Journal of Plant Development Sciences

Meerut, India

REVIEW

AMF-MEDIATED DEFENSE RESPONSES IN CROP PLANTS AGAINST PHYTOPATHOGENIC FUNGI

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Received-03.01.2024, Revised-14.01.2024, Accepted-25.01.2024

Abstract: In a symbiotic relationship, Arbuscular Mycorrhizal Fungi (AMF) enhance the host's absorption of nutrients such as phosphate and nitrate while the heterotrophic fungal partner is provided with photosynthates from the host plant. Mycorrhiza-induced resistance, or MIR, is a trait of AMF-colonized plants that is attributed to a variety of mechanisms, including enhanced plant nutrition, altered root morphology and rhizosphere environment, controlled synthesis of secondary metabolites, competition for invasion sites and nutrients, stimulation of the plant defense system to elicit defense responses that include morphological, biochemical, and molecular ones, thus effectively managing fungal diseases. Therefore, in sustainable agriculture, AMF can be employed as an important tool in integrated crop disease management.

Keywords: AMF, defense responses, mechanisms, phyto pathogenic fungi

INTRODUCTION

In most of the plant species' roots and some types of fungi have a mutualistic relationship known as mycorrhiza (Harley, 1989). A. B. Frank coined the term "mycorrhiza" in 1885. It comes from the Greek words "myco" or "mykes" which indicate "fungi" and "rhiza" which means "roots." There are different types of mycorrhizal associations such as 1) Ecto mycorrhiza 2) Endo mycorrhiza 3) Ectendo mycorrhiza 4) Ericoid mycorrhiza 5) Mono tropoid mycorrhiza 6) Orchid mycorrhiza and 7) Arbutoid mycorrhiza (Smith and Read,1997). A phenomenon known as arbuscular mycorrhizal symbiosis develops between fungi belonging to the phylum Glomeromycota and the roots of roughly 80% of terrestrial plant species (Schübler *et al*.,2001).

The Arbuscular Mycorrhizal Fungi (AMF) forms internal structures known as arbuscules,by infiltrating into the root cortex and facilitating the nutrient exchange between the partners. The host provides photosynthates to the heterotrophic fungal partner in exchange for the extracellular hyphal network's extensive spread into the surrounding soil, which allows it to go beyond the nutrient depletion zone and improve the supply of inorganic nutrient like phosphate and nitrate (Smith *et al*., 2011). According to Kapoor and Bhatnagar (2007), AM symbiosis is crucial for boosting plant growth and development as well as enhancing plant tolerance to biotic and abiotic stresses.

TAXONOMIC CLASSIFICATION

Fungi belong to:

Phylum-*Glomeromycota*

Class-*Glomeromycetes*

The phylum *Glomeromycota* is divided into 4 orders and 9 families. Order *Glomerales*: 1 family*Glomeraceae* (*Glomus*)
Order *Diversisporales*: 4 families: *Acaulosporaceae* (*Acaulospora*, *Entrophospora*), *Diversisporaceae* (*Diverssipora*), *Gigasporaceae* (*Gigaspora*, *Scutellospora*), *Pacisporaceae* (*Pacispora*)
Order *Archaeosporales*: 3 families: *Archaeosporaceae* (*Archaeospora*), *Ambisporaceae* (*Ambispora*), *Geosiphonaceae* (*Geosiphon*)
Order *Paraglomerales*: 1 family *Para glomeraceae* (*Paraglomus*) (Kirk *et al*., 2008).

SIGNIFICANCE OF AMF–PLANT SYMBIOSIS

By use of a "common mycorrhizal network" (CMN), which facilitates the movement of nutrients to plants, mycorrhizal symbiosis brings its benefits from the level of individual symbiotic plants to that of communities. When a plant experiences biotic or abiotic stress, it also uses CMN to convey alarm signals, alerting other plants that share CMN to the same stress (Leake *et al*., 2004).

AMF AS BIOCONTROL AGENT

AMF-colonized plants exhibit higher levels of resilience to several biotic and abiotic stresses.

