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ARTICLE

Ectomycorrhizal inoculation with *Astraeus odoratus* accelerates establishment, functional growth traits, and survival of *Dipterocarpus turbinatus* in degraded tropical forests

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ABSTRACT

Successful restoration of degraded tropical forests requires high-quality seedlings that can establish fast and are environmentally resilient. *Dipterocarpus alatus* (Gurjan) is a timber species of construction and furniture and most of the seedlings do not survive after transplanting, making the reforestation less effective. This study examined the effect of *Astraeus odoratus,* an edible ectomycorrhizal fungus, on seedling growth and nutrient uptake in the field. Four-month-old nursery-grown seedlings were inoculated with a liquid suspension of basidiospores (50 mL seedling^{-1}), and non-inoculated seedlings were used as controls. Growth parameters, accumulation of biomass, root colonization, and soil nutrient status were measured after four months, followed by the monitoring of the field transplant. Inoculated seedlings had much greater height (37.8 cm) and root collar diameter (5.89 mm) than controls (26.4 cm and 3.75 mm, respectively). Total dry biomass was also higher in treated seedlings (3.01 g) than in non-inoculated plants (2.34 g). According to the results, microscopic observations revealed ectomycorrhizal colonization with lateral roots and fungal sheaths. Enhanced phosphorus mobilization was through fungal enzymes. Inoculated seedlings had superior growth, a sign of successful establishment. Results confirm that *A. odoratus* bioaugmentation improved the growth of *D. alatus*. Integrating edible ectomycorrhizal fungi in nurseries offers a sustainable approach for restoring tropical forestry in the context of advantages for communities.

1. Introduction

The Gurjan tree (*Dipterocarpus alatus*) is one of the dipterocarp species that are highly distributed throughout tropical Southeast Asia and is known for its high economic and ecological value (Ali & Wallin, 1964; Pirard & Charoenpanwutikul, 2023). Its durable timber is used widely in the furniture industry, for structures, plywood, and export industries, making a major

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contribution to forestry-based economies in the region (Aréval et al., 2025). Ecologically, *D. alatus* has a crucial role in controlling the structure of forest canopies, in regulating microclimate, in stabilizing soils, and in increasing the capacity of carbon sequestration of lowland tropical ecosystems. However, fast population growth, agricultural encroachment, urban expansion, and unsustainable logging practices have caused forest degradation to increase rapidly, leading to habitat fragmentation and weak regeneration of natural habitats (Bolaniran et al., 2021; Vishal et al., 2024). The decrease of mature seed trees and soil fertility are other degradations that have been further compromising the resilience of these ecosystems (Pampolina et al., 2025). Consequently, reforestation and forest landscape restoration have become important strategies for the restoration of ecosystem functionality and the maintenance of biodiversity.

Despite the ecological significance of Gurjan, efforts to restore Gurjan have been limited because the seedling performance after transplantation is often poor. Gurjan seedlings are generally known to be slow in early stages of their growth, have slow root system development, and also have low survival rates in the field, especially in degraded lands having low available nutrients, changing pH and seasonality of availability of water. Such limitations decrease the success of plantations and increase the cost of restoration (Sridhar, 2019; Vishal et al., 2020). Therefore, interventions that can improve the vigor and adaptive capacity of seedlings in early stages would be necessary for improving long-term reforestation results.

Ectomycorrhizal symbiosis is a basic ecological process that is responsible for the productivity of the dipterocarp forest (Silva-Flores et al., 2022). Members of the genus Astraeus, in particular Astraeus odoratus, form mutualistic relations with the roots of dipterocarps, forming a sheath of fungus and Hartig net in which a two-way exchange of nutrients takes place. Through the very extensive extraradical hyphal networks, these fungi greatly increase the effective absorptive surface area of roots. This promotes the absorption of phosphorus, nitrogen, and micronutrients as well as soil moisture acquisition in drought conditions (Punsung et al., 2024). The secretion of homologs of extracellular enzymes (phosphatases) allows for the mobilization of the organically bound phosphorus, which in many tropical soils is a limiting nutrient. Along with nutrient cycle improvement, ectomycorrhizal colonization leads to the branching of roots, enhanced structural stability, and protection from soil-borne pathogens and abiotic stress as well.

