AATCC Review

28 April 2025: Received
17 June 2025: Revised
25 June 2025: Accepted
27 July 2025: Available Online

https://aatcc.peerjournals.net/

Original Research Article

Open Access

Arbuscular Mycorrhizal Symbiosis Improves Eggplant Performance and Defense Against Collar Rot Pathogen

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ABSTRACT

Arbuscular mycorrhizal fungi (AMF) are soil-borne microorganisms that form symbiotic relationships with numerous species of terrestrial plants. Suppression of fungal plant diseases and enhanced nutrient uptake are two of the many strategies with which AM fungi may promote plant growth and development. They are crucial in low-input agricultural systems that promote biological aspects over agrochemicals. However, the variability in AM fungal efficiency and the complexity of host-pathogen-AMF interactions pose significant challenges in developing effective biological control strategies. In this regard, a pot trial was conducted with three AM fungal isolates to study their influence on the suppression of collar rot of eggplant. In the in-planta study, AMF inoculation enhanced the activities of defense-related enzymes—PAL, PPO, and POD—while reducing disease incidence, with the UASDAMF consortium showing the most substantial reduction (28.33%). The AM fungi significantly reduced collar rot incidence through strong antagonistic activity against S. rolfsii. The plants treated with UASDAMF consortium demonstrated 32% improvement in shoot growth, 142% increase in yield over the control. The AM fungal species effectively enhanced plant nutrient content, specifically 100% increase in P content. Soil enzyme activities were found to be highest with 19% increase in the UASDAMF consortium at 90 DAT. This study contributes valuable insights into the application of native AM fungal consortia as a sustainable alternative to chemical controls in managing soil-borne diseases and improving crop productivity.

Keywords: *AM fungi, Antioxidant enzymes, Collar rot, Growth promotion, Plant Nutrient content, Sclerotium rolfsii, Soil enzyme activity, etc.*

Introduction

Eggplant (*Solanum melongena* L.) is predominantly cultivated in tropical and subtropical regions [1]. India is considered the center of origin for eggplant [2,3]. It accounts for approximately 15% of the country's total vegetable production and serves as a staple food for many. As of 2023, global eggplant production reached nearly 60 million tons annually, making it one of the most economically important solanaceous crops after potato and tomato [4]. The major producers include China, India, Egypt, Turkey, and Indonesia, with China and India together contributing 86% of the global output. In India, eggplant is cultivated on approximately 0.757 million hectares, yielding 13.153 million metric tonnes.

Eggplant is low in calories but highly nutritious, rich in vitamins, minerals, and bioactive compounds beneficial to human health [5,6]. Its high phenolic content including chlorogenic acid and anthocyanins gives it a strong oxygen radical scavenging capacity [7].

Eggplants have a long growth period, making them vulnerable to a wide range of diseases, pests, nematodes, and weeds [8]. Among these biotic stressors, fungal pathogens such as *Sclerotium rolfsii*, *Fusarium*, *Pythium*, *Verticillium*, and *Alternaria* cause several major diseases, often beginning at the nursery stage itself [9]. *Sclerotium rolfsii* is a particularly important soil-borne pathogen that affects both pre- and post-emergence stages of the crop. It is a polyphagous, facultative saprophytic fungus known for its ability to survive in the soil for extended periods through the formation of resilient sclerotia [10]. This fungus is responsible for various plant diseases, including root rot, stem rot, and southern blight [11]. In eggplants, it specifically causes collar rot, resulting in significant economic losses of up to 60% [12]. The disease is characterized by a white, cottony mycelial growth that eventually forms sclerotial bodies, which are initially white and later turn brown or black as they mature [13]. Affected plants exhibit symptoms such as leaf yellowing and drooping, reduced vigour, water-soaked lesions around the stem base, stem girdling, wilting, and ultimately complete plant death [14.

The use of fungicides to counter this issue can lead to unintended consequences, including the accumulation of agrochemicals in soil, water, and food, which may negatively impact the environment and human health [15,16]. As a result, recent research has increasingly focused on identifying sustainable alternatives for disease suppression [17]. One promising strategy involves the use of plant-associated microorganisms, particularly plant growth-promoting microorganisms (PGPMs), which enhance plant tolerance to pathogens, improve nutrient uptake, and promote overall plant health and productivity [18,19].

Among the PGPMs, mycorrhizal fungi are widely recognized as beneficial symbionts that colonize the roots of most terrestrial

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DOI: https://doi.org/10.21276/AATCCReview.2025.13.03.491

plants. Arbuscular mycorrhizal (AM) fungi form extensive hyphal networks and distinct structures—such as vesicles, arbuscules, hyphae, and spores—that enhance the tolerance of host plants to various biotic and abiotic stresses [20]. It is estimated that approximately 97% of known plant species have the potential to form mycorrhizal associations with nearly 6,000 fungal species [21].