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"Mycorrhiza-induced resistance" (MIR) is the term for this type of induced resistance that is seen against different pathogens, such as bacteria, viruses, and fungi (Bennett *et al*., 2006). It is accomplished by enhancing plant nutrition, altering the morphological structure of plant roots, enhancing the micro environment of the rhizosphere, controlling the synthesis of secondary metabolites, or directly competing with plant pathogenic microorganisms for nutrients as well as invasion sites, triggering plant defense system activation and thus improving disease resistance which are the main mechanisms that contribute to MIR (Chen *et al*., 2021, Jaiti *et al*., 2007, Song *et al*., 2011).

PLANT DEFENSE RESPONSES INDUCED BY AMF

AMF, when it colonizes plant roots activates plant defense mechanisms by triggering specific relay processes. Microbe associated molecular patterns (MAMP) are tiny compounds found on the surface of most of the plant pathogenic as well as defense-activating microbes, including AMF. Additionally, these microbes produce effector proteins into or out of plant cells. Plant receptor protein complexes, or pattern recognition receptors (PRR), can then recognize the MAMP and effector molecules, activating either MAMP-triggered immunity (MTI) or Effector-triggered immunity (ETI) in turn (Mc Dowell, 2019). These plant resistance (R) proteins will identify some effect or molecules, while others will target host proteins to decrease MTI (Chisholm *et al*., 2006). Effect or-triggered immunity (ETI) is a defense response that is initiated when effect or chemicals are recognized by R proteins (Dangl *et al*., 2013). Although the two responses qualitatively resemble each other in many ways, but ETI is quicker and stronger than MTI (Dodds and Rathjen, 2010). Hypersensitive reaction (HR) is one type of programmed cell death triggered by ETI responses. It is characterized by rapid, localized necrosis at the site of the first pathogen entry (Mur *et al*., 2008). During the first phase, the level of salicylic acid (SA) increases. Later on, an antagonistic effect is caused by higher levels of hormones such as abscisic acid (ABA) and jasmonic acid (JA) which suppresses this reaction. Although its involvement in MIR is debatable, ABA is thought to transmit the long-distance signals of MIR throughout the plant, whereas JA promotes the development of induced systemic resistance (ISR). Early stage SA induction causes systemic acquired resistance (SAR) to develop (Kadam *et al*., 2020). By inhibiting the plant immune mechanism and promoting the development of AMF symbiosis, one of the effector molecules such as SP7 (secreted protein 7), secreted by *Glomus intraradices*, helps to develop a biotrophic status of AMF in roots (Kloppholz *et al*., 2011). Later on, the linked AMF's myc factor causes cytosolic Ca^{2+} to rise, which in turn causes the production of Reactive Oxygen Species (ROS), Mitogen-Activated Protein Kinase (MAPK), and G-proteins alteration. The induction of lipoxygenase (LOX) by ROS also facilitates the production of JA. Several anti oxidant enzymes are produced, including catalases (CAT), peroxidases (POX), ascorbate peroxidase (APX), and superoxide dismutase (SOD). These enzymes are important in the metabolism of ROS and are phosphorylated by G-protein and MAPK. When a pathogen penetrates host tissues, MAPK and G-protein also activate genes involved in plant defense. The proteins that are produced by these defense related genes target and attempt to kill the invasive microorganisms. The antioxidant enzymes and ROS produced at the site of pathogen infection, however, function constitutively and initiate HR leading to the suppression of the diseases causing pathogen (Maharshi*etal*.,2019).

Important fungal pathogens controlled by AMF (Table.1)

AMFspecies	**Fungalpathogen**	**Host**	**Reference**
Glomus intraradices	*Phytophthora sojae*	Soybean	Marquez *et al*.(2018)
Rhizoglomus intraradices	*Magnaporthe oryzae*	Rice	Tian *et al*.(2019)
Glomus claroideum	*Fusarium oxysporum*	Cucumber	Ahammed *et al*.(2020)
Rhizophagus irregularis	*Magnaporthe oryzae*	Rice	Campo *et al*.(2020)
Rhizoglomus irregularis	*Botrytis cinerea*	Tomato	Sanmartin *et al*.(2020)
Funneliformis mosseae *Rhizophagus irregularis*	*Fusarium oxysporum*	Tomato	Singh *et al*.(2020)

MORPHOLOGICAL RESPONSES INDUCED BY AMF

AMF primarily induces lignification, deposition of callose and non-esterified pectins, the creation of structures resembling papillae against phytopathogenic fungi (Ahammed *et al*., 2020, Chen *et al*., 2021).