Astraeus odoratus, or smooth earth ball mushroom, as it is better known, is rather interesting since it yields edible fruiting bodies that are also harvested seasonally and then traded in local markets. This dual Eco-Economic Function makes this fungus a potential biological growth promoter as well as a livelihood supporting resource function (Munir et al., 2021, 2023; Li et al., 2024). Integrating *A. odoratus* in the production of Gurjan, internationally traded (nursery), is therefore a nature-based remedy in line with the principles of sustainable forest management. By helping to improve seedling growth performance, drought resilience, and nutrient-use efficiency, the potential of ectomycorrhizal bioaugmentation can improve the success of restoration in degraded landscapes. Simultaneously, higher production levels of mushrooms can open up additional income opportunities, i.e., motivate local populations to engage in forest conservation and restoration programs.

Given the urgent need to address the challenge of restoring degraded tropical forests under the support of sustainable rural development, this study examines the impact of *A. odoratus* inoculation on growth and nutrient dynamics and establishment performance of *D. alatus* seedlings. The aim of the research is to obtain scientific evidence for the integration of ectomycorrhizal biotechnology in tropical reforestation programs as a tool for strengthening ecosystem recovery processes and subsequent promotion of long-term environmental sustainability.

2. Materials and Methods

2.1 Experimental Design and Materials

A controlled nursery experiment to test the impact of smooth earth ball mushroom inoculation on Dipterocarpus turbinatus (Gurjan) seedlings in terms of early-stage growth and root colonization under control conditions. In transgenerational studies, before treatment, seedlings were reared under each of the uniform substrate compositions, watering regimes, and environmental exposures to minimize variability. Seedlings were established for four months after sowing, and then were put in inoculated or non-inoculated (control) treatments to ensure adequate root development available for colonization by the fungus. Both groups of treatment were also maintained under identical environmental conditions for the entire study.

Experimental materials consisted of Gurjan seeds, fresh smooth earth balls mushroom fruiting body (for basidiospores), rice husk, potting soil, and composted cow dung fertilizer, which were chosen to provide a balanced growth situation capable of dipterocarp seedling production. Seedlings were potted in 4 by 6-cm black polyethylene nursery bags. Laboratory equipment included a stereo microscope (assessing colonization on the roots), a hot air oven (drying the biomass), a digital analytical balance, a Vernier caliper (stem measurement), a ruler (height measurement), a blender (homogenization of spores), and graduated cylinders (volume measurement).

Figure 1. Preparation of nursery substrate showing (a) individual substrate components (rice husk, compost, and potting soil), (b) mixing process in a 1:1:2 ratio, and (c) filling of 4 x 6 cm polyethylene seedling bags.

2.2 Preparation of Growth Substrate

The growth substrate used in the nursery was a mixture of rice husk, composted cow dung fertilizer, and potting soil in the volumetric ratio of 1:1:2 (rice husk: composted cow dung: potting soil, v/v). In real-life terms, this mixture included: 2 parts potting soil; 1 part composted fertilizer; 1 part rice husk. This ratio has been chosen in order to ensure a balance of physical and chemical properties of the substrate. Potting soil contributed the major mineral matrix and water holding capacity, composted cow dung gave essential nutrients and organic matter, while rice husk improved porosity and aeration, contributing to the healthy respiration of the roots. All elements were well homogenized to avoid uneven distribution of nutrients and lack of structure in the mixture. Localized nutrient concentration gradients were minimised and there was better reproducibility from one seedling bag to another if properly mixed. The prepared substrate was filled in 4 x 6 cm polyethylene seedling bags and compacted gently. Compaction was done carefully to avoid leaving too much porosity, which could result in little moisture retention.

2.3 Seed Preparation and Planting

Gurjan seeds were soaked with distilled water at 24 h (overnight) before sowing. This pre-soaking treatment was applied in order to improve a uniform germination by softening the seed coat and increasing imbibition of water. After soaking, one seed was planted in each seedling bag at a suitable depth in the prepared substrate so as to get good soil contact and good positioning. Planting depth was kept the same in all the experimental units. Seedlings were kept on standard nursery conditions and watered every day so as to maintain adequate moisture levels. No fungal inoculation was used during the first four months of establishment, so that the seedlings had time to grow adequate root systems before the treatments were used.

