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Exploration of mycorrhizal fungi as potential biofertilizer in the management of plant biotic and abiotic stresses

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Abstract

Arbuscular mycorrhizal fungi (AMF) are fungi found in the soil and it can significantly enhance plant nutrient uptake and increase resistance to various environmental stresses. Arbuscular mycorrhizal symbiosis is the most common non-pathogenic symbiosis in the soil and is found in 80% of vascular plant roots. Most of AM fungi species belong to the sub-phylum Glomeromycotina within the phylum Mucoromycota. Arbuscular mycorrhizal (AM) fungi not only enhance the phosphorus supply to plants but also boost the absorption of zinc, copper, nitrogen and iron. AM fungi limit the uptake of Na and Cl. AM fungal hyphae make significant contributions in enhancing soil structure and its ability to retain water. Additionally, these fungi demonstrate resilience against certain root diseases and display a tolerance to drought conditions. Arbuscular mycorrhizal (AM) fungi serve as crucial endosymbionts, playing a significant role in enhancing plant productivity and contributing to the overall functioning of ecosystems. Their importance is paramount in the context of sustainable crop enhancement.

Keywords- Mycorrhiza, Photobionts, Disease, Biotic, Abiotic

Introduction

The word "mycorrhiza" comes from the Greek roots "myco" for "fungus" and "rhiza" for "root" (Latef *et al.*, 2016). Most terrestrial plant have symbiotic association with fungi in their roots. This common symbiosis known as mycorrhiza, assist as networks for the movement of nutrients and energy between plants and soils (Mohammadi *et al.*, 2011). Mycorrhizal associations, which aid in the absorption of nutrients from soil, are formed between hyphal fungus and the underground organs of plants in this plant part termed as photobiont and fungal hyphae as mycobiont (Brundertt, 2002; Huey *et al.*, 2020). Because mycorrhizae have an impact on plant diversity and productivity, mycorrhizal symbiosis is crucial to ecosystem health. The symbiosis besides being present in almost all plant in healthy vegetative condition is a form of “Biological fertilization” (Gianinazzi *et al.*, 2010) which has very good result in case of biotic or abiotic stresses condition (Ganugi *et al.*, 2019). Mycorrhizal relationships generally increase plant productivity; however, this is not always the case. Depending on the environment, symbiosis can involve a variety of species interactions, from mutualism to parasitism. Mycorrhizae are classified into two main groups i.e., ectomycorrhizae and endomycorrhizae (based on the structure of hyphae). Those mycorrhizal association in which hyphae of the fungi do not penetrates the individual cells within roots of plant is termed as ectomycorrhizae while endomycorrhizal fungi are those which invades the cell membrane by piercing the cell wall (Szabo *et al.*, 2014). Vesicular–arbuscular mycorrhizal fungi (VAM) and soil fungi are synonymous terms used to refer to arbuscular mycorrhizal fungi (Vogelsang *et al.*, 2004). VAM fungi found in the soil and it can significantly enhance plant nutrient uptake and increase resistance to various environmental stresses (Sun *et al.*, 2018). Most of AM fungi species belong to the sub-phylum Glomeromycotina within the phylum Mucoromycota (Spatafora *et al.*, 2016). Within this sub-phylum there are four distinct orders of AMF: Glomerales, Archaeosporales, Paraglomerales and Diversisporales, comprising a total of 25 genera (Redecker *et al.*, 2013). These fungi are considered obligate biotrophs, relying on the intake of plant photosynthetic products (Bago *et al.*, 2000) and lipids to complete their life cycle (Jiang *et al.*, in 2017). Close to 90% of plant varieties, which includes flowering plants, bryophytes, and ferns, have the capability to establish mutually beneficial associations with AMF (Zhu *et al.*, 2010 and Ahanger *et al.*, 2014). VAM fungi not only increase the uptake of phosphorus supply to crop plant but also helps in the absorption of minor nutrients (Hart and Forsythe, 2012). AM fungi limit the uptake of Na and Cl. AM fungal hyphae make significant contributions in enhancing soil structure and its ability to retain water (Candido *et al.*, 2015). Additionally, these fungi demonstrate resilience against certain root diseases and display a tolerance to drought conditions. Arbuscular mycorrhizal (AM) fungi serve as crucial endosymbionts, playing a significant role in enhancing plant productivity and contributing to the overall functioning of ecosystems. Their importance is paramount in the context of sustainable crop enhancement (Begum *et al.*, 2019). Arbuscular mycorrhizal fungi, also referred to as "bio-fertilizers," are soil-borne fungi that maysubstantially boost plant nutrient intake and resistance to a number of abiotic stress conditions (Begum *et al.*, 2019). At least 90% of plants are connected to fungi, and mycorrhizalfungi are significantly the most prevalent of them. A fungus and a green plant have a symbioticassociation known as mycorrhiza. The plant creates organic compounds like sugars through photosynthesis and gives them to the fungus, which then gives the plant water and mineral nutrients like phosphorus that it absorbs from the soil (Milton *et al.*, 2021).