The induction of resistance against *Colletotrichum orbiculare* in cucumber leaves by *Glomus intraradices* was studied by Lee *et al*., 2005. When comparing the leaves of AMF infested plants to those of untreated control plants, there was a noticeable deterioration in the disease severity. Pre-treatment with DL-3 amino butyric acid (BABA) was employed as a positive control and it was shown that this verity of disease was significantly reduced. On the plants leaves treated with *G. intraradices*, how ever, the frequency of callose development was noticeably high five days after inoculation. Consequently, they proposed that, resistance caused by *G. intraradices* colonization may be linked to an increase in callose development at the site of penetration by pathogen in the infected leaves.

Jalaludeen *et al*., 2020 assessed the relationship between *Glomus mosseae* and particular Act in omyceteson chilli peppers in relation to *F. oxysporum* in a green house setting. They also looked in to the possibility of Act in oomycetes and *G. mosseae* working together to induce resistance against *Fusarium* wilt. The AMF inoculum was 10 g of dry soil and 100 mature spores. They discovered that there was a decrease in root mortality and an induction of lignification in the dual-treated chilli pepper root. The lignin content was measured using lignothioglycolic acid derivatives (LTGA). The highest total lignin content was found in the roots of dual-treated chilli peppers on days10 and18, with 2.592 and 2.922 LTGA µg g-1 tissue, respectively, compared to the control samples, which had 1.259to1.212 LTGAµgg-1tissue.

BIOCHEMICAL RESPONSES INDUCED BY AMF

The biochemical responses that are triggered by AMF against plant pathogenic fungi include altered composition of root exudate (Sarathambal *et al*., 2023), the synthesis of phenolic compounds, phytoalexins and defense enzymes (Eke *et al*., 2016), the induction of signaling molecules (Nair *et al*., 2015), and more. Nair *et al*. (2015) measured the following items to investigate the role of jasmonic acid (JA) and salicylic (SA) acid in the expression of MIR against *A. alternate* such as

(i) levels of methyl jasmonate (MeJA) and jasmonic acid (JA); and

(ii) activity of enzymes reported to be involved in their biosynthesis, namely lipoxygenase (LOX) and

(iii) phenyl alanine ammonialyase (PAL). Compared to control plants, AM-colonized plants exhibited three times increased LOX activity; however, in contrast to controls, this did not rise further in response to pathogen application. In AM colonized plants, there was a four-fold increase in MeJA in the leaves when compared to controls, which was correlated with higher LOX activity in those plants. The findings imply that in response to AM colonization, the expression of MIR against *A.alternata* is significantly influenced by the systemic rise in JA.

