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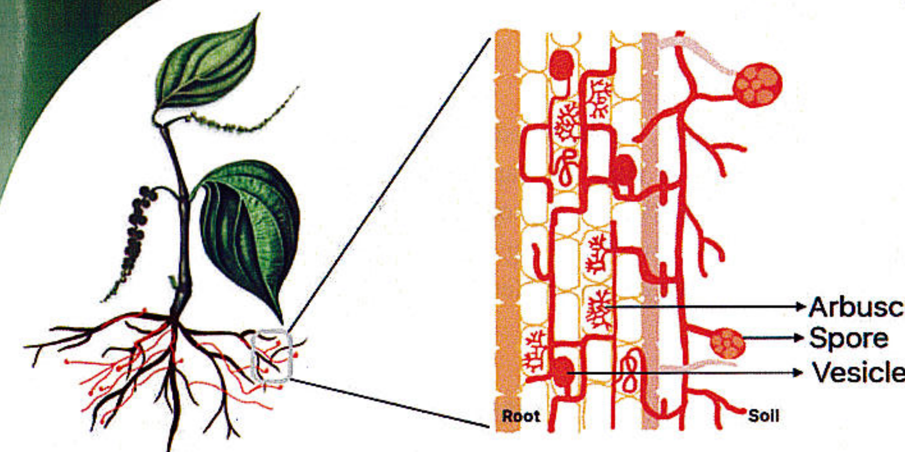
Arbuscular mycorrhizal fungi: A promising biostimulant for enhancing growth of major spices



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1. Introduction

India is the world's largest producer, consumer, and exporter of spices such as black pepper, cardamom, ginger and turmeric. Spices are an integral part of India's heritage, cuisines, and economy, earning the country its reputation as the "Land of Spices." However, the increasing reliance on chemical fertilizers in conventional farming systems has led to significant concerns about soil health, biodiversity loss, and environmental degradation. This scenario underscores the pressing need for sustainable agricultural practices that enhance productivity besides preserving soil fertility and maintaining ecological balance. Among various biostimulants, arbuscular mycorrhizal fungi (AMF) have emerged as pivotal allies in achieving sustainable spice production.

Arbuscular mycorrhizal fungi (AMF) are soil-borne, obligate symbionts that form mutualistic association with the roots of most terrestrial plants. These fungi colonize plant roots and develop unique structures called 'arbuscules' within the root cortical cells. In this symbiotic relationship, plants provide the fungi with sugars derived from photosynthesis, while the fungi supply the plants with phosphorus and other essential nutrients that are often unavailable to the plants (Janos, 1980). AMF also enhance water uptake and improve plant's resilience to abiotic stresses such as drought and salinity. These attributes make AMF invaluable in sustainable spice cultivation.

The role of AMF in improving soil health cannot be overstated. These fungi enhance soil structure by producing glomalin, a glycoprotein that contributes to soil aggregation and stability. Improved soil structure, in turn, enhances water infiltration and retention, which are crucial for spice crops often grown in regions prone to water scarcity. Furthermore, AMF colonization stimulates microbial diversity in the rhizosphere, creating a more resilient and balanced soil ecosystem (Berruti et al., 2016). This microbial diversity is essential for long-term sustainability of spice farming systems. Nutrient management is another critical aspect of spice farming, and AMF play a central role in this regard. Phosphorus, a vital nutrient for plant growth, is often present in insoluble forms in the soil, making it inaccessible to the plants. AMF possess specialized enzymes such as phosphatases that solubilize phosphorus, ensuring its availability to the plant. This is particularly beneficial for spice crops like turmeric and ginger, which have high nutrient demands. Studies have shown that AMF inoculation significantly enhances the uptake of phosphorus, nitrogen, and micronutrients, leading to improved growth and yield in spice crops. Disease resistance is another notable benefit of AMF. By enhancing the plant's immune response and competing with pathogenic microbes in the rhizosphere, AMF reduce the incidence of soil-borne diseases. For instance, ginger, a major spice crop, is highly susceptible to rhizome rot caused by *Pythium* spp. AMF colonization has been shown to suppress the growth of such

pathogens by inducing systemic resistance in the host plant (Sarathambal et al., 2024a).

In addition to improving nutrient uptake and disease resistance, AMF enhance stress tolerance of spice crops. Drought and salinity are major constraints in spice cultivation, particularly in semi-arid and coastal regions. AMF improve water-use efficiency and mitigate the adverse effects of salinity by regulating ion transport and maintaining cellular homeostasis (Evelin et al., 2009). These attributes are critical for sustaining spice production under changing climatic conditions. The economic implications of integrating AMF into spice cultivation are also noteworthy. By reducing the dependence on chemical fertilizers and pesticides, AMF contribute to cost savings for the farmers. Moreover, use of AMF aligns with the growing demand for organic spices in global markets, offering a premium price.