Mycorrhiza's significance in nutrient uptake and mobilization

Plants can absorb nutrients from the soil in two different ways (Smith *et al.,* 2011). One is a plant pathway, where no fungus is present and nutrients are directly absorbed by plant roots, and the other is a mycorrhizal channel, where nutrients are taken up by the extraradical mycelium of the associated fungus (Harrison *et al.*, 2002). The mycorrhizal route is employed when the mycorrhizal fungus colonizes the roots of the plant. About 15 essential macro- and micronutrients necessary for the growth of the plant can be absorbed and transported by mycorrhizal fungus (Fig. 1). AMFs thrive in temperate and arid settings where P is frequently a limiting factor because they are exceptionally good at mobilizing inorganic phosphorus (P) (Teotia *et al.*, 2017). By transporting nutrients (especially P) from the soil to the crop through their external mycelium, AMFs can increase nutrient uptake (Sun *et al.*, 2022). The plant and fungus species have an impact on how much P is ultimately absorbed through a common pathway. Numerous mycorrhizal fungi perform a crucial function in mobilizing mineral nutrients from unavailable organic substrates, mineral particles, and rock surfaces, in addition to improving the absorption of mineral nutrients by plants in the soil. Along with mobilizing nutrients, mycorrhizal fungi also serve as an essential C sink in the soil, contributing significantly to the cycling of such mineral elements (Teotia *et al.,* 2017). In high latitude and longitude or in other rocky environment mycorrhizal fungi helps to obtain the nutrients from primary rock surfaces (Milton *et al.*, 2021). A study done by (Sun *et al.,* 2022) in maize reflects that the application of AMFs helps to increase the shoot P, K, Ca, Mg, Mn and Zn contents.

Additionally, by increasing the availability of phosphorus to the host plant, AMFs have an impact on soil phosphatase enzymatic activity and soil physicochemical parameters. The versatile function of mycorrhiza depicted in Figure 1. Mycorrhizal maize roots have considerably greater alkaline phosphatase activity than non-mycorrhizal maize roots (Sun *et al.*, 2022). Not only AMFs help in the uptake of macronutrients, but they also help in the absorption of micronutrients like Fe, Cu, Zn, etc (Teotia *et al.*, 2017). AMF expands its absorption network past the rhizosphere's nutritional depletion zones, enabling access to a broader area of soil (Smith *et al.*2011).