A study was conducted by Eke *et al*. (2016) to assess the efficacy of four AMF formulations such as *Glomus intraradices*, *Glomus hoi*, *Gigaspora margarita*, and *Scutellospora gigantea* in improving growth of common bean (*Phaseolus vulgaris* L.) and biocontrol against *Fusarium solani* in green house conditions. The findings showed that all of the mycorrhizal preparations considerably decreased the incidence and severity of the *Fusarium* infection in bean plants that were affected. After being inoculated with *F. solani*, the mycorrhizal rhizospheric competency (root colonization and spore density) was affected. Furthermore, following mycorrhizal colonization, there was an increase in the amount of flavonoids and total soluble phenols as well as the specific activity of phenyl alanine ammonia lyase(PAL), suggesting that the defense mechanism of the plant had strengthened against the pathogen. The potential function of the AMF consortium in promoting plant systemic defense against *Fusarium oxysporum* f. sp. *lycopersici* (FOL) in tomato plants was investigated by Hashem *et al*. (2021). The wilt disease and fusaric acid production within vascular tissue was lessened by AMF inoculation which may have contributed to the decreased wilting. FOL had an antagonistic effect on AMF by inhibiting its colonization in the host, reduced the production of spores, arbuscules, and vesicles. AMF also reduced the harm caused by *Fusarium* wilt by raising chlorophyll levels and phosphate- metabolizing enzyme activity (acid and alkaline phosphatases). Furthermore, mycorrhizal-inoculated tomato plants exhibited elevated levels of antioxidant enzymes such as catalase, glutathione reductase, and others, which ultimately impacted the removal of reactive oxygen species. Furthermore, increased photosynthetic efficiency, an increase in phosphatase,and antioxidant enzymatic systems all led to tomato plants developing induced resistance to FOL. Sarathambal *et al*. (2023) studied the impact of mycorrhizal colonization on the constituents of root exudates in blackpepper plants infected with *Phytophthora capsici*. This is the first study to assess the root exudation profiles of *P.capsici* infection and/or AM colonization in blackpepper. In comparison to *P.capsici* inoculated plants, the root exudates of AM colonized plants exhibited higher levels of fattyacid/fattyacyl compounds, such as tetradecanoic acid, n-hexadecanoic acid, octadecanoic acid, and non acos-1-ene. On the other hand, the root exudates of *P. capsici*- inoculated plants, the majority of alkane hydrocarbons mostly found included (z)-3-tetradecene, octylcyclo hexane, 4-cyclohexylundecane, and decylcyclo hexane. According to multivariate analysis of the root exudate data, the content of root exudates during *Phytophthora* infection was normalized by AM colonization in black pepper roots and was comparable to control plants. According to the study, an AM- infected root modifies its metabolism and aids in the management of biotic stress in plants.

Other biochemical responses induced by AMF (Table.2)

Fungal pathogen	**Host**	**AMF species**	**Response**	**Reference**
Magnaporthe oryzae	Rice	*Rhizoglomus intraradices*	Regulation of auxin and SAmetabolism, increased α-linolenicacid production, improved JA synthesis, induce the shikimate pathway, syntheses of terpenoids and phenol, biosynthesis of brassino steroids	Tian *et al*., 2019
Fusariumoxysporum	Chilli Pepper	*Glomus mosseae*	Increased PO and PPO activities	Jalaluldeen *et al*., 2020
Fusarium oxysporum	Alfalfa	*Funneliformis mosseae*	Accumulation of antioxidant enzymes, plant hydrolase and plant hormones, such as superoxide dismutase, ß-1, 3-glucanase, chitinase, PAL, ABA, Ethylene and H_2O_2	Wang *et al*., 2020
P.parasitica	Trifoliateorange	*Funneliformismosseae*	Activities of root chitinase, PALand β-1, 3-glucanase	Tian *et al*., 2021
Verticillium dahliae	Artichoke	*Glomus viscosum*	Significant increase in APX, SOD activities, higher content of ascorbate and glutathione, decrease in the levels of lipid Peroxidation and H_2O_2	Villani *et al*., 2021
R.solani	*Viciafaba*	*Funniliformismosseae* *Gigasporagigantean*	Increased phenolic content, PPO and POContent	Gazzar *et al*., 2023
Phyotphthora nicotianae (Blackshank)	Tobacco	*Paraglomus occultum*	Accumulation of GSH, proline, total phenols, and flavonoids	Li *et al*., 2023

MOLECULAR RESPONSES INDUCED BY AMF

AMF invasion triggers several molecular changes at the genetic level that result in the activation of the plant defense system and different genes are triggered in the host plant that are in charge of the defense mechanism against phytopathogens. Rashad *et al*. (2020) examined the potential of endophytic *Bacillus amyloliquefaciens* GGA and/or AMF to control *Sclerotium cepivorum* causing white rot disease in garlic. The use of the combined therapy of *B. amyloliquefaciens* GGA and AMF decreased disease severity and incidence more than the individual treatments, as demonstrated by the results from pot studies. Using qRT-PCR, the transcript levels of the defensin gene in garlic plants were measured in response to the various applied treatments. All treatments significantly increased the expression of defensin in the two harvests taken as compared to the control treatment. Compared to 60 days post inoculation (dpi), the induction effect was largest at 30 dpi. The highest levels of gene expression were seen in the two harvests in *S. cepivorum* inoculated plants treated with AMF and *B. amyloliquefaciens* GGA(13.2-fold increaseat 30dpi, and 9.5-fold at60 dpi). Additionally, there were variable degrees of impact on chitinase gene expression. Expression was higher at 30 dpi than it was at 60 dpi. When compared to the untreated control, the plants that were inoculated with *S. cepivorum* and treated with *B.amyloliquefaciens* GGA and AMF exhibited the highest levels of gene expression(8.9-times increase at 30 dpi). Garlic plant growth and yield metrics improved as a result of this treatment.

