https://doi.org/10.51483/IJAGST.5.2.2025.12-22 ISSN: 2710-3366

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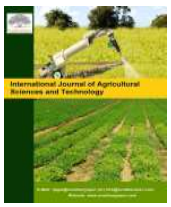

Research Paper Open Access

Synergistic Effects of a Mycorrhizal Consortium on Growth, Morphophysiological Traits, and Nodulation Efficiency in *Dalbergia latifolia*: Implications for Sustainable Forestry and Industry Applications

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Article Info

Volume 5, Issue 2, November 2025
Received : 25 March 2025
Accepted : 09 September 2025
Published : 25 November 2025
doi: 10.51483/IJAGST.5.2.2025.12-22

Abstract

Dalbergia latifolia (Indian Rosewood) faces growth limitations due to nutrient deficiencies. This study explores the effects of Arbuscular Mycorrhizal (AM) fungi on its growth over 12 months. AM fungi, particularly *Glomus mosseae*, significantly enhanced plant growth, with *G. mosseae* producing the tallest plants (112 cm) after 12 months. *G. leptotichum* resulted in the longest leaves (6.73 cm), and *G. fasciculatum* produced the widest leaves (5.1 mm). Shoot elongation was highest at 3 months in *G. fasciculatum* (16.33 cm) and at 12 months in *G. mosseae* (76 cm). Root growth was most pronounced in *G. fasciculatum* and *G. leptotichum*, improving nutrient and water uptake. Chlorophyll content peaked at 9 months in *G. mosseae* (60.33 SPAD) and remained high at 12 months (57 SPAD). AM fungal colonization reached 35%, with *G. fasciculatum* showing the highest rate. These findings highlight AM fungi's potential to enhance the growth and productivity of *D. latifolia* for sustainable forestry.

Keywords: *Arbuscular mycorrhizal fungi, Dalbergia latifolia, Growth enhancement, Glomus mosseae, Root nodulation, Sustainable forestry*

1. Introduction

Dalbergia latifolia Roxb., widely recognized as Indian rosewood, is a highly valued timber species in the Fabaceae family. Although it holds significant commercial value, this species is found in limited distribution across tropical and subtropical regions (Arunkumar *et al.,* 2021). In addition to its timber value, *D. latifolia* is known for its medicinal properties, especially its tannin content, which has been used in treating leprosy and parasitic infections (Kirtikar and Basu, 2005). Listed as 'Vulnerable' by the International Union for Conservation of Nature (IUCN) and included in Appendix II of CITES, *D. latifolia* is experiencing population decline due to overharvesting, illegal trade, habitat destruction, and environmental degradation (Arunkumar *et al.,* 2021; Sasidharan *et al.,* 2020). Therefore, it is essential to implement conservation strategies and artificial regeneration programs within its native habitats. Additionally, large-scale cultivation and afforestation initiatives are vital to ensuring the long-term sustainability of this species (Sujatha *et al.,* 2008).

Arbuscular mycorrhizal (AM) fungi, beneficial soil microbes that establish symbiotic relationships with plant roots, have been shown to enhance nutrient uptake, particularly phosphorus (P), zinc (Zn), and copper (Cu), while also improving plant resilience to both biotic and abiotic stresses (Wahab *et al.,* 2023). Beyond their role in nutrient acquisition,

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AM fungi contribute to soil structure, nutrient cycling, and overall ecosystem sustainability (Martin and Heijden, 2024). By optimizing water and phosphorus absorption, these fungi foster plant growth, positioning them as valuable biofertilizers for enhancing plant health and productivity (Brundrett, 2009).

This study examines the effects of AM fungi on the growth performance of *D. latifolia* and evaluates their potential to support sustainable cultivation practices for this valuable timber species. Previous research has demonstrated the positive influence of AM fungi on plant growth, with Kapoor *et al.* (2008) emphasizing their role in micropropagation, and Karthikeyan *et al.* (2009) focusing on medicinal plants. Moreover, the beneficial effects of AM fungi on nutrient uptake and root development have been observed in various species (Mridha and Dhar, 2007). This study builds on these findings by applying them to *D. latifolia*, exploring the broader potential of AM fungi in enhancing the cultivation of this high-value timber species.