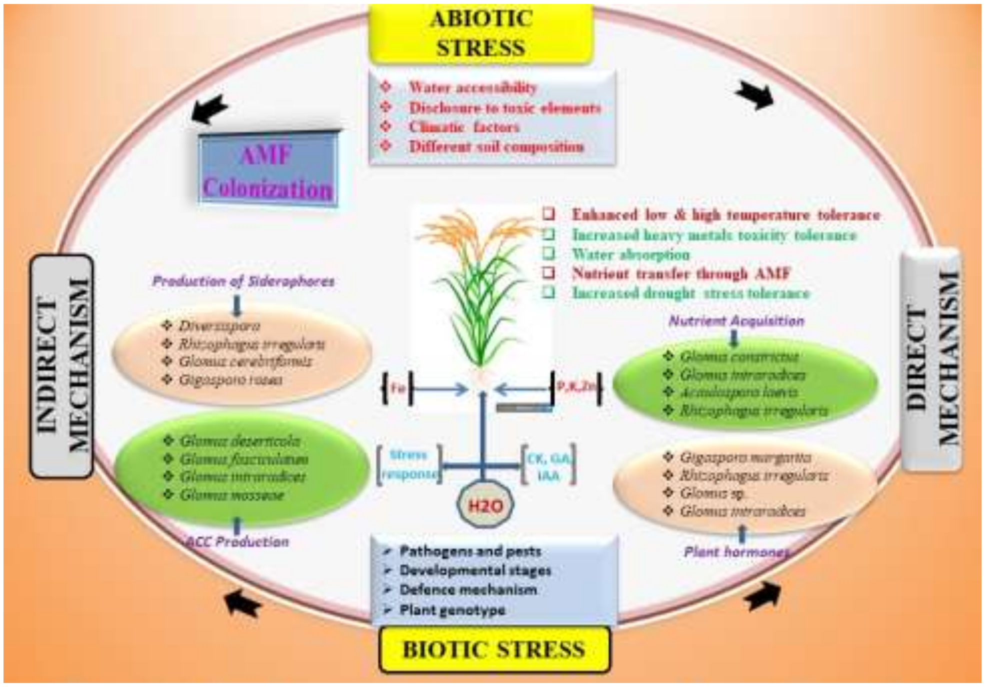

Fig. 1: Versatile functions of mycorrhiza in crop plants

Mycorrhiza's significance to biotic stress resistance

AMF contributes to disease resistance by competing for colonization sites and enhancing the plant's defensive mechanism. AMF colonization has a protective effect known as mycorrhiza-induced resistance (MIR), which offers systemic defense against a variety of attackers and shares traits with induced systemic resistance (ISR) after root colonization by non-pathogenic rhizobacteria and systemic acquired resistance (SAR) after infection by pathogens. AMF causes plants to produce more antioxidant enzymes, which can help them fight off infections and other stresses (Diagne *et al.,* 2020). Among the diseases that can be resisted byusing AMFs are those that affect plants, such as the migratory nematode *Pratylenchus penetrans* and the sedentary nematode Meloidogyne incognita (Diagne *et al.,* 2020). The Significance of mycorrhizal fungi of different species in Agriculture tabulated in Table 1. Another example is the charcoal root-rot disease in soybeans, which can be resisted by using AMF inoculation (Spagnoletti *et al.,* 2020). Mycorrhizae can aid in the rebuilding of tissues following attacks, therefore the improvement in plant development can be beneficial. Compared to the application of water or non-mycorrhizal root exudates, the use of mycorrhizal root exudates further decreased nematode invasion in mycorrhizal plants and temporarily paralyzed nematodes.There aren't many studies on how AMF affects herbivorous insects. Some AMFs inhibit an insect's ability to chew. For instance, mycorrhizal infection improved the resistance of leaves to the chewing insect *Arctia caja* in *Plantago lanceolate* L (Diagne *et al.,* 2020).

Mycorrhiza's significance in drought tolerance

One of the main factors that can significantly lower plant productivity is drought (Posta *et al.,* 2020). AMF has been shown to enhance plant performance under drought stress (Balestrini *et al.,* 2018). By reducing drought and tolerating it, mycorrhizal plants cope with water shortages (Bernardo *et al.,* 2019). Drought moderation is refereed by unintended AMF advantages and increased liquid intake, whereas drought tolerance is mediated by direct AMF advantages that improve the plant's natural ability to cope with stress (Posta *et al.*, 2020). Underacute conditions of drought, the symbiotic association of diverse plants with mycorrhizal fungi can increase the root size and efficiency, leaf area index and biomass (Begum *et al.*, 2019). It's possible that better access to tiny soil pores, increased surface area for water absorption given by AMF hyphae, or improved apoplastic water flow are the causes of the improvement in plant fitness brought on by AMF (Diagne *et al.,* 2020). Abscisic acid is regulated by the administration of AMF, which affects how stomata function. Stomatal conductance and other associated physiological processes are controlled by ABA reactions (Diagne *et al.,* 2020). Stomatal closure is induced by ABA, which also lowers cell water loss (Ouledali *et al.,* 2019).

Mycorrhiza's significance in heavy metal bioremediation

Multiple studies revealed that AMF had spread to more than 80% of the plants growing onmining sites (Wang *et al.*, 2017). They have good capacity to improve the defense system in crop plants and encourage plant growth and development, AMFs are widely thought to sustenance plant formation in soil with heavy metal contamination. AMF can remove heavy metals by "metal-binding" hyphae, which lowers the bioavailability of elements including Cu, Pb, Co, Cd and Zn (Diagne *et al.*, 2020).