Zhang *et al*. (2018) assessed *Rhizophagus irregularis* CD1's impact on resistance of cotton to*Verticillium* wilt and plant growth promotion. In comparison to the control, AMF colonization significantly increased the amount of inorganic phosphate (Pi) in the roots and leaves. It also prevented *Verticillium dahlia* from developing symptoms and significantly increased the expression of genes linked to pathogenesis, such as GhHSR203J, GhHIN1, GhPR1, GhPR3, GhPR4, GhPR5, and GhPR9, as well as genes related to lignin synthesis. Cotton treated with mycorrhiza also showed up-regulation of the genes that encode for important enzymes associated with the JA production pathway, including GhLOX1, GhACO1, and GhOPR3.Tests were conducted on the antimicrobial properties of AMF against *Verticillium* *dahliae in vitro*. The nonvolatile solutes were kept from diffusing between the two compartments by utilizing divided Petri plates. They discovered that the mycelial growth of *V. dahliae* was inhibited by AMF symbionts, in contrast to AMF hyphae or spores. Based on *in vitro* investigations, it was determined that the AMF endosymbiont might impede the growth of phytopathogenic fungi, such as *V.dahliae,* by emitting volatile compounds.

Other molecular responses induced by AMF (Table.3)

Fungal Pathogen	Host	AMFspecies	Response	Reference
Fusarium oxysporum	Cucumber	*Glomus claroideum*	Increased the activity and transcripts of SOD, APX and the content of glutatathione and proline	Ahammed *et al*., 2020
Botrytis cinerea	Tomato	*Rhizoglomus irregularis*	JA defense-related genes were upregulated	Sanmartín *et al*., 2020
P.parasitica	Trifoliate orange	*Funneliformis mosseae*	Up-regulation of SAsynthesisgenes(PtPAL1andPtEPS1) Higher expression of pathogenesis-related protein gene1(PtPR1), PtPR4, andPtPR5	Tian *et al*., 2021
Fusarium oxysporum	Tomato	*Rhizophagus irregularis*	Induced expression of the JA synthesis genes including AOC and LOX and increased activities Of PPO and PAL	Wang *et al*., 2022
P.capsici	Black pepper	*Rhizophagus irregularis*	Up-regulation of pathogenesis related genes *viz*., APX, osmotinand β-1, 3-glucanase, PAL and NPR1 in blackpepperleaves and roots	Sarathambal *et al*., 2023

CHALLENGES TO THE USE OF AMF AS A BIO CONTROL AGENT

Due to its obligatory biotrophicity, it is not possible to produce AMF inoculum on a large scale. After field introduction, there can be some unfavorable interactions between the native AMF and the residing microbial community. The compatibility of the AMF association with the host plant is crucial because it influences both the AMF colonization and the favorable or unfavorable effects on the hostplant that result from it. It is exceedingly difficult to maintain the diversity of AMF in soil because a variety of factors that may indirectly change soil AMF diversity viz., the host's genotype, the amount of fertilizer and pesticide applied, tillage, crop rotation, the impact of related microbes, etc.

CONCLUSION

Plant diseases are on the rise due to plant pathogens in the farming environment becoming more resistant as a result of the extensive use of chemicals. Hence, environmentally friendly methods of controlling plant diseases are therefore crucial. Within the mycorrhizae, AMFs are the most prevalent, biomass-rich, and important beneficial fungal group. They have a particular antagonistic or inhibitory effect on plant pathogens. AMF can activate the plant defense system and induce defense responses including morphological, biochemical,and molecular ones. It can also effectively manage crop diseases by competing with pathogens for space and photosynthates, regulating secondary metabolite formation in plants by altering the morphological structures of plant roots. Therefore, AMF can be utilized as an important candidate in integrated crop disease management in sustainable agriculture.