Key benefits of AM association with plants

The networking filament of mycorrhiza associated with plant roots helps to grab nutrients from the soil. It is assumed that one kilometre of hyphae (fine filaments) may be associated with a plant growing in a one litre pot and it can access water and nutrients in the smallest pores in the soil. In return, the fungi obtain carbohydrates and other nutrients from plants. They utilize these carbohydrates for their growth and to synthesize and excrete molecules like glomalin (glycoprotein). It is estimated that approximately 95 per cent of all vascular plants on earth are mycorrhizal. Plants and mycorrhiza have developed this mutually beneficial relationship as a mechanism for increased survival (Smith & Read, 2008).

2. Types of mycorrhiza

Classification of mycorrhizal fungi is based on the inter-relation between fungal hyphae and plant root cells which are of two types *viz.* Ectomycorrhizae and Endomycorrhizae (Arbuscular mycorrhizal fungi)

3.1 Ectomycorrhizae

Ectomycorrhizae form a compact mantle of hyphae on the outer surface of plant roots. The hyphal strands penetrate the root surface and grow between cortical root cells and then extend outward from the mantle to soil surface. Genera like *Rhizopogon villosulus, Rhizopogon luteolus, Rhizopogon amylopogon, Rhizopogon fulvigleba, Pisolithus tinctorius, Suillus granulatus, Laccaria bicolor, Laccaria laccata, Scleroderma cepa, Scleroderma citrinum etc.*, form ectomycorrhizae. This type of mycorrhizae commonly occur on coniferous plants like pine (Pinaceae), birch (Betulaceae), beech and oak (Fagaceae) and other woody plants. Due to their restricted host range, ectomycorrhizae provide benefits only for forestry seedlings and woody ornamentals.

3.2 Endomycorrhizae (arbuscular mycorrhizal fungi)

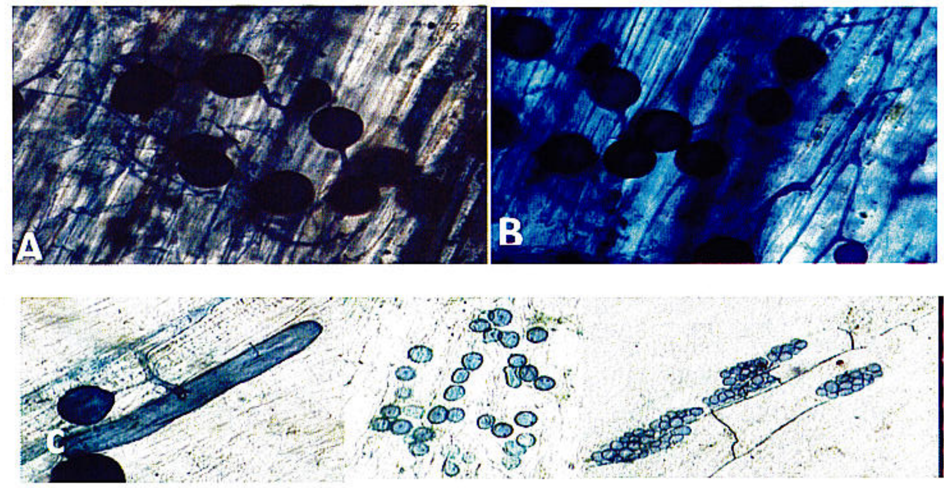
Endomycorrhizae form a symbiotic association with the host in which the hyphae penetrate and colonize epidermal and fleshy cortical cells of the plant roots. Unlike ectomycorrhizae which produce a surface mantle of hyphae, endomycorrhizae colonize only on the root surfaces as individual threads. Once the roots are colonized, individual hyphae extend from the root surface outward into the surrounding soil forming a vast hyphal network. The common fungal genera forming endomycorrhizal association include *Acaulospora, Entrophospora, Gigaspora, Glomus, Sclerocystis* and *Scutellospora etc.* The commonly encountered mycorrhizal species are *Glomus intraradices* (also referred as *Rhizophagus irregularis*), *Glomus mosseae, Glomus aggregatum, Glomus etunicatum, Glomus deserticola, Glomus clarum, Glomus monosporum, Paraglomus brasilianum* and *Gigaspora margarita*

Endomycorrhizae occur on almost all seed bearing plants (except those colonized by ectomycorrhizae), rain-forest tree species, most agricultural crops and a vast variety of ornamental greenhouse crops. In fact, about 85 per cent of the plant families in the world are colonized by endomycorrhizae. Arbuscular mycorrhiza is a main component of biodiversity particularly in tropical and subtropical ecosystems. They can modify the structure and functioning of a plant community, enhance plant growth under low fertility conditions and also impart tolerance to drought and diseases. AM fungi can enhance mineral nutrient acquisition and also play a major role in the regulation of soil biological activity due to their abundancy in the surface strata and constitute a major input of carbon and energy in soil and also improve soil aggregation and stability, the important factors for agriculture sustainability. There are plants that are devoid of endomycorrhizae like members of the cruciferaceae such as cabbage, cauliflower, canola, and crambe that do not establish arbuscular mycorrihizal fungi on their roots.