Soak Gurjan seeds　　Planting the soaked

Figure 2. Seed preparation and planting procedure depicting (a) soaking of Gurjan seeds for 24 h and (b) seed planting, one seed per nursery bag.

2.4 Preparation of Smooth Earth Ball Mushroom Spore Suspension

Fresh, smooth earth ball mushroom fruiting bodies were collected and thoroughly washed to remove surface debris and contaminants. Cleaning ensured that external impurities would not interfere with spore preparation. Using a sterile knife, the outer peridium was carefully removed to expose the internal basidiospore mass. The basidiospore mass was then transferred to a clean container and mixed with sterile distilled water at a 1:1 (v/v) ratio. The mixture was homogenized using a blender to obtain a uniform liquid spore suspension. Homogenization facilitated even spore dispersion and improved the consistency of inoculum application. Immediately before application, the suspension was further diluted with sterile distilled water at a 1:1 (v/v) ratio to improve dispersion and ensure optimal inoculum distribution during application.

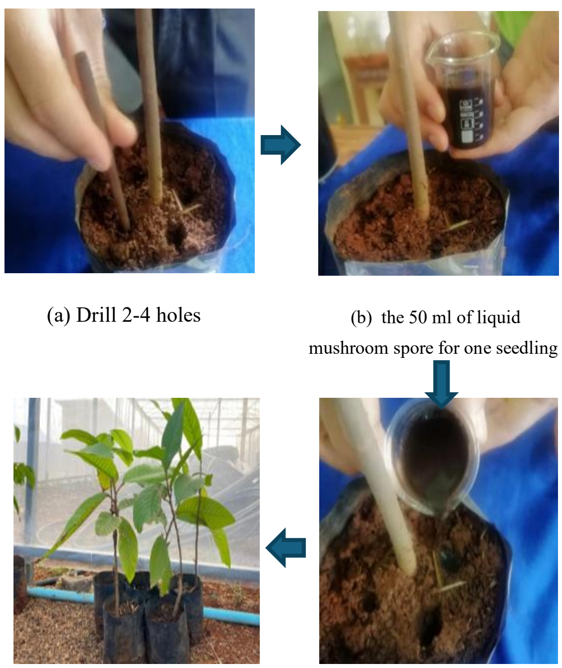
Figure 3. Preparation of smooth earth ball mushroom spore suspension showing (a) cleaned fruiting bodies, (b) removal of peridium to expose basidiospores, and (c, d) blending and preparation of homogeneous liquid spore suspension.

2.5 Fungal Inoculation Procedure

Fungal inoculation was performed at the four-month-old age. At this stage, however, root systems were sufficiently developed to allow ectomycorrhizal colonization. Two to four small holes were carefully made in the substrate in the area close to the root collar of each seedling. The holes were strategically placed to allow for the highest survival of root-spore contact, for the most efficient colonization. A total of about 50 mL of the liquid mushroom spore suspension was applied to each of the seedling bags (Figure 4). The inoculum was poured directly into the prepared holes in order to ease infiltration into the rhizosphere. After inoculation, the surface of the substrates was massaged slightly to restore its structure to ensure the close contact of spores and soil particles. Watering was suspended for 48 h (two days) after inoculation in order to enhance the establishment of the fungus and decrease the possibility that the inoculum could be washed away.

2.6 Growth Measurements and Laboratory Analyses

After 4 months of colonization (eight months after sowing), seedlings were taken for comprehensive growth and colonization assessment. Seedling height was measured from the root collar to the apical meristem with the help of a ruler. Stem diameter was measured at the root collar, with the use of a Vernier calliper, in order to be precise. Root systems were washed carefully to remove attached substrate and analyzed under a stereo microscope in order to evaluate colonization by fungi. The percentage of colonization was established by visual examination of the presence of ectomycorrhizal structures. Shoots and roots were separated and oven-dried at 70C for 72h to get constant DW. Dry biomass was measured by using a digital analytical balance. Substrate (soil) samples were obtained and analyzed for total N, available P, and exchangeable K and standard laboratory methods