REFERENCES

Ahammed, G., Mao, Q., Yan, Y., Wu, M., Wang, Y., Ren, J., Guo, P., Liu, A. and Chen, S. (2020). Role of melatonin in arbuscular mycorrhizal fungi induced resistance to Fusarium wilt in cucumber. *Phytopathol,* **110**(5):999-1009.
Google Scholar

Bennett, A., Garcia, J., Bever, J., Bennett, A., Alers-garcia, J. and Bever, J. (2006). Three-way Interactions among mutualistic mycorrhizal fungi, plants, and plant enemies: hypotheses and synthesis. *AmNat,* **167**(2):141-152.
Google Scholar

Campo, S., Martín-Cardoso, H., Olivé, M., Pla, E., Catala-Forner, M., Martínez-Eixarch, M. and San Segundo, B. (2020). Effect of root colonization by arbuscular mycorrhizal fungion growth, productivity and blast resistance in rice. *Rice,* **13**(1):1-14.

Google Scholar

Chen, M., Bruisson, S., Bapaume, L., Darbon, G., Glauser, G., Schorderet, M. and Reinhardt, D. (2021). VAPYRIN attenuates defense by repressing PR gene induction and localized lignin accumulation during arbuscular mycorrhizal symbiosis of *Petunia hybrida*. *New Phytol*. **229**(6): 3481-3496.

Google Scholar

Chen, Q., Wu W, Qi S., Cheng, H., Li, Q., Ran, Q., Dai, Z., Du, L., Egan, S. and Thomas, T. (2021). Arbuscular mycorrhizal fungi improve the growth and disease resistance of the invasive plant *Wedelia trilobata*. *J Appl Microbiol,* **130**(2):582-591.

Chisholm, S., Coaker, G., Day, B. and Staskawicz, B. J. (2006). Host-microbe interactions: shaping the evolution of the plant immune response. *Cell,* **124**(4):803-814.

Google Scholar

Dangl, J.L., Horvath, D.M.and Staskawicz, B.J. (2013). Pivoting the plant immune system from dissection to deployment. *Science,* **341**(6147):746-751.

Google Scholar

Dodds, P.N. and Rathjen, J.P. (2010). Plant immunity: towards an integrated view of plant-pathogen interactions. *Nat Rev Genet,* **11**(8):539-548.

Eke, P., Chatue, G. C., Wakam, L. N., Kouipou, R. M., Fokou, P. and Boyom, F. (2016). Mycorrhiza consortia suppress the Fusarium rootrot (*Fusarium so*lani f.sp. *phaseoli)* in common bean (*Phaseolus vulgaris* L.). *Biol Control,* **103**:240-250.

Google Scholar

Gazzar, N., El-Hai, K. M., Teama, S. A. and Rabie, G, H. (2023). Enhancing *Vicia faba'*s fungi in the protection of date palm *(Phoenix dactylifera* L.) against bayoud disease. *PhysiolMol Plant Pathol.,* **71**(4-6):166-173.

Google Scholar

Kloppholz, S., Kuhn, H. and Requena, N. (2011). A secreted fungal effector of *Glomus intraradices* promotes symbiotic biotrophy. *Curr Biol,* **21**(14): 1204-1209.

Google Scholar

Leake, J., Johnson, D., Donnelly, D., Muckle, G., Boddy, L. and Read, D. (2004). Networks of power and influence: the role of mycorrhizal mycelium in controlling plant communities and agroecosystem functioning. *Can J Bot,* **82**(8):1016-1045.

Lee,C,S.,Lee,Y.J.andJeun,Y.C.(2005) Observations of infection structures on the leaves ofcucumber plants pre-treated with arbuscular mycorrhiza *Glomus intraradices* after challenge inoculation with *Colletotrichum orbiculare*. *Plant Pathol J*,**21**(3):237-243.