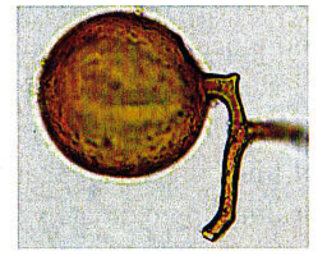
4. Occurrence of AM in spice crops

Arbuscular mycorrhizal fungi belong to the phylum Glomeromycota are obligate symbionts which colonize plant roots and extend their hyphal networks into the surrounding soil. This network expands the effective root system, allowing plants to access nutrients that are otherwise immobile, such as phosphorus, zinc, and copper. The symbiosis is characterized by a mutual exchange wherein the plants supply carbon compounds to the fungi, while the fungi enhance the plant's access to nutrients and water. Most horticultural nurseries prefer the mycorrhizal inoculation in potting media to increase crop uniformity, reduce transplant mortality and increase productivity (Sarathambal et al., 2022a). Spice crops like black pepper, ginger, turmeric and cardamom also colonize endomycorrhizae fungi in its roots. The Figure depicts the colonization of AM fungi inside, black pepper, ginger and turmeric (Sarathambal et al., 2022b). Based on our observations most of the spices possessed AM

fungal spores as a regular component of the soil microflora Among the recovered AM fungal spore population, *Glomus* species was dominant in most of the cultivated regions. This might be due to the high sporulation capacity and high viability of the *Glomus* species, while, others were scanty due to the longer reproductive period.



Colonization of AM in the roots of a) black pepper b) turmeric c) ginger



Spore of *Rhizophagus* sp. in soil

4.1 Effect of AM fungi on black pepper

Black pepper is one among the most widely used spices globally. Due to the rising demand in international markets, black pepper cultivation has expanded significantly over the past decade, both in traditional and non-traditional regions. However, one major challenge in its cultivation is the availability of high-quality planting material of high-yielding varieties. Traditional propagation methods adopted in black pepper face limitations such as high mortality rate, poor survival, and inadequate rooting of transplanted cuttings. To address these challenges, there is a need to enhance traditional propagation systems with effective input management strategies that boost the production of quality planting material.

One promising approach is the incorporation of suitable bio-inoculants into potting mixtures to improve the performance of planting materials. Many horticultural nurseries now adopt mycorrhizal inoculation in potting media, which helps enhance crop uniformity, reduce transplant mortality, and increase productivity. The use of arbuscular mycorrhizal fungi (AMF) as bio-inoculants is particularly beneficial, as it can increase productivity while reducing reliance on chemical fertilizers.

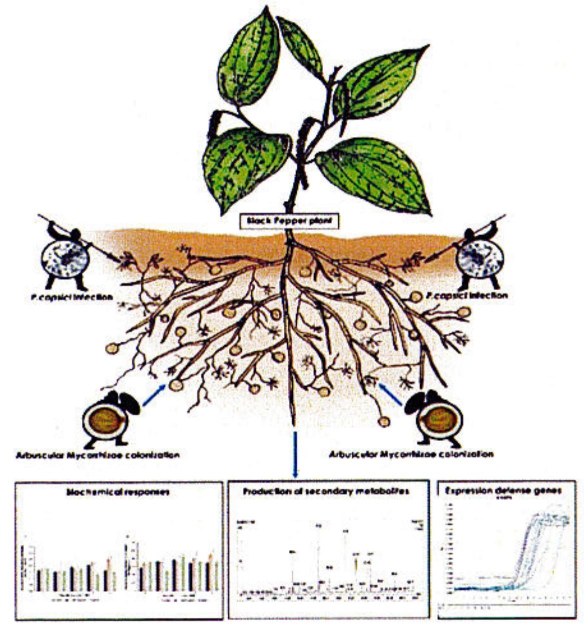
In natural soils, plants often associate with a diverse array of microorganisms that significantly influence their growth and health. Approximately 95% of all vascular plants are estimated to form mycorrhizal associations. These symbiotic relationships have evolved as a mechanism to enhance plant survival. Arbuscular mycorrhizal fungi, belonging to the phylum