(a) Drill 2-4 holes

(b) the 50 ml of liquid mushroom spore for one seedling

(c) Leave the seedlings in the seedling sursery

(d) Fill the hole with liquid mushroom spore

Figure 4. Applying the smooth ball mushroom spores to the Gurjan seedling roots

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2.6 Statistical Analysis

Data were first tested for normality using the Shapiro-Wilk and the homogeneity of variances test using Levene's test. These diagnostic tests ensured the compliance of parametric statistical assumptions: Independent-samples t-tests were used to compare the means for the treatments at a $p < 0.05$ significant level. Cohen's d was calculated to understand the effect size to give an estimate of treatment magnitude. Ninety-five percent confidence intervals of major growth parameters were calculated for greater statistical interpretability. Pearson correlation analysis was performed to assess the relationships of the colonisation percentage with the growth traits and the accumulation of biomass and soil nutrient content. All statistical analyses were conducted with R and the statistical software SPSS.

3. Results and discussion

3.1 Seedling Growth Enhancement Following Ectomycorrhizal Inoculation

Eceria inoculation on *A. odoratus* seedlings significantly enhanced the vegetative growth of seedlings of Dipterocarpus alatus under nursery conditions (Holste et al., 2016; Lodge, 2024). After four months of colonisation by fungi (in this case, eight months of total seedling age), inoculated seedlings were 37.8 cm high as compared to the non-inoculated controls of 26.4 cm. This is 43.2% growth in height and was statistically significant ($p < 0.001$), and of a large effect size. The 95% confidence intervals of inoculated seedlings did not overlap significantly with the control group, emphasising the robustness of the effect of the treatment. The large growth and development exhibited in terms of height signify improvements in the rate of colonisation by ectomycorrhizal infection at a crucial phase in the establishment of height above ground (Tisarum et al., 2022). Height increment in young dipterocarp seedlings is of particular importance in seeking to increase light interception, decrease competition from understory vegetation, and optimally prepare transplants (Brearley, 2026). As well, early height advantage may also minimise susceptibility to herbivory and surface heat stress in exposed places for restoration.

The observed improvement in height is consistent with well-established ecological theory that ectomycorrhizal fungi lead to improved efficiency in gaining nutrients in soils, and tropical soils are phosphorus-limited (Ganesh et al., 2021). In the case of substrates, very weathered phosphorus is strongly attached to iron and aluminum oxides and is unlikely to be available to plant roots alone. The extraradical hyphal network of ectomycorrhizal fungi is extended beyond the radius of rhizosphere depletion, and organically bound and mineral-associated Phosphorus is used. Through the secretion of extracellular phosphatases, the fungus can mineralise these compounds and make P available to the host plant in exchange for the photosynthetically derived C. This improved nutrient exchange is likely to be the cause of more rapid elongation of shoots of inoculated seedlings (Gonkhom et al., 2025).

3.2 Stem Diameter Development and Structural Investment

Root collar diameter increased from 3.75 mm in the control treatment to 5.89 mm in inoculated seedlings, representing a 57% improvement ($p < 0.001$; Cohen's $d \approx 1.7$). Root collar diameter was enlarged from 3.75 mm in the control treatment to 5.89 mm in inoculated seedlings or 57% improvement ($p < 0.001$; Cohen's $d \approx 1.7$). Stem thickening is one of the important indicators of mechanical stability and probability of long-term survival in a restoration planting (Figure 5). Diameter growth indicates the accumulation of carbon units from its leaves and the strengthening of the tree's reinforcement by increasing of lignin and vascular tissues. Enhanced stem diameter indicates that not only was mycorrhizal colonization able to enhance nutrient acquisition, it also would have enhanced effective carbon allocation into supportive tissues. In restoration situations, the seedlings will be less susceptible to lodging, drought-induced hydraulic failure, and transplant shock when more stem tissue thickness is present (Kiruba & Saeid, 2022; Li et al., 2024). Therefore, the significant enhancement in root collar diameter that occurred here is suggestive of a significant enhancement in structural resilience. Comparative studies on dipterocarps and other ectomycorrhizal trees have seen lots of enhanced diameter growth in response to inoculation with fungus, and more so in nutrient-poor soils of the tropics. These results strengthen the relative importance of below-ground mutualisms in the support of aboveground structural development.