Additionally, *D. latifolia* has gained attention for its potential role in agroforestry systems. The tree database compiled by Orwa *et al.* (2009) provides guidance on selecting suitable species for agroforestry, highlighting *D. latifolia* as a key candidate for such systems. This underscores the significance of AM fungi in promoting the sustainable cultivation and ecological benefits of this species, positioning it as an ideal choice for agroforestry and conservation efforts.

2. Materials and Methods

2.1. Study Site and Experimental Conditions

The nursery trials were conducted at the forest nursery of the Institute of Wood Science and Technology (IWST), Bengaluru, Karnataka, India (latitude 13.012411° N; longitude 77.570306° E; altitude 866 m). The study site is situated in the Eastern Dry Zone and receives an average annual rainfall of approximately 900 mm. The area experiences moderate climatic conditions, with temperatures ranging from a minimum of 13°C during winter to a maximum of 35°C during the summer.

2.2. Planting Material Collection and Seed Treatment

Mature seeds of *Dalbergia latifolia* were collected during the seed-bearing season in January from a candidate plus tree in the Bhadra Tiger Reserve, Chikkamagaluru Forest Division, Karnataka, India. The seeds were assessed for health and viability according to the International Seed Testing Association (ISTA, 1996) guidelines. Before sowing, the seeds were surface-sterilized with a 2% Bavistin solution, thoroughly rinsed, and soaked in cold water for 24 hours to enhance germination.

2.3. Nursery Experiment and Experimental Design

Dalbergia latifolia seeds were germinated in a sand bed containing heat-sterilized sand (121°C for 1 hour). At 30 days post-germination, uniform, healthy seedlings, free from diseases and pests, were selected and transplanted into 15 × 12-inch plastic pots filled with an autoclaved mixture of red soil and sand (1:1, v/v). Arbuscular mycorrhizal (AM) fungal inoculation was performed by applying 10 g of inoculum (containing spores and hyphal fragments) 2 inches away from the stem and 5 inches below the root zone during transplantation. Each treatment was replicated three times, resulting in a total of 30 plants for the study. The plants were maintained under nursery conditions with regular irrigation and proper care throughout the experimental period. Control plants were kept without AM fungal inoculation.

The experiment followed a randomized block design (RBD) with four treatments and three replications:

T1 (Control): *D. latifolia* without AM fungal inoculation.

T2: *D. latifolia* inoculated with *Glomus mosseae*.

T3: *D. latifolia* inoculated with *Glomus fasciculatum*.

T4: *D. latifolia* inoculated with *Glomus leptotichum*.

Growth parameters were recorded at 3-, 6-, 9-, and 12-month intervals post-inoculation.

2.4. Arbuscular Mycorrhizal (AM) Fungal Inoculum

The AM fungal species used in this study were *Glomus mosseae*, *Glomus fasciculatum*, and *Glomus leptotichum*. The inoculum was obtained from Dr. D. J. Bagyaraj, NASI Honorary Scientist & Chairman of the Centre for Natural Biological Resources and Community Development (CNBRCD), Bengaluru, Karnataka, India. The inoculum consisted of a sand-soil mixture containing AM fungal spores, mycelia, and colonized root fragments.

2.5. Estimation of AM Fungal Root Colonization

AM fungal colonization was assessed at 3-, 6-, and 12-month intervals following the method of Phillips and Hayman (1970). Root samples were randomly collected, cut into 1 cm segments, and cleared by autoclaving with 10% KOH at 108 kPa for 15 minutes. After neutralizing the alkalinity with 10% HCl, the roots were stained with 0.03% trypan blue in lactoglycerol. The stained root fragments were examined under a microscope for AM fungal structures, and the percentage of root colonization was calculated using the following formula:

% Root Colonization = (Total number of root bits examined / Number of root bits with AM fungal structures) × 100.