It is well established that arbuscular mycorrhizae contribute to increased production of plant hormones, enhance the activity of both symbiotic and asymbiotic nitrogen-fixing organisms in the rhizosphere, and reduce the severity of root pathogen attacks [22,23]. Roots colonized by AM fungi remain more active and functional for a longer duration than non-mycorrhizal roots [24]. These fungi play a crucial role in the uptake and translocation of nutrients—including phosphorus, sulfur, nitrogen, and various micronutrients—from the soil to the host plant [25]. Apart from improving plant nutrition, AM fungi also contribute significantly to enhancing plant tolerance to both biotic and abiotic stresses [26]. The activation of systemic resistance in plants against pathogens and pests by mycorrhizal fungi is known as mycorrhiza-induced resistance (MIR). This phenomenon has been extensively documented in the scientific literatures, emphasizing its role in strengthening plant defense mechanisms against a broad range of biotic stressors [27,28].

The introduction of bioagents that serve dual roles—as biocontrol agents against pathogens and as biofertilizers—offers the potential to improve the nutritional status of infected plants while inducing resistance to soil-borne pathogens. Therefore, this study aims to evaluate the impact of AM fungal inoculation in eggplants under challenge conditions with *Sclerotium rolfsii*. The objective is to manage plant diseases effectively while simultaneously enhancing plant growth and nutrient uptake, thereby contributing to sustainable agriculture.

Materials and Methods

The three AM fungal isolates *viz., Glomus fasciculatum, Glomus leptotichum* and *Glomus macrocarpum* were procured from Department of Agricultural Microbiology, UAS Dharwad. UASDAMF consortia consisting *Glomus macrocarpum, Gigaspora margirata* and *Acaulospora laevis* (used as standard check) were obtained from the Weed Scheme, UAS Dharwad.

Mass Production of Arbuscular Mycorrhizal Fungi (AMF)

Finger millet (*Eleusine coracana*) seeds were surface-sterilized by soaking in 10% sodium hypochlorite solution for 30 minutes, followed by three rinses with sterile distilled water. The sterilized seeds were sown in plastic pots containing a sterile vermiculite substrate that had been autoclaved at 121°C for 30 minutes. AM fungal inoculum was added to each pot and sown with three seeds each. The pots were maintained under controlled conditions with a 12-hour photoperiod at 30°C and a 12-hour dark period at 23°C. Plants were irrigated regularly with sterile distilled water to maintain adequate moisture.

Mass Production of *Sclerotium rolfsii*

Eggplant (*Solanum melongena* L.) plants exhibiting collar rot symptoms were sampled, and infected stem tissues were cut into small segments. These were surface-sterilized with 1% sodium hypochlorite for 2 minutes, rinsed thoroughly with sterile distilled water, and then transferred aseptically onto Petri plates containing sterilized potato dextrose agar (PDA). Plates were incubated at 28°C for three days.

Emerging fungal colonies were subcultured to obtain pure cultures. *Sclerotium rolfsii* was mass-multiplied using a sterilized sand-cornmeal. After mixing and autoclaving the substrate, 5 mm mycelial discs from actively growing fungal cultures were inoculated into the medium and incubated at room temperature for 30 days to facilitate mycelial colonization.

Pot Experiment

Eggplant seeds were surface-sterilized using 2% sodium hypochlorite for 10 minutes and rinsed thrice with sterile distilled water. Seeds were sown in nursery beds previously amended with AMF inoculum and maintained for 45 days. Potting soil was collected from adjacent cultivated fields and thoroughly homogenized. Each pot (8 kg capacity) was filled with the field soil and inoculated with *S. rolfsii* at 4% (w/w). Forty-five-day-old AMF-precolonized eggplant seedlings were transplanted into the pots. At the time of transplanting, an additional 30 g of AMF inoculum was applied. Two weeks post-transplantation, a uniform dose of fertilizer was administered to all pots. Soil moisture was maintained consistently by regular irrigation. The experiment was conducted under natural conditions, with ambient temperature ranging from 25°C to 30°C and relative humidity between 30% and 70%.

Observations

The experimental observations were recorded at periodic intervals. The plant height was measured from the base of the plant up to the tip of the fully opened leaf and expressed in centimeters. For root growth studies, the plants were uprooted, roots were washed and the average root length was measured. To estimate the dry matter accumulation, samples with shoots, roots, and leaves were washed and then air-dried under shade for 24 h and then oven-dried at 60 °C until a constant weight was obtained, and then expressed as g plant^{-1}.