The inoculation success and colonisation rates of ectomycorrhizal colonisation were confirmed through microscopic analysis on inoculated seedlings using fine root tips greater than 70%. Whereas, in contrast, only negligible colonization of control seedlings was observed. The difference between treatments was extremely significant ($p < 0.001$) and associated with a very large effect size. Colonized roots showed some typical morphological adaptations in colonization, such as high lateral branching density, formation of fungal mantle, and observable hyphal sheathing. These structural changes increase the absorptive surface area and increase the soil exploration capacity (Phadanno et al., 2020; Qiang et al., 2023). Development of a Hartig net results in an efficient exchange of nutrients between fungal hyphae and root cortical cells, and phosphorus and nitrogen can be transferred to the host plant rapidly. The enhanced branching of roots in inoculated seedlings was probably responsible for the enhanced water uptake capacity. In degraded tropical soils, in which the availability of moisture changes seasonally, the increase of root surface area may have a considerable positive effect on drought tolerance. Furthermore, the fungal mantle can prevent the soil-borne pathogens from infecting the plant root, that is, it's a protection mechanism that will contribute to the seedling's survival.

3.3 Biomass and Carbon Dynamics, Soil Nutrients and Phosphorus Utilization

Total dry biomass was increased from 2.34 g in control seedlings to 3.01 g in inoculated seedlings, which represented a 28.6% increase ($p < 0.01$). Root biomass showed especially high response and increased by about 74%, while shoot biomass increased by around 16%. The disproportionately larger gain in root biomass looks like it was metabolizing more carbon for the symbiotic association belowground (Figure 6). According to the carbon-nutrient exchange theory, plants invest carbon in mycorrhizal partners if their nutrient return is greater than their metabolic cost. The large increase in root biomass is suggestive that the symbiosis has conferred enough nutrient benefit to 'pay' for increased carbon investment (Rachmat et al., 2021). Increased root mass is involved with better anchorage, soil stabilisation and nutrient uptake. In restoration plantings, strong root systems are vital to surviving drought stress and soil instability. Therefore, the improved root development of inoculated seedlings due to inoculation probably results in long-term advantages of survival beyond the nursery stage (Figure 7).

Soil examination showed lower residual concentrations of phosphorus in inoculated treatments than in the control, showing higher efficiency of uptake. Fungal phosphatase enzymes are suggested by the reduction in available phosphorus, leading to active mobilization and absorption. In tropical soils where phosphorus availability is usually the limitation, improved phosphorus acquisition represents a substantial physiological advantage. The nitrogen level was also found to be moderately reduced in inoculated treatments, suggesting increased uptake (use). Potassium concentrations were relatively stable, so it appears that the main nutrient benefit of the symbiosis was associated with phosphorus cycling (Rachmat et al., 2021). These results are consistent with other, broader-scale ecological studies showing that ectomycorrhizal fungi are quite capable of mobilizing P in nutrient-poor tropical substrates. The improvement in nutrient-use efficiency increases photosynthetic performance and biomass production, which may strengthen the growth benefits recorded in this study.

3.4 Field Performance, Ecological Mechanisms, Forest Restoration, Socioeconomic Integration

Following transplant in the field at 4x4m spacings, inoculated seedlings had better canopy development and leaf density than controls. Enhanced in canopy structure signifying less photosynthetic capacity and removal, and faster establishment. Early performance in the field is a good indicator of long-term survival of restoration programs (Aréval et al., 2025). The enhanced vigor ensued by the inoculation of seedlings indicates that early mycorrhizal colonization provides permanent beneficial effects, such as soil drought tolerance and soil pathogens (Tisarum, et al., 2022). These results support the frameworks in restoration ecology on the importance of belowground symbioses in supporting ecosystem recovery. Without the mycorrhizal relationships, reforestation efforts may fail to duplicate natural forest processes (Figure 7).