Glomalin is a glycoprotein that AMF hyphae can secrete (Herath *et al.*, 2021). It improves growth, yield, and nutrient status by binding heavy metals in the mantle hyphae and corticalcells' cell walls, preventing their uptake (Begum *et al.,* 2019).

Mycorrhiza's significance in salinity tolerance

Soil salinization is a well-known environmental issue that poses a serious danger to the world'sfood security (Begum *et al.*, 2019). Saline areas have been known to naturally contain AMF (Beltrano *et al.,* 2013). In plants exposed to salinity, AMF colonization enhances stomatal conductance and lessens oxidative damage (Pedranzani *et al.*, 2015). In plants grown under saline stress, inoculation of AMF was also seen to promote the accumulation of different organic acids, leading to an up-regulation of the osmoregulation process (Begum *et al.,* 2019). For instance, *F. mosseae* inoculation of tomato plants with salty water irrigation enhanced plant biomass, fruit fresh output, and the amount of P, K, Cu, Fe and Zn in the shoots. In a different study, the same AMF colonized plant roots, lowering Na levels while increasing the activity of numerous enzymes related to reducing salt stress (Diagne *et al.*, 2020)

Mycorrhiza's significance in coping with extreme temperatures

One of the most significant environmental factors that might impair plant development and productivity is temperature (Zhu *et al.,* 2011). Plants with AMF inoculation typically grow better under heat stress than those without it (Begum *et al.,* 2019). It is widely accepted that AMF enhances plant performance to withstand temperature (heat or cold) stress by improving food and water intake, photosynthetic capacity and efficiency, shielding plants from oxidative damage, and increasing osmolyte accumulation (Diagne *et al.,* 2020). AMF can also help the host plant retain moisture, produce more secondary metabolites, which strengthens the plant's immune system, and produce more protein, which benefits the plant resist to low temperature stress (Begum *et al.*, 2019). Overall mycorrhizal fungi help crop plants in root elongation, water absorption at higher temperature (Mathur *et al.*, 2020).

Table 1. Significance of mycorrhizal fungi of different species in Agriculture

AMF Species	Host plant	Importance	Response of plant after AMFs inoculation	References
Diversispora eburnea	*Zea mays L.*	Nutrient uptake	High Alkaline phosphatase, enlargement of root surface, increase in photosynthetic pigment, increase in intake of Phosphorus and magnesium	Sun *et al.* (2022)
Gigaspora margarita	*Lotus japonicus L.*	Nutrient uptake	Phosphorus concentrations in plant shoots and roots were significantly increased	Zhang *et al.* (2015)
Glomus versiforme, Rhizophagus intraradices	*Lonicera japonica* Thunb.	Heavy Metals tolerance	Decreased Cd concentrations in shoots and roots, reduced Cd concentrations in shoots but increased Cd concentrations in roots	Jiang *et al.* (2016)
Glomus monosporum, G. clarum, Gigaspora nigra, and Acaulospora laevis	*Trigonella foenum-graecum L.*	Heavy Metals tolerance	Increased antioxidant enzymes activities and malondialdehyde content.	Abdelhameed and Rabab (2019)
Rhizophagus intraradices, Funneliformis mosseae, F. geosporum	*Zea mays*	Extreme temperature tolerance	Increased leaf length, plant height, leaf number, chlorophyll a, photosynthetic rate, stomatal conductance, and transpiration rate	Mathur *et al.* (2016)
G. versiforme, R. irregularis	*Hordeum vulgare L*	Extreme temperature tolerance	Increasing the survival rate, alleviation of low-temperature stress	Hajiboland *et al.* (2019)
Rhizophagus irregularis	*S. lycopersicum Lactuca sativa Linn*	Drought stress tolerance	Improved shoot dry weight, stomatal conductance, photosystem II efficiency, ABA and strigolactone contents	Ruiz-Lozano *et al.* (2015)
Glomus mosseae	*Triticum aestivum*	Drought stress tolerance	Increased osmotic potential, chlorophyll content and fluorescence, activities of antioxidant enzymes, ascorbic acid, enzymes of N and P	Rani (2016)