2.6. Enumeration of AM Fungal Spores

Extrametrical chlamydospores were quantified using the wet sieving and decanting method (Gerdemann and Nicolson, 1963). A 100 g representative soil sample from each treatment was suspended in water, stirred thoroughly, and passed through a series of sieves (1000, 300, 205, 105, and 45 µm). The material retained on the bottom two sieves was transferred to a nylon mesh with an equivalent pore size. Spores retained on the mesh were then transferred to Petri dishes and counted under a microscope.

2.7. Morphological and Physiological Evaluations

The following growth and physiological parameters were assessed:

- Plant height (cm),
- Average leaf length (cm),
- Average leaf width (mm),
- Shoot length (cm),
- Shoot width (mm),
- Root length (cm),
- Root width (cm),
- Number of nodules,
- Total chlorophyll content in fresh leaves, was determined using Arnon's (1949) method.

2.8. Data Analysis

Experimental data were subjected to one-way analysis of variance (ANOVA) using Microsoft Excel software. Treatment means were compared and ranked using Duncan's Multiple Range Test (DMRT) at a 5% level of significance (Little and Hills, 1978).

3. Results

3.1. AM Fungal Colonization

The effects of AM fungal inoculation on the growth and physiological parameters of *Dalbergia latifolia* were assessed over 12 months. Statistically significant differences (p d" 0.05) were observed in various growth parameters between AM fungal-inoculated plants and the control group (T1), as shown in Table 1. The percentage of AM fungal colonization,

Table 1: Effect of AM Fungal Inoculation on Growth and Chlorophyll Content of *D. latifolia* at Different Time Intervals

Parameter	T1 (Control)	T2 (*Glomus mosseae*)	T3 (*Glomus fasciculatum*)	T4 (*Glomus leptotichum*)
3 Months				
Plant Height (cm)	21.66 ± 0.577b	29.66 ± 2.082a	32.66 ± 5.508a	27.66 ± 0.577a
Average Leaf Length (cm)	2.83 ± 0.289b	3.53 ± 0.058a	3.63 ± 0.231a	3.53 ± 0.115a
Average Leaf Width (mm)	1.93 ± 0.115b	3.07 ± 0.379a	3.00 ± 0.000a	3.00 ± 0.000a
Shoot Length (cm)	11.9 ± 0.1b	16.00 ± 1.00a	16.33 ± 0.577a	16.00 ± 0.577a

Table 1 (Cont.)