Glomeromycota, are among the most abundant soil fungi. They improve plant growth by enhancing nutrient uptake, particularly phosphorus, and increasing water-use efficiency (Zhang et al., 2016). Furthermore, these fungi help plants withstand biotic and abiotic stresses by boosting their resilience. AMF have also been reported to stabilize soil structure, which promotes microbial growth. Beyond nutritional benefits, AMF improve plant growth and yield by defending plants against various stresses. For instance, research has shown that AMF colonization in the adventitious roots of strawberry stem cuttings enhances their growth and vigor (Singh et al., 2013). Additionally, AMF influence soil enzyme parameters by stimulating microbial activities, exuding up to 20–30% of soil microbial carbon, and transferring fresh plant carbon to soil microbes (Kaiser et al., 2015). The enhanced phosphorus nutrition in mycorrhizal plants often leads to higher photosynthetic rates compared to non-mycorrhizal plants (Auge et al., 2016). Physiological studies have also shown that carbon movement from shoots to roots is more efficient in AMF-inoculated plants, as demonstrated in tomato plants (Boldt et al., 2011). Another significant benefit of AMF is their ability to mitigate oxidative stress. When plants are exposed to biotic and abiotic stresses, they produce reactive oxygen species (ROS), which can damage cellular components. The symbiotic association with AMF induces transient ROS production during initial colonization, but this is followed by increased activity of antioxidant enzymes like catalase, peroxidase, superoxide dismutase, and others, which alleviate oxidative damage (Garg et al., 2015). In black pepper, studies have shown a positive correlation between the percentage of root colonization by AMF and the performance of black pepper cuttings. AMF inoculation has synergistic effects on the growth and nutrient uptake of black pepper plants. Mycorrhizal plants exhibit increased leaf photosynthetic rates and stomatal conductance due to improved mineral nutrient uptake. Additionally, higher activity of antioxidant enzymes like polyphenol oxidase in roots and β-1,3-glucanase in leaves has been observed in AMF-inoculated plants. However, no significant differences in peroxidase activity in roots were noted between inoculated and uninoculated plants.

In summary the following advantages were found upon applying AM fungi on black pepper crops

- AM enhances the rooting of black pepper cuttings and also increases root biomass as well as uptake of nutrients (Sarathambal et al 2023a).
- AM association with black pepper enhances the defense related enzymes mainly peroxidases which ultimately provide protection from diseases.
- AM pre-inoculation significantly increased the activity of pathogenesis related genes CAPX (PR7), Osmotin (PR5) and β-1,3-glucanase (PR2), phenylalanine ammonia-lyase (PAL) and NPR in black pepper leaves and roots upon *Phytophthora* inoculation (Sarathambal et al 2023b).

- AM inoculation increased the soil enzyme activity, beneficial microbes of black pepper rhizosphere and defence response.



- The roots of black pepper plants produce fatty acids in response to arbuscular mycorrhizal (AM) colonization. These fatty acids help boost the plants' immune response

Arbuscular mycorrhizal (AM) fungi offer several benefits when used in black pepper nurseries:

Already several packages are available for AM fungi application in nurseries as well as under pot culture for horticulture crops.

Improved nutrient uptake: AM fungi form a symbiotic relationship with plant roots, enhancing the plant's ability to absorb essential nutrients such as phosphorus, nitrogen, and micronutrients.

Increased drought tolerance: Mycorrhizal associations can improve a plant's water retention and resistance to drought, which is beneficial in nurseries where maintaining proper moisture levels can be challenging.

Enhanced plant growth: The improved nutrient and water uptake facilitated by AM fungi leads to increased plant growth, promoting healthier and more robust seedlings and young plants.

Disease resistance: AM fungi can help protect plants from certain soil-borne pathogens (eg. *Phytophthora capsici*) by enhancing the plant's immune responses and promoting the growth of other beneficial microorganisms.

Reduced fertilizer requirement: By enhancing nutrient uptake, mycorrhizae reduce the need for synthetic fertilizers, which can be cost-effective and environmentally friendly.

Soil health improvement: Mycorrhizal associations contribute to soil health by improving soil structure and increasing microbial diversity. This, in turn, benefits the overall nursery ecosystem.

Sustainable practices: Incorporating AM fungi in nursery operations aligns with sustainable and environmentally friendly practices, reducing the need for chemical inputs and promoting a natural and holistic approach to plant growth.

Transplant success: Using mycorrhizae during the nursery phase prepare young plants for successful transplanting into gardens or larger agricultural systems, as they are already adapted to a mycorrhizal association.

Crop quality: Improved nutrient uptake results in higher-quality plants with better nutritional content, making them more desirable for sale or transplantation.

Cost savings: While there may be initial costs associated with introducing mycorrhizae in the nursery, the long-term benefits can lead to cost savings through reduced fertilizer and water usage and increased plant quality.

Incorporating AM fungi into nursery practices can be a sustainable and effective way to optimize plant growth and health, ultimately leading to more successful plant establishment under field conditions.