			metabolism, and contents of N, P, and K	
Glomus sp.	*L. esculentum*	Biotic stress tolerance	Production of antimicrobial compounds from the mycorrhizal root that arrested the mycelial growth of the fungal pathogen (*Fusarium oxysporum* f. sp. *lycopersici*), reduced the disease incidence, increased the plant growth, dry weight, N, P, K content, chlorophyll content and yield of the plant	Kumari *et al*. (2019)
F. mosseae	*Solanum lycopersicum L.*	Biotic stress tolerance	Higher resistance against *Cladosporium fulvum* infection, higher fresh and dry weight, increases in total chlorophyll contents and net photosynthesis rate	Wang *et al.* (2017)
R. irregularis	*Digitaria eriantha Steud.*	Salinity stress tolerance	Increased stomatal conductance, antioxidant enzymes activities (CAT et APX), jasmonate content, and reduced root and shoot hydrogen peroxide accumulation	Pedranzani *et al.* (2015)
Glomus etunicatum, Glomus intraradices, Glomus mosseae	*Cucumis sativus L.*	Salinity stress tolerance	Increased biomass, photosynthetic pigment synthesis, and enhanced antioxidant enzymes	Hashem *et al.* (2018)

Impact of arbuscular mycorrhizas in plant nutrient and growth

In over 90% of plants, according to van der Heijden et al. (2015), Mycorrhizal fungi frequently escape unnoticed in biodiversity surveys, despite their significance for plant life histories (Soudzilovskaia *et al.*, 2020). This is due to the fact that most mycorrhizal fungi frequently fail to form fruiting bodies, making them difficult to spot in the wild (Egli 2011; Büntgen *et al.*, 2013). AMF are fungi that live in the soil and have been shown to dramatically increase plant nutrient uptake and resilience to a variety of abiotic stressors (Sun *et al.*2018). The sub-phylum Glomeromycotina of the phylum Mucoromycota is where the bulk of AMF species are found (Spatafora *et al.*, 2016). This sub-phylum contains 25 species and four orders of AMF, namely Glomerales, Archaeosporales, Paraglomerales and Diversisporales (Redecker *et al.*, 2013). These fungi can develop and aid plants in absorbing nutrients and water. Plants feed fungi by sending sugars from their leaves. Mycorrhizae can also enhance root surface area, which enables plants to absorb water and nutrients more effectively from a large soil volume (Nadeem *et al.*, 2014). Numerous studies have demonstrated that, in contrast to their non-mycorrhizal counterparts, mycorrhizal plants typically modified their drought physiology later during soil drying or in somewhat drier soils (Augé 2001; Augé *et al.*, 2015). The comparison between colonization of AM fungi and without AM fungi illustrated in Figure 2.