Mycorrhizal colonization

Mycorrhizal colonization in plant roots was assessed following the method described by Phillips and Hayman [29]. Root samples were cut into approximately 1 cm segments and fixed in FAA solution (formalin:acetic acid:ethanol in a ratio of 5:5:90, v/v/v). The fixed roots were cleared by autoclaving in 10% potassium hydroxide (KOH) at 15 lbs pressure for 15 minutes. After cooling, the samples were acidified with 1% hydrochloric acid (HCl) for 5 minutes to neutralize residual alkali. The root segments were then stained overnight in 0.05% trypan blue solution. Excess stain was removed by decantation, and the roots were mounted in lactoglycerol (lactic acid:glycerol:water) for microscopic observation. The AMF root colonization was calculated by the following formula,

$$\text{AMF root colonization} = \frac{\text{No. of root bits showing mycorrhizal colonization}}{\text{Total No. of root bits observed}} \times 100$$

Mycorrhizal spore count

AM spores were isolated following the wet sieving and decantation method outlined by Gerdemann and Nicholson [30]. 10 g of soil sample was taken in a beaker, 1000 ml of water was added and stirred well. The heavier soil particles were allowed to settle for a few seconds and the suspension was passed through sieves arranged in the descending order of their mesh size. This was repeated 5-6 times, till the suspension appeared clear. The content was collected and examined under stereomicroscope.

Estimation of antioxidant enzymes

Extraction of enzyme

200 mg of leaf samples were crushed in liquid nitrogen, and 2 mL of pre-cooled extraction buffer (0.1 M phosphoric acid buffer, pH 7.8 plus polyethylene pyrrolidone) was added to the mixture and centrifuged (13,000 g) for 20 minutes at 4 °C. The Bradford assay was used to quantify total protein.

Phenylalanine ammonia-lyase (PAL)

The PALase was measured using a modified version of the Burrell and Rees technique [31]. 0.2 ml of the enzyme extract was transferred to tubes with 2.5 ml of borate buffer and 1 ml of 0.1 mM phenylalanine (pH 8.8) and incubated at 32 ºC for 30 minutes. To halt the enzyme activity, 0.5 ml of 1M trichloroacetic acid was added. The absorbance was read at 290 nm in an UV-VIS spectrophotometer. The trans-cinnamic acid standard curve was prepared to quantify cinnamic acid, and the PAL activity was reported as µ moles of cinnamic acid generated per minute per gram of fresh weight.

Estimation of polyphenol oxidase (PPO)

Polyphenol oxidase (PPO) activity was assayed following the method of Hsu et al. [32]. The reaction mixture consisted of 100 µL of enzyme extract, 2.4 mL of phosphate buffer (pH 6.0), and 0.5 mL of pyrogallol solution as the substrate. The components were mixed thoroughly in a cuvette, and the initial absorbance was recorded immediately at 495 nm. Subsequent absorbance readings were taken at 5-minute intervals. The average change in absorbance per minute was calculated. One unit of PPO activity was defined as the amount of enzyme causing a 0.1 increase in absorbance per minute. Enzyme activity was expressed as the change in absorbance per minute per milligram of protein ($\Delta A495\ min^{-1}\ mg^{-1}$ protein).

Estimation of peroxidase (POD)

Peroxidase activity was determined following the method of Addy and Goodman [33], with slight modifications. A reaction mixture containing 3 mL of 0.05 M pyrogallol reagent and 0.01 mL of enzyme extract was prepared and the initial absorbance was recorded at 436 nm using a spectrophotometer. Subsequently, 0.5 mL of 3% hydrogen peroxide (H_2O_2) was added to the reaction mixture, gently inverted once and immediately placed back into the spectrophotometer. The change in optical density (OD) was monitored between 30 and 150 seconds. Peroxidase activity was expressed as the change in absorbance per minute, where an increase of 0.01 OD unit per minute was considered equivalent to one unit of enzyme activity.

Disease scoring

Sclerotium rolfsii infection was seen close to the collar area. The following formula [34] was used to determine the illness incidence based on the onset of symptoms:

$$\text{Disease incidence (\%)} = \frac{\text{Number of infected plants}}{\text{Total number of plants}} \times 100$$

Estimation of soil enzymatic activity

Dehydrogenase

The method outlined by Casida *et al.* [35] was employed to determine the dehydrogenase activity with slight modifications. 10 grams of soil sample and 2 grams of $CaCO_3$ were mixed and added to test tubes. 8 ml of distilled water, 1 ml of 3% 2, 3, 5-triphenyl tetrazolium chloride (TTC), and 1 ml of 1% glucose were added to each. The tubes were sealed and incubated in the dark. After 24 hours, the contents were transferred to a beaker and 10 ml of methanol was added. The slurry was filtered using Whatman No. 50 filter paper. The process was continued until the red colour was eliminated. Methanol was added to make up the volume to 50 ml. The intensity of red color was read using UV-VIS spectrophotometer (Thermo Scientific, USA) at 485 nm. The findings were presented as µg of triphenyl formazan generated g^{-1} day^{-1}.