Google Scholar

immunity against *Rhizoctonia solani* rootrot diseases by arbuscular mycorrhizal fungi and nano chitosan. *BMC Plant Biol,* **23**(1): 403.

Google Scholar

Harley, J.L. (1989). The significance of mycorrhiza. *Mycol Res,* **92**(2):129-139.

Google Scholar

Hashem, A., Akhter, A., Alqarawi, A. A., Singh, G., Almutairi, K.F.andAbd_Allah, E. F. (2021). Mycorrhizal fungi induced activation of tomato defense system mitigates *Fusarium* wilt stress. *Saudi J Biol Sci,* **28**(10): 5442-5450.

Google Scholar

Jaiti, F., Meddich, A. and El-Hadrami, I. (2007). Effectiveness of arbuscular mycorrhizal

Google Scholar

Jalaluldeen, A. M., Sijam, K. and Ramadan, N. A. (2020). Active changes of lignifications-related enzymes in chilli pepper response to *Glomus mosseae* against *Fusarium oxysporum*. *Aust J Basic Appl Sci,* **14**(6):1-6.

Google Scholar

Kadam, S., Pable, A. A. and Barvkar, V. T. (2020). Mycorrhiza induced resistance (MIR): a defense developed through synergistic engagement of phytohormones, metabolites and rhizosphere. *Funct Plant Biol,* **7**(10):880-890.

Google Scholar

Kapoor, R. and Bhatnagar, A. K. (2007). Attenuation of cadmium toxicity in mycorrhizal celery(*Apium graveolens* L.).*World J Microbiol Biotechnol,* **23**:1083-1089.

Google Scholar

Kirk, P. M., Cannon, P. F., Minter, D. W. and Stalpers, J. A. (2008). Dictionary of the Fungi, 10thed.Wallingford, UK: CABI.

Google Scholar

Li, J., Cai, B., Chang, S., Yang, Y., Zi, S. and Liu, T. (2023). Mechanisms associated with the synergistic induction of resistance to tobacco black shank in tobacco by arbuscular mycorrhizal fungi and β-amino butyric acid. *Front Plant Sci,* **14**.

Google Scholar

Maharshi, A., Kumar, G., Mukherjee, A., Raghuwanshi, R., Singh, H. B. and Sarma, B. K. (2019). Arbuscular mycorrhizal colonization and activation of plant defense responses against phytopathogens. *Microbial Interventions in Agriculture and Environment: Volume 1: Research Trends, Priorities and Prospects*: 219-240.

Google Scholar

Marquez, N., Giachero, M.L., Gallou, A., Debat, H.J., Cranenbrouck, S., DiRienzo, J.A., Pozo, M. J., Ducasse, D. A. and Declerck, S. (2018). Transcriptional changes in mycorrhizal and nonmycorrhizal soybean plants upon infection with the fungal pathogen *Macrophomina phaseolina*. *Mol Plant Microbe Interact,* **31**(8):842-855.

Google Scholar

McDowell, J.M. (2019). Focus on activation, regulation, and evolution of MTI and ETI *Mol Plant Microbe Interact*, **32**(1):5
Google Scholar

Mur, L. A., Kenton, P., Lloyd, A. J., Ougham, H. and Prats, E. (2008). The hyper sensitive response; the centenary is upon us but how much do we know? *J Exp Bot*, **59**(3):501-520.
Google Scholar

Nair, A., Kolet, S. P., Thulasiram, H. V. and Bhargava, S. (2015). Systemic jasmonic acid modulation in mycorrhizal tomato plants and its role in induced resistance against *Alternaria alternata*. *Plant Biol*, **17**(3):625-631.
Google Scholar

Rashad, Y. M., Abbas, M. A., Soliman, H. M., Abdel-Fattah, G. G. and Abdel-Fattah, G. M. (2020). Synergy between endophytic *Bacillus amyloliquefaciens* GGA and arbuscular mycorrhizal fungi induces plant defense responses against white rot of garlic and improves host plant growth. *Phyto pathol Mediterr*, **59**(1):169-186.
Google Scholar