The improved increase in growth results from the following mechanism: fungal hyphal networks aid in increasing the soil exploration, secretion of the phosphatase contributes to the mobilizing of organic phosphorus, increased root branching supports absorption by roots, and better conductance promotes drought resistance. The mutualistic exchange of carbon and nutrients is optimal in nutrient limitation. These mechanisms optimize the performance of seedlings in addition to fertilization. Astraeus odoratus bioaugmentation highly enhances seedling growth parameters. Integrating ectomycorrhizal inoculation into nursery systems provides one way of achieving a state-scale intervention for reforestation in degraded tropical ecosystems. Unlike chemical fertilisation, mycorrhizal bioaugmentation makes use of natural processes by increasing biodiversity (Bolaniran et al., 2021; Vishal et al., 2024). Additionally, *Astraeus odoratus* produces fruit bodies that could be used for edible purposes for local trade and could generate community income. The strategy involved to achieve this is forest stewardship and sustainable development.

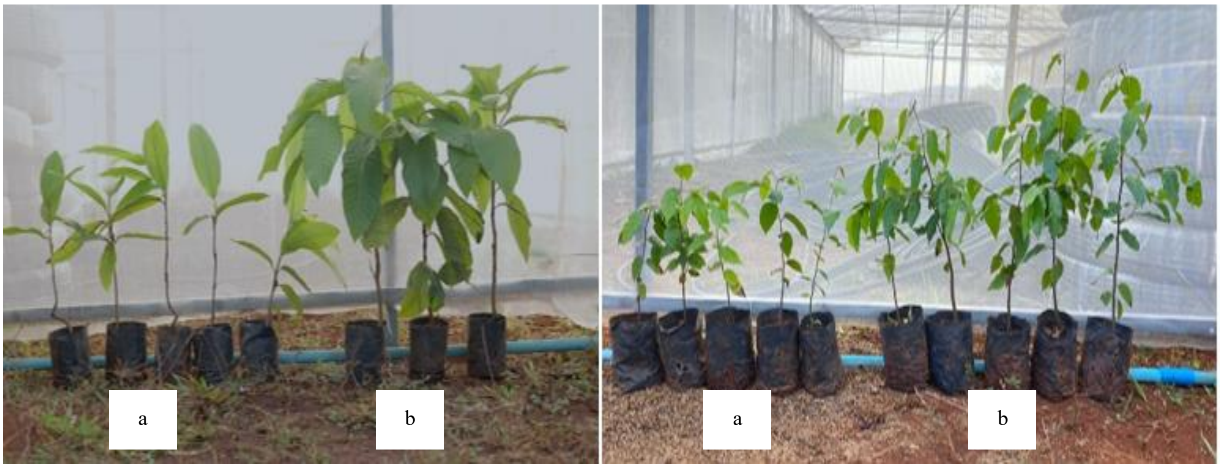

Figure 5. The height of an 8-month-old seedling: a) Planted without smooth ball mushroom culture, b)Planted with smooth ball mushroom culture

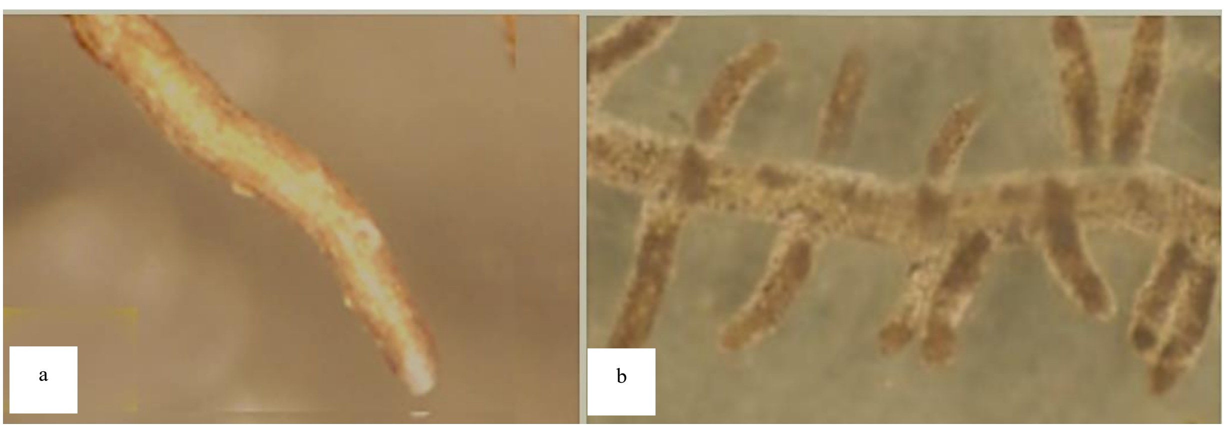

Figure 6. Smooth ball mushroom culture in the seedling roots: a) the seedling roots without smooth ball mushroom culture, b) the seedling roots with smooth ball mushroom culture