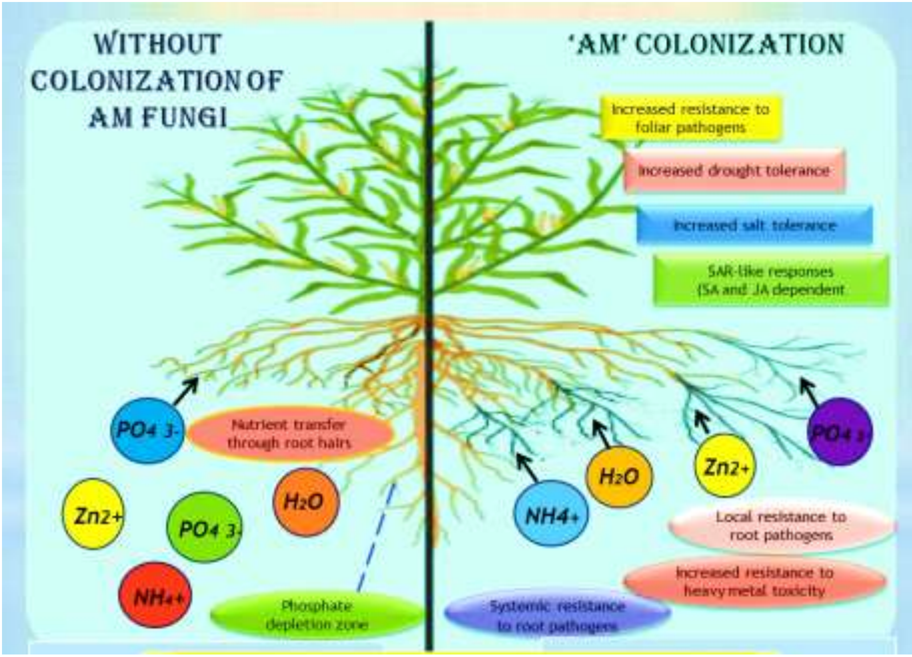

Fig. 2: Comparison between colonization of AM fungi and without AM fungi

In an effort to identify the underlying mechanisms, studies have revealed a complex reorganization of the mycorrhizal plant's response to water stress, including sustained stomatal opening (Augé *et al.,* 2015), higher plant water potentials (Abdalla and Ahmed 2021; Porcel and Ruiz-Lozano 2004), differential expression and activation of root aquaporins (Sharma *et al.*, 2021), altered osmolytes. Leaching, mineralization, and nitrification are only a few of the chemical reactions in soils that release H+ ions and regulate soil pH (Neina, 2019). It is challenging to identify the precise mechanism by which the biological community and biological activities of the soil are controlled by pH (Neina, 2019). Changes in the physical-chemical characteristics of the soil have an impact on these fungi's abundance, richness and community composition.

According to Bowles *et al.* (2016), the formation of a hyphal network by plant roots and the AMF considerably improves roots' access to a vast soil surface area and improves plant growth. By enhancing the availability and transport of different nutrients, AMF enhance plant nutrition (Rouphael *et al.*, 2015). AMF enhance soil quality by affecting the texture and structure of the soil, which benefits plant health (Zou *et al.*, 2016; Thirkell *et al.,* 2017). According to Paterson et al. (2016), fungal hyphae can hasten the breakdown of soil organic materials. The present review focuses 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 AMF can enhance plant growth under stressful environments. This is due to the significance of AMF and the research advancements related to their applications in agriculture.

According to Brundrett's definition from 2002, mycorrhizae's modified absorptive organs, which mostly consist of plant roots (photobiont) and fungus hyphae (mycobiont), develop mutualistic interactions with one another. Nutrient transfer between the organisms is the primary goal of this connection (Brundrett, 2002). AMF and plants were known to coexist 400 million years ago (Selosse *et* *al.*, 2015). Such connections are made through a series of biological processes that have a range of beneficial consequences on both agricultural and natural biotas (Van der Heijden *et al.*, 2015).

The role of mycorrhizal fungi in plant disease management

In present days plant pathogens are a major cause for increasing losses in agriculture. There are four main methods to control these pathogens, those are traditional methods, physical methods, chemical methods, biological methods. Many synthetic chemicals are used in chemical method as an instant way to control these pathogens, whereas these chemical compounds are a threat to sustainability of natural resources. Biological method is a method in which pathogens can be controlled with least damage to the environment. In past few years mycorrhizae has attained interest of many researchers due to its positive advances in terms of protection against plant diseases. Mycorrhizae is a symbiotic association between plant roots and fungi. It absorbs nutrients and water for plants and in turn plants provide shelter and photosynthetic supplements to it. Mycorrhiza belongs to phylum: Glomeromycota and genus: Glomus. Mycorrhizal fungi are of three types, they are endomycorrhiza, ectomycorrhiza and endo-ectomycorrhiza. Arbuscular mycorrhizae are endomycorrhizal fungi which are most commonly found in the environment.

Controlling plant diseases is very important in present day agriculture and food storage but currently used methods are eradicating both disease-causing pathogens along with non-target organisms Brimner *et al.* (2003). The efficiency of mycorrhizal fungi in plant disease management tabulated in Table 2.

Table 2. Mycorrhizal fungi in disease management

Pathogen	Impact	Species	Example	Reference
1. Fungi	Positive	*Glomus mossae*	Soyabean infected by *Rhizoctonia solani* and *M. phaseolina*	Zamboline *et al.* (1983).
2. Bacteria	Positive	*G. mosseae or G. fasciculatum*	Mulberry infected by *P. syringae* pv. Mori Causing bacterial blight	Sharma *et al.* (1995).
3. Nematodes	Positive	*G. mosy*	Nematode infection in tobacco by *Meloidogyne incognita* and *T. basicola*	Liu *et al.* (2012).

4. Viruses	Negative Cause: increase in virus multiplications due to enhanced phosphorous levels	*G. fasciculatum*	Yellow mosaic Bigeminy virus in mung bean	Jayaram *et al.* (1995).

Signalling pathways between fungi and plant resulted in identification of nutrient transporters that revealed cellular processes portraying symbiosis Bonfante *et al.* (2010).