Phosphatase

Phosphatase activity was determined following the method described by Eivazi and Tabatabai [36]. One gram of soil was placed in a 50 mL Erlenmeyer flask containing 0.2 mL of toluene and 4 mL of universal buffer (pH 7.5). Subsequently, 1 mL of para-nitrophenyl phosphate (p-NPP) solution was added, and the mixture was stirred for 2 minutes. The flasks were then incubated at 37 °C for 1 hour. After incubation, 1 mL of 0.5 M $CaCl_2$ and 4 mL of 0.5 M NaOH were added to stop the reaction. The contents were mixed thoroughly and filtered through Whatman No. 42 filter paper. The intensity of the yellow color, was measured at 420 nm using a Thermo Scientific spectrophotometer (USA). Phosphatase activity was expressed as micrograms of PNP released per gram of soil per hour (µg PNP g^{-1} soil h^{-1}).

Urease

The urease activity of soil samples was evaluated using the Tabatabai and Bremner technique [37]. 10 g of samples were treated with 1 ml of toluene and 10 ml of phosphate buffer and incubated at 30°C. After 24 hours, 15 mL of 1N KCl was added, and the contents were filtered through Whatman No. 42. The filtrate volume was made to 100 ml using distilled water. To 1 ml of extractant, 2 ml of 10% sodium tartrate, and 0.5 ml of Nessler's reagent were added, incubated for 30 minutes, and the volume was made to 25 ml with distilled water. The yellow color generated was measured at 610 nm using a UV-VIS spectrophotometer (Thermo Scientific, USA). The data were presented as µg NH_4-N g^{-1} soil day^{-1}.

Yield and plant nutrient analysis

The change in colour of fruits from green to purple was an indication of maturity for harvesting. Total number of fruits per plant, average fruit yield and total fruit weight per plant were recorded. The plant nitrogen content was estimated following the micro-Kjeldahl method as outlined by Jackson [38]. Phosphorus was estimated by vanadomolybdate phosphoric yellow colour method [38]. Potassium content was estimated by the flame photometry method [39]. Micronutrients *viz*., copper, iron, manganese, and zinc in the plant digest were estimated using AAS.

Statistical analysis

The analysis and interpretation of data were performed using Fischer's method of analysis of variance technique as described by Gomez and Gomez [40]. The level of significance used in the 'F' and 't' tests was p = 0.01. Critical difference values were calculated wherever the 'F' test was significant.

Results

The data presented in Table 1 highlight the impact of various treatments on plant height, root length, and total dry weight in brinjal at 45 and 90 days after transplanting (DAT).

The control group inoculated with *Sclerotium rolfsii* exhibited the lowest growth metrics, with plant height reaching 56.17 cm and root length of 10.80 cm, alongside a total dry weight of 10.89 g by 90 DAT. In contrast, plants treated with different *Glomus* species showed significantly enhanced growth. *Glomus macrocarpum* led to the highest increase, with a plant height of 74.30 cm, root length of 23.24 cm, and total dry weight of 16.80 g at 90 DAT. Similarly, the *Glomus fasciculatum* also demonstrated substantial growth promotion, achieving a plant height of 72.04 cm, root length of 21.45 cm, and a total dry weight of 14.90 g. The negative control group, which did not receive any AMF treatment, performed better than the *S. rolfsii* group but showed significantly lower growth metrics compared to AMF-treated plants. These results underscore the potential of AM fungi, in promoting plant growth and biomass accumulation in eggplants under pathogenic stress conditions.

Table 2 indicates significant differences in root colonization and spore count across the various treatments. In the presence of *S. rolfsii*, root colonization was lowest at 15.00%, with a corresponding spore count highlighting its adverse effect on both parameters. The negative control exhibited similar values, suggesting baseline conditions in the absence of AM fungi. Among the AMF treatments, *G. fasciculatum* and *G. macrocarpum* significantly enhanced root colonization to 62.33% and 65.00%, respectively, with spore counts of 145.00 and 162.00 per 50 g of soil, indicating their robust symbiotic association. *G. leptotichum* showed comparable results. *G. fasciculatum* was comparable to UASDAMF consortium, demonstrating its superior efficacy in enhancing both parameters over others. These findings underscore the differential impacts of AMF species on root colonization and spore proliferation.