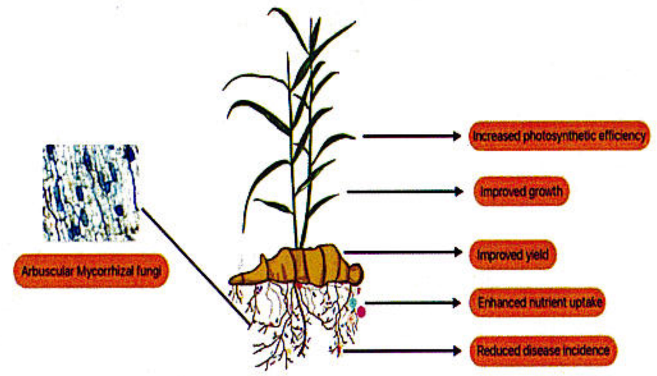
Point to be considered while applying Arbuscular Mycorrhizae under nursery conditions

- ✓ Maintain adequate soil moisture for mycorrhizal establishment. Well-drained and sterile soil mix helps to promote mycorrhizal colonization.
- ✓ Don't use contaminated or low-quality inoculum, as it may introduce pathogens or ineffective mycorrhizal species.
- ✓ Don't apply mycorrhizae in soils with high salinity, as it may negatively impact their effectiveness.
- ✓ Refrain from using fungicides immediately following the application of mycorrhizae, as they can hinder the establishment of mycorrhizal fungi. In such cases, re-inoculation may be necessary to reintroduce arbuscular mycorrhizal (AM) fungi.
- ✓ Don't excessively fertilize the plants, as this may reduce their reliance on mycorrhizal associations.
- ✓ Do ensure that the soil pH is within the optimal range for the establishment of mycorrhizal fungi.

4.2 Effect of AM fungi on ginger

Ginger (*Zingiber officinale* Rosc.) is a medicinal herb belonging to the Zingiberaceae family, predominantly found in tropical regions such as India, China, Indonesia, and Nigeria. The rhizome of ginger is rich in phytochemicals, including zingiberene, α-curcumin, gingerols, and shogaols, which are the primary bioactive compounds in ginger-based dietary supplements. These compounds possess significant biological and pharmacological properties, such as antioxidant,

antilipidemic, antihyperglycemic, anti-inflammatory, antimicrobial, and anticancer activities (Ravindran et al., 1994). Despite its importance, ginger cultivation faces numerous challenges, including insect pests and both pathogenic and non-pathogenic diseases that negatively impact production. Among these, bacterial and fungal infections are particularly detrimental, often leading to substantial yield losses (Bhai et al., 2019). With a growing consumer preference for organic products (Marsh et al., 2021), it is essential to transition ginger production towards organic farming methods that minimize dependence on chemical fertilizers. Conventional farming often relies heavily on mineral fertilizers to enhance yields; however, prolonged use can degrade soil biological fertility (Igiehon and Babalola, 2018).



Various approaches have been developed to lessen dependency on synthetic fertilizers, with biostimulants emerging as a promising solution for sustainable agriculture. Arbuscular mycorrhizae (AM) are widely recognized biostimulants that offer multiple benefits, including functioning as biofertilizers, bioprotectors, and bioregulators. In this context, AM fungi (*Rhizophagus* sp.), with or without compost, were evaluated for their effects on ginger plants under field conditions over a two-year period. The results revealed a positive correlation between the co-application of AM fungi and vermicompost, which significantly improved ginger performance under field conditions. These amendments demonstrated synergistic effects on plant growth and nutrient uptake compared to the application of either AM fungi or vermicompost alone (Sarathambal et al 2024a).

4.2.1 Enhanced growth and disease resistance in ginger through arbuscular mycorrhizal inoculation and vermicompost amendment