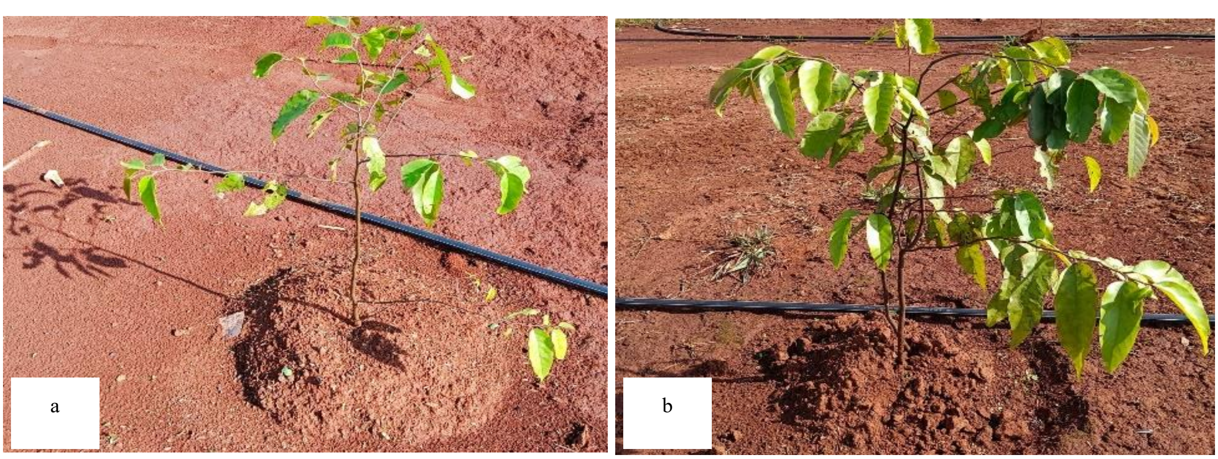

Figure 7. The growth of the seedlings after planting in the area for 4 months: a) Without mushroom culture, b)With mushroom culture

3. Comparative Dipterocarp Restoration Literature Synthesis

Comparative evidence from dipterocarp restoration is in agreement with the central result of this study that the degree of early establishment success is strongly correlated with presence and functioning of ectomycorrhizal (ECM) symbionts. Studies show EMC inoculation benefits are greatest with nutrient-poor soils with limited natural inoculum (Table 1). Degraded tropical substrates are low in phosphorus, have low organic matter and microbial diversity, which inhibits dipterocarp growth. ECM fungi improve nutrient uptake by increasing soil exploration and accessing nutrient pools by enzymatic activities within dipterocarp genera. The enhanced biomass under inoculation demonstrates the significance of ECM symbioses as a survival mechanism in stressful environments in these seedlings (Bolaniran et al., 2021; Vishal et al., 2024). . ECM fungi improve nutrient acquisition both through soil exploration and through enzymatic activities in dipterocarp genera and from nursery fields to field transition. The larger diameter and biomass size in inoculated seedlings proved that ECM symbiosis plays an important role in survival under stressful environments.

Table 1. Summary of Major Findings and Restoration Significance

Parameter	Observed Outcome	Ecological Interpretation	Restoration Significance
Height	Significant increase	Improved nutrient acquisition and shoot vigor	Faster canopy development
Root Collar Diameter	Significant increase	Structural robustness and hydraulic stability	Higher survival probability
Total Dry Biomass	Significant increase	Enhanced carbon allocation efficiency	Stronger early establishment
Root Colonization	>70% fine root tips	High host–fungus compatibility	Effective bioaugmentation
Soil Phosphorus	Lower residual P	Enhanced fungal-mediated uptake	Improved nutrient cycling
Field Vigor	Improved canopy formation	Increased adaptive capacity	Greater restoration success likelihood

