammatory, and immune system-modulating activity
Tocotrienols, tocopherols	Green foods, soy, cereals	Antioxidant, antiproliferative and apoptotic activities, involved in preventing or reducing the risk of breast cancer
Erythrodiol, uvaol, oleanolic, and maslinic acid	Olive fruits	Cytotoxic effects on human breast cancer cells

VI CONCLUSION

This study demonstrated the use of phytochemicals derived from mycorrhizal fungus symbiotic associations and their function in health-promoting properties such as antioxidant, antibacterial, and anti-inflammatory properties. The AMF connection, which aids in plant survival, and the administration of phytochemicals that function as bio-control agents with nematocidal and larvicidal properties are also included in the paper's conclusions. AMF serves as a buffer against abiotic stresses, improving plants' resistance to things like salt, dehydration, heavy metal pollution, and the loss of essential nutrients.

Plant illness Biocontrol is a novel strategy that has a lot of potential for more research. When biocontrol agents move from the lab to the field, they have to make multiple attempts to reach a high peak. In the course of future research, examining uncharted microbial diversity may reveal new strains with potent biocontrol capabilities. Researchers' comprehension of the interactions among infections and useful microbes may be improved by combining modern omics and metagenomic techniques. Using synthetic biology principles, it may be possible to create benign bacteria with improved biocontrol capability in the future. microorganisms that produce more antibacterial compounds or more easily colonize plant surfaces are examples of microorganisms that scientists may engineer to be more effective in fighting disease. Furthermore, managing pests effectively and sustainably is made possible by biopesticides based on nanotechnology. Biopesticides, particularly nano-biopesticides, have the power to drastically alter global agriculture when it comes to protecting crops for sustainable agriculture. Future research should look at the social and economic effects of using biocontrol technologies more extensively. Analyzing the advantages and economic viability for farmers and the agricultural sector as a whole would be advantageous. For biocontrol methods to be widely used, farmers, extension agents, and lawmakers must be educated about them. It is expected that in future, AM fungus will be of good importance in monitoring plant illnesses and lowering the incidence of pathogens, making them one of the eco-friendly and pragmatic remedies. In addition to acting as a biocontrol agent against phytopathogens brought on by detrimental flora and fauna, the AMF improves crop productivity by utilizing available resources, preventing the overuse of pesticides, and preserving effluent in accordance with the needs of the agroecosystem. Research indicates that arbuscular mycorrhizal fungi promote not only plant growth and health but boosts a plant's tolerance to abiotic and biotic stressors also. Numerous abiotic and biotic factors affect the biocontrol effect of AMF. As a result, in order to establish a scientific and reliable standard for evaluating the biocontrol effect of AMF and to provide a theoretical framework for its use in biocontrol work, it is important to thoroughly study the factors which can increase the goodness of plants like the good inoculation timing, inoculating dose, environmental circumstances, farming practices, and the amount of fertilization.

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