The table 3 demonstrates significant variations in enzyme activities and disease incidence among different treatments against *S. rolfsii* in egg plants. The application of AM fungi notably enhanced enzyme activities and reduced disease incidence. Among the AM fungi, *G. macrocarpum* elicited the highest enzyme activities, with PAL, PPO, and peroxidase levels and the lowest disease incidence of 33.33%. Similarly, treatments with *G. fasciculatum* and *G. leptotichum* resulted in increased enzyme activities and reduced disease incidences compared to controls. The negative control exhibited the lowest levels of PAL, PPO and POD activities with no disease incidence. In contrast, plants treated with *S. rolfsii* alone showed significantly higher disease incidence (68.33%) but lower enzyme activities. The UASDAMF consortium was the most effective treatment, significantly increasing enzyme activities, respectively, and reducing disease incidence to 28.33%. These findings highlight the potential of AMF in enhancing plant defense mechanisms and reducing disease severity in eggplants.

Table 4 shows enzyme activity levels of dehydrogenase, phosphatase, and urease assessed in various treatments for 45, 60, and 90 days after treatment (DAT). For dehydrogenase activity, all AM fungal treatments demonstrated higher activity compared to the *S. rolfsii* and the negative control. Among the AM fungi, the *G. macrocarpum* consistently showed the highest dehydrogenase activity. The UASDAMF Consortium and *G. fasciculatum* treatments also showed significantly higher activities, particularly at 60 DAT, where activities were recorded at 48.74 and 48.40, respectively. Phosphatase activity was similarly enhanced in AM fungi treatments compared to the *S. rolfsii* and negative control groups.

The UASDAMF Consortium recorded the highest phosphatase activity at 45 and 90 DAT. *G. macrocarpum* followed closely, especially at 60 DAT. Urease activity was highest in the UASDAMF Consortium at all-time points, peaking at 45 DAT. Other AM fungi treatments also demonstrated superior urease activities over the *S. rolfsii* and negative control, highlighting the efficacy of AM fungi in promoting enzyme activities crucial for soil fertility.

Table 5 shows the impact of various treatments on the yield of eggplants. Plants infected with *S. rolfsii* produced the fewest fruits per plant (5.00), with the lowest average fruit weight (33.37 g) and fruit weight per plant (166.85 g), indicating significant disease-induced yield loss. In contrast, plants treated with different species of *Glomus* demonstrated marked improvements in fruit yield. *G. fasciculatum* and *G. leptotichum* both resulted in an average of 9.33 fruits per plant, with similar fruit weights of 367.01 g and 362.43 g, respectively. *Glomus macrocarpum* showed a higher yield with 9.67 fruits per plant and a total fruit weight of 384.09 g. The UASDAMF Consortium treatment was the most effective, producing 10.00 fruits per plant with the highest average fruit weight (40.50 g) and total fruit weight (405.00 g), suggesting a strong potential for enhancing yield in eggplant.

The effects of different treatments on the nutrient content and micronutrient accumulation in eggplant plants are summarized in Table 6. The inoculation with *Sclerotium rolfsii* resulted in lower levels of both macro- well as micronutrients as compared to the negative control. In contrast, all treatments with arbuscular mycorrhizal (AM) fungi significantly enhanced nutrient uptake. *G. fasciculatum* and *G. leptotichum* showed similar enhancements in nutrient accumulation, with slight variations. *G. macrocarpum* treatment exhibited the substantial increase in concentrations of nitrogen (1.22%), phosphorus (0.40%), and potassium (1.56%), along with increased levels of copper (55 mg kg^{-1}, iron (285 mg kg^{-1}, manganese (82 mg kg^{-1}, and zinc (54 mg kg^{-1}). The UASDAMF Consortium treatment demonstrated the most substantial improvement, resulting in the highest concentrations of all measured nutrients, including nitrogen (1.23%), phosphorus (0.42%), and potassium (1.58%), and significantly elevated levels of copper (58 mg kg^{-1}), iron (290 mg kg^{-1}), manganese (86 mg kg^{-1}), and zinc (55 mg kg^{-1}). These results underscore the beneficial role of AM fungi in enhancing nutrient uptake and micronutrient accumulation by plants.

Discussion

The findings of this study demonstrate that arbuscular mycorrhizal (AM) fungi significantly enhance the growth of eggplant. The growth enhancement observed in this study can be attributed to the improved nutrient uptake facilitated by AM fungi [41]. AM fungi form symbiotic associations with plant roots, which increase the surface area for nutrient absorption, particularly for phosphorus, a critical element for plant growth. This mycorrhizal effect has been extensively documented in various crop species, where increased phosphorus uptake is linked to improved plant growth and biomass accumulation [42]. Moreover, the colonization of eggplant roots by AM fungi likely enhanced the synthesis of phytohormones such as auxins and cytokinins, which are known to stimulate root and shoot growth. Such hormonal modulation could explain the observed increase in plant height, leaf area, and overall biomass in AM fungi-inoculated plants.