Comparative restoration trials reveal inoculation effects being greater for trait(s) that are belowground than those that are aboveground, especially early development. Dipterocarp seedlings have increased lateral root formation, fine root branching and root biomass after ECM establishment, which directly improves drought tolerance and uptake of nutrients (Punsung et al., 2024). The morphological changes in root cells, such as fungal mantle formation and lateral branching, are in accordance with this pattern. Many restoration failures result from early hydraulic system limitations of plants, and seedlings may die because of the inability to access water, rather than from photosynthesis problems (Sridhar, 2019; Vishal et al., 2020).. ECM induced root expansion therefore reduces transplant shock and increases establishment success.

Literature reveals that the effects of ECM on dipterocarp restoration are context-dependent, depending upon the compatibility of the fungus. ECMs are beneficial for phosphorus uptake, drought resistance and pathogen resistance and need to be host compatible. Inoculation success is dependent on the use of ecosystem-specific fungi of the target dipterocarp species. A. odoratus has the potential to restore Gurjan rationale using its association of natural dipterocarp ties and nutrient uptake network. High colonisation is an indicator of good compatibility since inoculation may fail due to fungal-host mismatch. The four-month inoculation and eight-month evaluation is in line with successful programs. Studies focus on preventing conditions that prevent fungi establishment. Good colonization and growth benefits suggest good nursery conditions for ECMs as aid to restoration guidelines.

Beyond the aspect of growth, though, functional outcomes of the dipterocarp restoration require study of nutrient cycling and soil aggregation. ECM fungi play a role in terms of decomposition, nutrient redistribution and soil microbial variation. Active ECM sources of nutrient cycling stand restored. A decreased amount of residual nutrients in inoculated treatments is an indication of increased uptake. While the existing information covers N, P and K percentages, enzyme assays in the future can better link the ECM and ecosystem function (Silva-Flores et al., 2022). Southeast Asian restoration often falls short without short-term gain, with edible ECM fungi bringing advantage, waiting for the forests to reach maturity. *A. odoratus* respires valuable mushrooms (restoration through ecology & income generation). Studies recommend switching inoculation from nursery to field trials with long-term monitoring.

Growth advantages that lead to increased survival, as well as canopy closure, but the results depend on site conditions. Field observations show improved canopy shape; monitoring survival and colonization persistence are important. Studies show that colonisation can be reduced by poor soil conditions. There is evidence of the efficacy of ectomycorrhizal bioaugmentation in improving the performance of dipterocarp seedling production in degraded systems, especially when both compatible fungi and pre-transplantation inoculation are used. Results with *A. odoratus* are an example for restoration enhancement with livelihood benefits.

4. Conclusions

This study has shown that ectomycorrhizal bioaugmentation with Astraeus odoratus has a significant effect on the growth performances, biomass accumulation, nutrient use efficiency and early field establishment of Dipterocarpus alatus seedlings in tropical nursery and restoration settings. Inoculated seedlings showed significant improvement in height, root collar diameter and total dry biomass over non-inoculated controls with large effect sizes, suggesting that there were biologically meaningful improvements as opposed to minor gains. Root colonization was well over 70% of fine root tips, indicating that there is good host-fungus compatibility and good symbiotic establishment. The improvements in growth response were associated with changes in root system fate, which comprises growth of lateral roots and development of fungal mantles, which increases absorptive surface area and enhance phosphorus mobilization. Lower residual soil phosphorus in inoculated treatments showed improved nutrient uptake via fungal activity. Better root development resulted in better vigor and canopy development after transplantation, thus exhibiting more adaptive capacity. These results point to belowground mutualisms during recovery of tropical forests. Dipterocarp restoration is highly contingent upon the re-establishment of mycorrhizal network regardless of the planting density or fertilization. Integrating ectomycorrhizal inoculation in nursery systems is one nature-based approach that can be on a large scale. Astraeus odoratus produces an edible fruiting body, which results in livelihood benefits to the communities and forest recovery is linked to local incentives. The results favour the option of ectomycorrhizal bioaugmentation in dipterocarp reforestation. To determine colonization persistence and associated carbon sequestration and forest management behaviors, future field trials will enable colonization to and from landscape positions to be determined.

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