Increase in absorption of phosphorous by plant is one of the earliest proposed mechanisms of AMF-mediated pathogen or disease tolerance that is still applicable Xavier *et al.* (2004). As a result of mycorrhizal association there is a change in root exudate composition followed by change in permeability of root membrane of the plant Graham *et al.* (1981) resulting in alternation of rhizosphere microbial equilibrium Brejda *et al.* (1998). Mycorrhizal plants can tolerate plant pathogens and reduce root damage pathogens as mycorrhizae can increase plant nutrition and health Declerck *et al.* (2002). Arbuscular mycorrhizal fungi can reduce the damage caused by bacteria, fungi, nematodes and other pathogens of cucumber, tomato, olive, strawberry, mandarin orange, melon, soybean, maize, potato, banana, and other plants Weng *et al.* (2022). For example, in fungal infestation soybean plants without mycorrhizal association infected with *Rhizoctonia solani* and *M. phaseolina* has shown lower shoot and root weigh along with less plant height whereas plants with mycorrhizal association were able to tolerate infestation of pathogens Zamboline *et al.* (1983). The mechanism of action of mycorrhizal fungi depicted in Figure 3.

The mechanisms exhibited by AMF to protect host from pathogens are competition for colonization sites, enhanced nutrient absorption, damage compensation of plant, morphological and anatomical changes in roots and change in microbial composition in rhizosphere, yet in viral infections mycorrhizae associated plants are more susceptible to viruses than non-mycorrhizal plants as enhanced phosphorous levels**.**

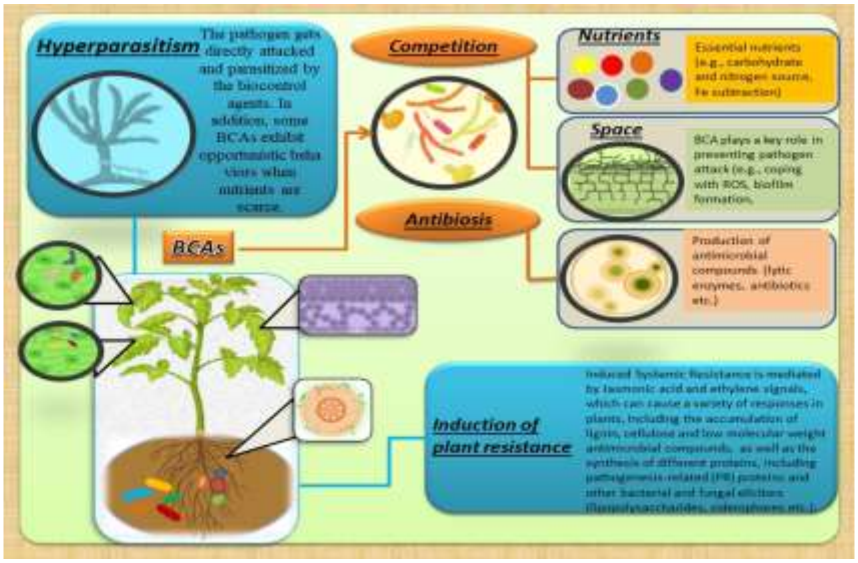

Fig.3: Various mode of action of mycorrhizal fungi

In mulberry, inoculation of mycorrhizae along with 60 -90 kg of phosphorous per hectare reduced the infestation of bacterial blight Sharma *et al.* (1995). In tobacco, Pre-inoculation of plants with *G. mosy* can reduce the number of *Meloidogyne incognita* and *T. basicola* propagules and resulting in increase of plant resistance towards pathogenic nematodes Liu *et al.* (2012). The usage of AMF along with other beneficial microorganisms at once, has reduced the occurrence of plant diseases and damage. Namely, *Trichoderma* used along with AMF in different combinations has given different results in plant disease control Martinez *et al.* (2011).

Conclusion

With the introduction of mycorrhizal fungi, they showed as a valuable substitute towards the indiscriminate use of chemicals either it is fertilizer or fungicides. Mycorrhizal fungi also help in enhancing photosynthetic rate and other gas exchange-related traits, as well as increased water uptake Mycorrhiza play a versatile role in up taking the essential nutrients (macro & micro) from the soil *viz.*, nitrogen, phosphorus and many more. They also provide protection from biotic and abiotic factors. AMF sustainably improves plant growth, productivity and also helps to reduce the diseases causes by plant pathogenic agents. So use of mycorrhizal fungi in crop plants could be more beneficial in comparison to chemicals because pesticides harming the colonization of microbiome, environment and human health's.

Conflict of Interest

The authors declare they have no conflict of interest.

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