The results also align with previous studies highlighting the pivotal role of AM fungi in promoting plant health and stress tolerance [43].

The symbiotic relationship between AM fungi and plant roots facilitates a greater soil exploration capacity through an extensive hyphal network, allowing more efficient uptake of water and nutrients [44]. This is particularly beneficial for eggplant, as it requires a substantial amount of nutrients for optimal growth and fruit production. Moreover, the mycorrhizal colonization was associated with increased root length and surface area, which are critical factors for nutrient uptake [45]. This enhanced root architecture also contributes to better anchorage and stability of the plant, which is vital for supporting the above-ground biomass [46].

One of the most notable findings of this study is the significant reduction in disease severity caused by *S. rolfsii* in mycorrhizal plants. The disease resistance conferred by AM fungi could be attributed to several mechanisms, including induced systemic resistance (ISR), improved nutritional status, and alterations in root exudation patterns. The findings align with previous reports of AM fungi inducing systemic resistance in host plants, thereby reducing disease incidence and severity [47]. Mycorrhizal colonization triggers ISR, a plant defense mechanism that is activated in response to pathogen attack and involves the production of defense-related enzymes and secondary metabolites [48]. The increased activity of enzymes like chitinases, glucanases, and peroxidases observed in this study suggests that AM fungi may prime the plant's defense system, making it more responsive to pathogen invasion [49].

AM fungi are known to activate plant defense pathways by inducing the production of secondary metabolites such as phenolics, flavonoids, and pathogenesis-related proteins, which can deter pathogens [50]. Additionally, AM fungi may enhance the physical barriers of plant roots, such as lignin and callose deposition, making them less susceptible to pathogen attack [51]. The suppression of *Sclerotium rolfsii* observed in this study could also be due to the competitive exclusion of pathogens by the AM fungal community, which limits pathogen access to root tissues [52].

Alterations in root exudation patterns by mycorrhizal plants could also influence pathogen dynamics in the rhizosphere [53]. AM fungi modify the composition of root exudates, leading to changes in the microbial community and suppression of soil-borne pathogens [54]. In this study, the lower disease incidence in mycorrhizal plants might be partly due to the enhanced microbial antagonism against *S. rolfsii* in the rhizosphere, as suggested by the higher abundance of beneficial microorganisms observed in the mycorrhizal treatments. Furthermore, the improved nutritional status of mycorrhizal plants may enhance their ability to mount effective defense responses. Adequate phosphorus nutrition, for instance, is known to enhance the synthesis of phenolic compounds, which play a crucial role in plant defense against pathogens [55].

The role of AM fungi in enhancing mineral nutrition was evidenced by the increased uptake of essential nutrients, such as phosphorus (P), nitrogen (N), potassium (K), and micronutrients like zinc and copper [56]. Mycorrhizal plants showed significantly higher concentrations of these nutrients in their tissues compared to non-mycorrhizal plants. The translocation of nutrients is crucial for maintaining plant health, especially under nutrient-deficient conditions [57]. This enhancement in nutrient uptake can be attributed to the mycorrhizal hyphae's ability to access soil pores that are too small for roots to penetrate, thus increasing the effective root surface area for nutrient absorption [58]. The improved nutritional status of plants inoculated with AM fungi aligns with findings from previous studies, which report similar enhancements in nutrient acquisition [59]. Furthermore, AM fungi enhance soil structure and microbial diversity, which can indirectly improve nutrient availability and uptake by plants [60].

Phosphorus is a critical nutrient for plant growth, and its availability often limits crop productivity [61]. The ability of AM fungi to enhance phosphorus uptake is well documented and is primarily due to the expression of phosphate transporter genes in both the fungus and the host plant [62]. In this study, mycorrhizal eggplants exhibited a marked increase in phosphorus content, which could explain the observed improvement in growth parameters. Additionally, the enhanced uptake of N, K, Zn, and Cu further indicates the broad-spectrum nutrient acquisition capability of AM fungi, which is vital for the overall metabolic and physiological functions of the plant.

Conclusion

The results of this study provide compelling evidence that AM fungi *viz., Glomus fasciculatum, G. leptotichum* and *G. macrocarpum* play a critical role in enhancing the growth, nutrition, and disease resistance of eggplants, particularly against soil-borne pathogen, *S. rolfsii*. This symbiotic relationship offers a sustainable alternative to chemical fertilizers and pesticides, contributing to eco-friendly agricultural practices. The integration of AM fungi into crop management systems could reduce reliance on agrochemicals, enhance crop resilience, and improve yield quality and quantity.