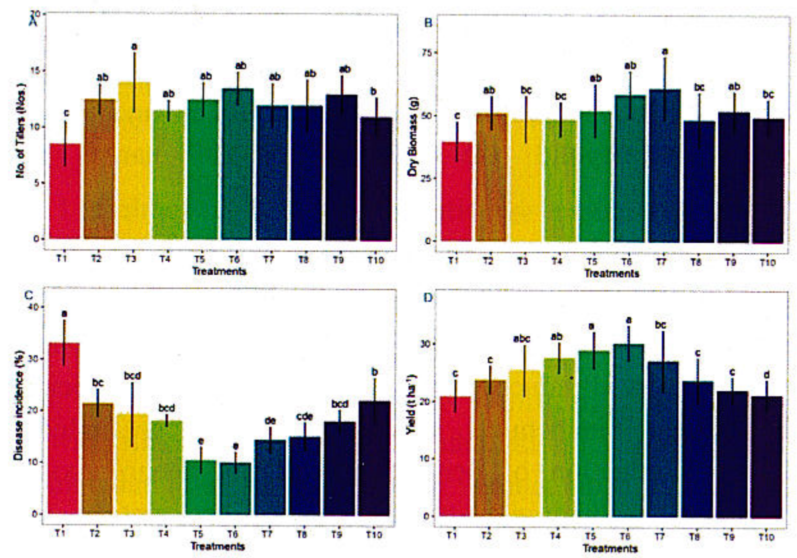
Arbuscular mycorrhizal (AM) inoculation, in conjunction with vermicompost application, significantly enhanced the growth, tillering, and biomass accumulation in ginger plants. The co-inoculation of AM (75 g) with vermicompost (75 g) resulted in a 33% increase in the number of tillers and a 36% improvement in overall biomass compared to the uninoculated control (Paymaneh et al., 2023). This enhanced growth is primarily attributed to the extensive network of mycorrhizal extra-radical hyphae that facilitate nutrient uptake from the surrounding soil and transport them to plant roots in exchange for carbon. The use of vermicompost in combination with AM-inoculated ginger plants significantly improved biomass compared to the

application of AM or vermicompost alone, highlighting the synergistic benefits of this approach.

Several studies have documented the positive effects of AM inoculation on the growth and rhizome production of ginger (Jabborova, 2022 and Uma et al., 2010). The AM-uninoculated control samples, particularly those assessed in the morning, exhibited minimal spore counts, indicating the presence of indigenous AM flora with limited effects on plant growth and nutrient absorption (Sarathambal et al., 2023a). This suggests that external AM inoculation plays a crucial role in enhancing plant development beyond the contributions of native AM communities.

The interaction between AM fungi and vermicompost not only promotes plant growth but also significantly reduces disease incidence, particularly from pathogenic fungi such as *Pythium* spp. The observed reduction in disease occurrence is associated with various biochemical defense mechanisms, including increased production of peroxidase and polyphenol oxidase enzymes, along with elevated total phenol content in AM-inoculated plants. These mechanisms bolster the host plant's defense response, thereby mitigating pathogen attack. Bhai et al. (2012) reported that the co-inoculation of *Glomus* sp. with plant growth-promoting rhizobacteria (PGPR) isolates enhanced root growth in ginger while maintaining low disease incidence. Similarly, Meng et al. (2017) demonstrated that ginger inoculated with *Glomus versiforme* exhibited the lowest disease index and the highest level of disease suppression.

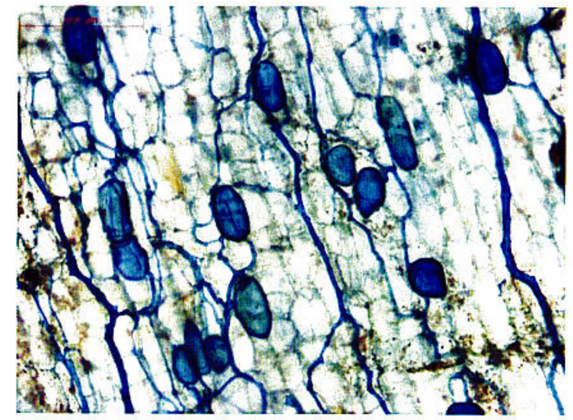
The combined application of AM fungi and vermicompost has been shown to increase ginger yields by up to 30%, with improvements in tillering and biomass linked to enhanced plant nutrition and optimized photosynthetic efficiency.



Effect of AM and vermicompost application on A) number of tillers, B) dry biomass, C) disease incidence and D) yield of ginger

The structural colonization of ginger roots by AM fungi, evident through microscopic examination, provides direct evidence of mycorrhizal symbiosis and its beneficial impact on

plant development. The findings underscore the potential of AM inoculation and vermicompost amendment as an effective strategy for sustainable ginger cultivation, promoting both plant health and productivity.