Sanmartin, N., Sanchez-Bel P., Pastor, V., Pastor-Fernandez, J., Mateu, D., Pozo, M., Cerezo, M. and Flors, V. (2020). Root-to-shoot signalling in mycorrhizal tomato plants upon *Botrytis cinerea* infection. *Plant Sci*, **298**:110595.
Google Scholar

Sarathambal, C., Jeevalatha, A., Sivaranjani, R., Biju, C. N., Charles, S., Srinivasan, V., George,P., Peter,B. and Radhika, R. (2023).Arbuscular mycorrhizal colonization alters biochemical, molecular defense responses and root exudate composition against *Phytophthora capsici* infection in black pepper. *Rhizosphere*, **25**:100651.
Google Scholar

Schübler, A., Schwarzott, D., Walker, C. (2001). A new fungal phylum, the *Glomeromycota*: phylogeny and evolution. *Mycol Res*, **105**: 1413–1421.
Google Scholar

Singh, M., Mishra, M., Srivastava, D. K., Singh, P. K. (2020). Biological control of *Fusarium* wilt of tomato by arbuscular mycorrhizal fungi with intercropping. *Plant Pathol Quar*, **10**:1-9.
Google Scholar

Smith, S. and Read, D. (1997). Mycorrhizal symbiosis, 2 ed. Academic Press, London.
Google Scholar

Smith, S.E., Jakobsen, I., Grønlund, M.andSmith, F.A. (2011). Roles of arbuscular mycorrhizas in
Google Scholar
plant phosphorus nutrition: interactions between pathways of phosphorus uptake in arbuscular mycorrhizal roots have important implications for understanding and manipulating plant phosphorus acquisition. *Plant Physiol*, **156**(3):1050-1057.
Google Scholar

Song, Y. Y., Cao, M., Xie, L. J., Liang, X. T., Zeng, R. S., Su, Y. J., Huang, J. H., Wang, R. L. and Luo, S. M. (2011). Induction of DIMBOA accumulation and systemic defense responses as mechanism of enhanced resistance of mycorrhizal corn (*Zea mays* L.) to sheath blight. *Mycorrhiza*, **21**:721-731.
Google Scholar

Tian, L., Chang, C., Ma, L., Nasir, F., Zhang, J., Li, W., Tran, L. P. and Tian, C. (2019). Comparative study of the mycorrhizal root transcriptomes of wild and cultivated rice in response to the pathogen *Magnaporthe oryzae*. *Rice*, **12**: 1-19.
Google Scholar

Tian, L., Zou, Y. N., Wu, Q, S. and Kuča, K. (2021). Mycorrhiza-induced plant defense responses in trifoliate orange infected by *Phytophthora parasitica*. *Acta Physiologiae Plantarum*, **43**:1-8.
Google Scholar

Villani, A., Tommasi, F. and Paciolla, C. (2021). The arbuscular mycorrhizal fungus *Glomus viscosum* improves the tolerance to *Verticillium* wilt in artichoke by modulating theantioxidantdefense systems.*Cells*, **10**(8):1944.
Google Scholar

Wang, X., Ding, T., Li, Y., Guo, Y., Li, Y. and Duan, T. (2020). Dual inoculation of alfalfa (*Medicago sativa* L.) with *Funnelliformis mosseae* and *Sinorhizobium medicae* can reduce *Fusarium* wilt. *J Appl Microbiol*, **129**(3):665-679.
Google Scholar

Wang, H., Hao, Z., Zhang, X., Xie, W. and Chen, B. (2022). Arbuscular mycorrhizal fungi induced plant resistance against *Fusarium* wilt in jasmonate biosynthesis defective mutant and wild type of tomato. *J Fungi*, **8**(5):422.
Google Scholar

Zhang, Q., Gao, X., Ren, Y., Ding, X., Qiu, J., Li, N., Zeng, F.andChu, Z. (2018). Improvement of *Verticillium* wilt resistance by applying arbuscular mycorrhizal fungi to a cotton variety with high symbiotic efficiency under field conditions. *Int J Mol Sci*, **19**(1):241.
Google Scholar