Future Scope of the Study

Future research can focus on large-scale field trials to validate these results under diverse agro-climatic conditions. Moreover, molecular investigations on the signaling pathways and gene expression patterns involved in AM-induced resistance could provide deeper insights into plant–fungus–pathogen interactions.

Declarations

Author contributions

All authors contributed to the conception and design. The experiment was performed, and the first draft of the manuscript was written by Avinash, S. H. The study was reviewed, and the manuscript was edited by P. Jones Nirmalnath and Yashoda Hegde. Statistical analysis was performed by Manasa, S.G., and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Data availability

All data generated or analysed during this study are included in this published article.

Compliance with Ethical Standards

Not applicable

Funding

No funds, grants, or other support were received for the present study.

Table 1: Influence of AM fungi on plant height, root length and dry weight of eggplant

Treatment	Plant height (cm)		Root length (cm)		Total dry weight (g)	
	45 DAT	90 DAT	45 DAT	90 DAT	45 DAT	90 DAT
Sclerotium rolfsii	27.83±0.9^{a}	56.17±1.67^{a}	9.60±0.31^{a}	9.60±0.46^{a}	6.12±0.26^{a}	10.89±0.46^{a}
Negative control	30.16±0.92^{a}	61.10±1.86^{b}	12.03±0.37^{b}	12.03±0.94^{b}	7.45±0.39^{b}	11.90±0.63^{a}
Glomus fasciculatum	35.00±1.02^{bc}	72.04±2.1^{cd}	17.50±0.59^{c}	17.50±0.63^{cd}	9.46±0.28^{c}	14.90±0.44^{b}
Glomus leptotichum	33.93±1.47^{b}	70.17±2.21^{c}	18.37±0.8^{cd}	18.37±0.98^{c}	9.15±0.43^{c}	14.60±0.68^{b}
Glomus macrocarpum	36.50±1.92^{bc}	74.30±1.37^{d}	18.40±0.97^{cd}	18.40±1.2^{de}	10.36±0.54^{d}	16.80±0.87^{c}
UASDAMF Consortium	37.40±2.11^{c}	74.57±2.05^{d}	19.20±1.08^{d}	19.20±1.36^{d}	9.87±0.56^{cd}	15.40±0.88^{b}

***Note**: DAT- Days after transplantation; Values are means ± SD from three sets of independent experiments. Significant differences among treatments were tested at P = 0.05 by Duncan post hoc test.*

Table 2: Assessment of AMF root colonization and spore count/50 g

Treatment	Root colonization	Spore count 50 g^{-1} of soil
Sclerotium rolfsii	15.00±0.72^{a}	47.00±2.26^{a}
Negative control	18.33±0.96^{a}	55.67±2.92^{a}
Glomus fasciculatum	62.33±1.82^{bc}	145.00±4.24^{c}
Glomus leptotichum	57.67±2.69^{b}	130.00±6.06^{b}
Glomus macrocarpum	65.00±3.36^{c}	162.00±8.37^{d}
UASDAMF Consortium	67.33±3.85^{c}	173.00±9.9^{d}

***Note:** Values are means ± SD from three sets of independent experiments. Significant differences among treatments were tested at P = 0.05 by Duncan post hoc test.*

Table 3. Anti-oxidant enzyme activity in eggplants as influenced by the inoculation of AM fungi

Treatment	PAL activity	PPO activity	POD activity	Disease incidence (%)
Sclerotium rolfsii	0.28±0.01^{a}	1.58±0.05^{b}	2.64±0.13^{b}	68.33±14.14^{c}
Negative control	0.26±0.01^{a}	1.29±0.04^{a}	2.07±0.11a	0±0^{a}
Glomus fasciculatum	0.5±0.02^{b}	2.95±0.09^{c}	4.86±0.14^{c}	35.00±8.54^{b}
Glomus leptotichum	0.49±0.02^{b}	2.94±0.09^{c}	4.73±0.22^{c}	40.00±4.08^{b}
Glomus macrocarpum	0.52±0.03^{b}	3.06±0.06^{c}	5.01±0.26^{c}	33.33±10.8^{b}
UASDAMF Consortium	0.51±0.03^{b}	3.99±0.11^{d}	5.76±0.33^{d}	28.33±9.57^{b}

***Note:** PAL: Phenylalanine ammonia lyase; PAL: Polyphenol oxidase; POD: Peroxidase; Values are means ± SD from three sets of independent experiments. Significant differences among treatments were tested at P = 0.05 by Duncan post hoc test.*