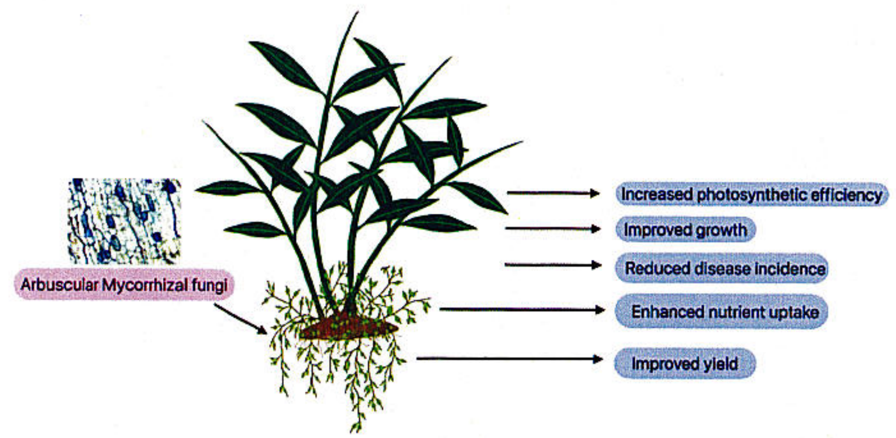


Colonization of arbuscular mycorrhizal fungi in ginger roots

4.3 Effect of AM fungi on cardamom

Cardamom (*Elettaria cardamomum* (L.) Maton), known as the Queen of Spices, is a valuable spice native to the Western Ghats region of India and also grown in countries like Guatemala, Sri Lanka, and Tanzania (Prasath et al., 2009). In India, it is cultivated at elevations of 900–1400 m in Kerala, Karnataka, and Tamil Nadu, with the Indian Cardamom Hills being a major growing area. Besides its culinary use, cardamom is employed in traditional medicine for digestive and kidney disorders. However, cardamom production faces challenges such as disease and poor planting material survival, necessitating improved propagation methods. The use of arbuscular mycorrhizal (AM) fungi as a bioinoculant in potting mixtures is emerging as a sustainable solution to enhance seedling health, increase production, and reduce reliance on chemical fertilizers (Sarathambal et al., 2022a). Furthermore, the use of AM fungus as a bioinoculant is being promoted as a method of increasing production while reducing the demand for chemical fertilisers. Arbuscular mycorrhizal (AM) fungi play a crucial role in horticultural ecosystems by forming a mutually beneficial relationship with a majority of plants (Ziane et al., 2021). Arbuscular mycorrhizal (AM) fungi significantly enhance the rooting of cardamom plants. This symbiotic relationship not only promotes deeper root growth but also increases overall root biomass. As a result, the plants are better equipped to absorb essential nutrients from the soil, leading to improved growth and vitality (Kandiannan et al., 2000). The association between AM fungi and cardamom improves the plant's ability to defend itself against diseases. This is achieved through the upregulation of defense-related enzymes. These enzymes play a crucial role in the plant's immune response, helping to protect against pathogens and reduce the incidence of diseases (Wang et al., 2022). AM inoculation positively impacts the microbial activity within the rhizosphere of cardamom. It increases soil enzyme activity, which is vital for nutrient cycling and soil health. Additionally, the presence of AM fungi fosters a

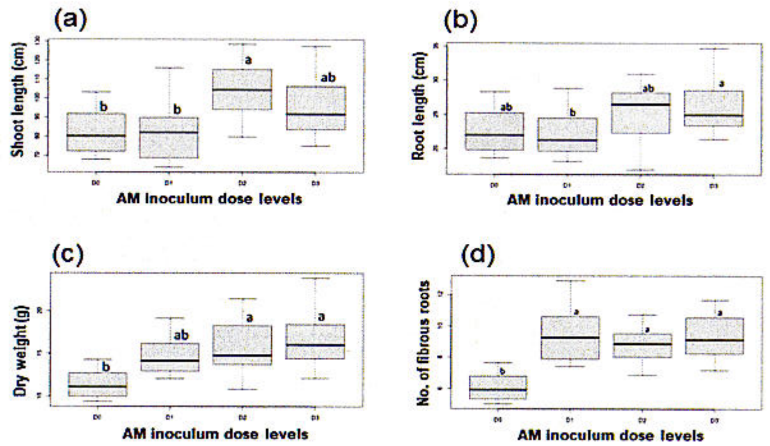
diverse community of beneficial microbes, contributing to a more robust and resilient soil ecosystem (Sarathambal et al., 2024b).



4.3.1 Arbuscular mycorrhizal (AM) fungi application rates on growth and mycorrhizal parameters of cardamom seedlings

Several critical factors, *viz.*, ability of the introduced AM fungi to survive in the new habitat and outcompete native AM fungi, must be examined before using arbuscular mycorrhizal (AM) inoculum in agricultural applications.. The inoculum must contain a sufficient number of infective propagules that can survive and multiply after being introduced to field environments. When these features are taken into account, AM inoculum can be applied in a way that make best use to crop species by improving nutrition uptake, growth, and yield (Douds and Reider, 2003). The main factor influencing the plant's growth was the dosage of

AM inoculum, with three different levels being tested (5 g, 10 g, and 15 g).



D0: Control (no application), D1:5 g, D2:10 g, D3:15 g

Plant growth parameters a). shoot length, b). root length, c). dry weight and d). number of fibrous roots as influenced by different rates of AM application

Out of these dosages, it was found that applying 10 g of AM was the most effective in achieving maximum growth for cardamom seedlings. In contrast to the dosage, application sequence did not significantly affect most of the growth parameters of the seedlings.