Table 4: Estimation of enzyme activity in soil inoculated with AM fungi

Treatment	Dehydrogenase			Phosphatase			Urease		
	45 DAT	60 DAT	90 DAT	45 DAT	60 DAT	90 DAT	45 DAT	60 DAT	90 DAT
Sclerotium rolfsii	39.33±1.89^{a}	40.45±1.2^{a}	27.35±0.81^{a}	36.24±1.75^{ab}	40.63±1.21^{b}	30.93±1.49^{a}	23.65±0.7^{a}	27.05±1.3^{a}	17.7±0.53^{a}
Negative control	35.35±1.86^{a}	38.04±1.16^{a}	29.21±0.89^{b}	33.01±1.73^{a}	37.21±1.13^{a}	28.02±1.47^{a}	22.35±0.68^{a}	26.44±1.39^{a}	17.24±0.53^{a}
Glomus fasciculatum	44.98±1.32^{b}	48.4±1.41^{b}	33.47±0.98^{c}	39.12±1.14^{bc}	43.54±1.27^{c}	35.29±1.03^{b}	30.05±0.88^{b}	33.82±0.99^{b}	22.15±0.65^{b}
Glomus leptotichum	44.14±2.06^{b}	47.6±1.5^{b}	33.78±1.06^{c}	38.97±1.82^{bc}	43.51±1.37^{c}	35.05±1.63^{b}	29.98±0.94^{b}	33.72±1.57^{b}	21.88±0.69^{b}
Glomus macrocarpum	45.18±2.33^{b}	48.97±0.9^{b}	35.23±0.65^{c}	39.49±2.04^{bc}	43.81±0.81^{c}	35.49±1.83^{b}	30.49±0.56^{b}	34.23±1.77^{b}	22.54±0.42^{b}
UASDAMF Consortium	45.37±2.6^{b}	48.74±1.34^{b}	34.35±0.95^{c}	40.87±2.34^{c}	43.92±1.21^{c}	36.81±2.11^{b}	30.78±0.85^{b}	34.41±1.97^{b}	22.87±0.63^{b}

***Note**: DAT: Days after transplantation; Values are means ± SD from three sets of independent experiments. Significant differences among treatments were tested at P = 0.05 by Duncan post hoc test.*

Table 5: Yield parameters of eggplant influenced by AM fungi

Treatment	Number of fruits plant^{-1}	Average fruit weight (g)	Fruit weight plant^{-1} (g)
Sclerotium rolfsii	5.00±0.82^{a}	33.37±1.61^{a}	166.85±8.03^{a}
Negative control	8.00±0.96^{b}	36.10±1.9^{ab}	288.80±15.17^{b}
Glomus fasciculatum	9.33±0.50^{c}	39.28±1.15^{bc}	367.01±10.73^{c}
Glomus leptotichum	9.33±0.5^{c}	38.79±1.81^{bc}	362.43±16.89^{c}
Glomus macrocarpum	9.67±0.96^{c}	39.72±2.05^{bc}	384.09±19.84^{cd}
UASDAMF Consortium	10.00±1.41^{c}	40.50±2.32^{c}	405.00±23.17^{d}

***Note**: Values are means ± SD from three sets of independent experiments. Significant differences among treatments were tested at P = 0.05 by Duncan post hoc test.*

Table 6: Plant nutrient content of eggplant influenced by AM fungi

Treatment	Nitrogen (%)	Phosphorous (%)	Potassium (%)	Copper (mg kg^{-1})	Iron (mg kg^{-1})	Manganese (mg kg^{-1})	Zinc (mg kg^{-1})
Sclerotium rolfsii	0.91±0.03^{a}	0.21±0.01^{a}	0.78±0.02^{a}	30±1.44^{a}	135±4.01^{a}	59±2.84^{a}	38±1.83^{a}
Negative control	1.09±0.03^{b}	0.23±0.01^{b}	0.91±0.03^{b}	36±1.89^{b}	158±4.81^{b}	68±3.57^{b}	44±2.31^{b}
Glomus fasciculatum	1.21±0.04^{c}	0.39±0.01^{b}	1.48±0.04^{c}	51±1.49^{c}	270±7.88^{c}	76±2.22^{c}	50±1.46^{c}
Glomus leptotichum	1.18±0.04^{c}	0.4±0.01^{cd}	1.53±0.05^{cd}	54±2.52^{cd}	274±8.62^{cd}	78±3.63^{c}	52±2.42^{c}
Glomus macrocarpum	1.22±0.02^{c}	0.4±0.01^{cd}	1.56±0.03^{d}	55±2.84^{cd}	285±5.26^{de}	82±4.23^{cd}	54±2.79^{c}
UASDAMF Consortium	1.23±0.03^{c}	0.42±0.01^{d}	1.58±0.04^{d}	58±3.32^{d}	290±7.98^{e}	86±4.92^{d}	55±3.15^{c}

***Note:** Values are means ± SD from three sets of independent experiments. Significant differences among treatments were tested at P = 0.05 by Duncan post hoc test.*

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