4.3.2 AM fungi application rates on nutrient uptake and soil enzymes of cardamom seedlings

Significant uptake of P and Ca were noticed with 10 g of optimal dose of AM inoculum (Sarathambal et al., 2024b). Similar finding was reported in other crop species such as tomato, pepper, rice, maize, cotton and soybean etc. (Cimen et al., 2010). 5 g dosage of AM inoculum is sufficient for the maximum uptake other essential nutrients like Fe, Cu and Zn in cardamom seedlings. Given that Indian agricultural soils are deficient in Zn, the mycorrhizal association can be an important tool to address this issue. The increased uptake of these nutrients could be due to their absorption and mobilization by the fungi, which in turn enhances the uptake of these nutrients by plants.

Our study found that the AM treatments significantly affected with the high alkaline and acid phosphatase activity with a 10 g inoculum dose. Pooled analysis results revealed that the nutrient uptake was positively correlated with the mycorrhizal treatments in cardamom seedlings. Particularly, the dose of inoculum significantly influenced the P, Ca, Fe, Mn, Zn, Cu content of the cardamom seedlings except that of N and Mg (Sarathambal et al., 2024b).

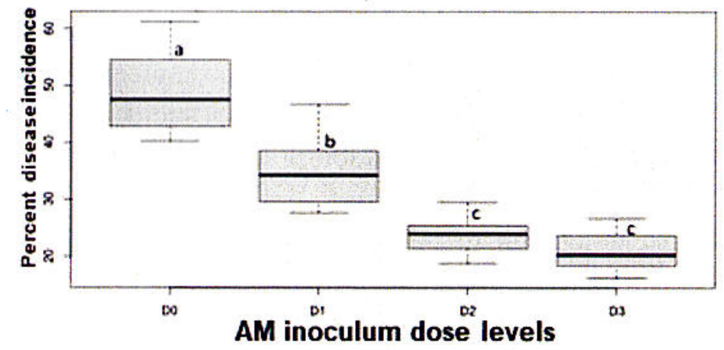
This suggests that the increase in phosphatase activity in the rhizosphere soil could be attributed to a higher phosphatase release from mycorrhizal roots. Additionally, AM fungal inoculation may impact the soil microbial community, which plays a key role in determining the potential for enzyme synthesis

(Kandeler et al., 2002). Hence, to optimise plant nutrition, mycorrhizal inoculation must be carefully tailored to the individual crop and soil needs.

4.3.3 AM fungi application rates on disease incidence of cardamom seedlings

Based on the results, it was noticed that inoculation of AM fungi to polybags reduced the disease incidence when compared to inoculated control and more specifically addition of 10 g to polybags significantly reduced the percent disease incidence (PDI). The disease incidence recorded upon fifteen days post challenge inoculation showed maximum incidence in control (49.28 PDI), followed by treatment D1 (5 g). The treatment D2 (10 g) and D3 (15 g) showed reduced disease incidences and found to be statistically on par. Irrespective of number of times of application, the initial dosage had the maximum influence over the disease control.

The reduced disease incidence in treatment D2 indicates that, initial application of 10 g of AM inoculum is sufficient and further repeated application is not influencing the disease incidence statistically (Sarathambal et al., 2024b).



D0: Control (no application), D1:5 g, D2:10 g, D3:15 g

Per cent disease incidence as influenced by different rates of AM application

5. Conclusion

Arbuscular mycorrhizal (AM) fungi offer an underutilized yet highly promising avenue for transforming spice cultivation. These symbiotic organisms naturally enhance plant growth, nutrient uptake, and resilience to biotic and abiotic stresses. By forming associations with plant roots, AM fungi increase the availability of essential nutrients like phosphorus, nitrogen, and micronutrients, often limited in agricultural soils. Additionally, they improve soil structure by producing glomalin, a glycoprotein that stabilizes soil aggregates, enhances water retention, and promotes microbial diversity. These benefits collectively contribute to healthier and more productive spice crops such as black pepper, ginger, turmeric, and cardamom. The adoption of AM fungi in spice farming aligns with the growing global demand for organic and sustainably produced spices. AM fungi reduce reliance on chemical fertilizers and pesticides, leading to environmentally friendly cultivation practices that preserve soil fertility and biodiversity. However, despite their potential, the widespread utilization of AM fungi in spice cultivation faces several challenges. These include the need for targeted research to develop region- and crop-specific bioinoculants, cost-effective production and delivery systems, and extensive farmer education programs to promote awareness and adoption. As consumer preferences shift toward sustainable and organically grown spices, integrating AM fungi into spice farming represents a strategic approach to enhance productivity while ensuring long-term ecological balance. By investing in research, developing affordable bioinoculant formulations, and fostering awareness among farmers, the spice industry can leverage AM fungi to achieve a sustainable transformation, ensuring high-quality yields that meet market demands while safeguarding the environment.

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