Parameter	**T1 (Control)**	**T2 (*Glomus mosseae*)**	**T3 (*Glomus fasciculatum*)**	**T4 (*Glomus leptotichum*)**
Shoot Width (mm)	0.25 ± 0.006c	0.40 ± 0.10ab	0.43 ± 0.058a	0.30 ± 0.00bc
Root Length (cm)	9.83 ± 0.29c	11.67 ± 0.58b	13.33 ± 0.58a	10.33 ± 0.58c
Root Width (cm)	0.243 ± 0.012b	0.433 ± 0.058a	0.50 ± 0.10a	0.433 ± 0.058a
Number of Nodules	30.33 ± 0.577b	64.00 ± 1.00a	63.33 ± 0.577a	62.67 ± 0.577a
Total Chlorophyll Content (SPAD)	29.00 ± 1.00d	37.33 ± 0.577b	33.33 ± 0.577c	45.00 ± 1.00a
6 Months				
Plant Height (cm)	28.86 ± 0.321b	42.00 ± 1.00a	40.67 ± 1.155a	40.33 ± 0.577a
Average Leaf Length (cm)	3.90 ± 0.10b	5.03 ± 0.208a	4.10 ± 0.173b	4.10 ± 0.173b
Average Leaf Width (mm)	3.70 ± 0.265b	4.47 ± 0.153a	3.47 ± 0.473b	3.47 ± 0.473b
Shoot Length (cm)	15.90 ± 0.10b	16.33 ± 0.577b	20.67 ± 2.082a	16.00 ± 1.732b
Shoot Width (mm)	0.32 ± 0.023b	0.40 ± 0.00a	0.43 ± 0.058a	0.30 ± 0.00b
Root Length (cm)	13.07 ± 0.208c	25.67 ± 0.58b	29.67 ± 1.16a	25.67 ± 0.577b
Root Width (cm)	0.33 ± 0.017b	0.367 ± 0.058b	0.53 ± 0.153a	0.433 ± 0.058ab
Number of Nodules	79.67 ± 5.508c	135.67 ± 6.028a	101.67 ± 7.37b	86.67 ± 6.807c
Total Chlorophyll Content (SPAD)	39.67 ± 1.528c	46.33 ± 0.577b	45.67 ± 0.577b	51.33 ± 0.577a
9 Months				
Plant Height (cm)	41.67 ± 0.577c	70.33 ± 1.528b	73.67 ± 2.082a	73.00 ± 1.00ab
Average Leaf Length (cm)	4.86 ± 0.078b	5.03 ± 0.058a	5.00 ± 0.00a	4.97 ± 0.058a
Average Leaf Width (mm)	4.02 ± 0.012b	4.13 ± 0.153b	4.27 ± 0.153b	4.63 ± 0.231a
Shoot Length (cm)	25.73 ± 0.058c	45.33 ± 4.041a	43.33 ± 1.53b	37.67 ± 3.215b
Shoot Width (mm)	0.53 ± 0.058b	0.73 ± 0.058a	0.60 ± 0.00b	0.57 ± 0.058b
Root Length (cm)	16.20 ± 0.10c	26.33 ± 0.58b	29.67 ± 1.55a	26.00 ± 1.732b
Root Width (cm)	0.48 ± 0.029b	0.50 ± 0.00b	0.60 ± 0.00a	0.67 ± 0.058a
Number of Nodules	81.67 ± 4.72b	103.33 ± 2.082a	96.67 ± 6.028a	101.67 ± 4.359a
Total Chlorophyll Content (SPAD)	32.00 ± 2.64d	60.33 ± 0.577a	51.00 ± 1.00b	45.33 ± 0.577c
12 Months				
Plant Height (cm)	60.50 ± 0.10b	112.00 ± 4.00a	109.00 ± 4.36a	108.00 ± 2.65a
Average Leaf Length (cm)	4.05 ± 0.006c	4.90 ± 0.656b	6.43 ± 0.404a	6.73 ± 0.153a
Average Leaf Width (mm)	3.55 ± 0.017d	3.97 ± 0.153c	5.10 ± 0.10a	4.30 ± 0.20b

Table 1 (Cont.)

Parameter	T1 (Control)	T2 (*Glomus mosseae*)	T3 (*Glomus fasciculatum*)	T4 (*Glomus leptotichum*)
Shoot Length (cm)	37.47 ± 0.379c	76.00 ± 3.00a	67.00 ± 1.732b	69.00 ± 3.00b
Shoot Width (mm)	0.48 ± 0.008b	0.77 ± 0.153a	0.87 ± 0.058a	0.87 ± 0.058a
Root Length (cm)	24.37 ± 0.321d	35.33 ± 2.082c	45.67 ± 0.577a	42.33 ± 0.577b
Root Width (cm)	0.43 ± 0.058b	0.73 ± 0.058a	0.80 ± 0.00a	0.77 ± 0.058a
Number of Nodules	85.00 ± 5.00c	136.00 ± 4.58a	128.00 ± 2.65b	129.33 ± 5.69ab
Total Chlorophyll Content (SPAD)	38.00 ± 3.00c	57.00 ± 1.00a	45.33 ± 0.577b	43.00 ± 1.00c

Note: Data represent the mean ± standard deviation. Means followed by different letters (a,b,c) within the same row indicate significant differences among treatments at $p \leq 0.05$, as determined by Duncan's Multiple Range Test. Values sharing the same letter are not significantly different from each other.

along with the number of vesicles, arbuscules, and sporulation in the rhizosphere, increased progressively over time. Micro-propagated plants inoculated with *Glomus fasciculatum* (T3) showed 40% colonization, while normal plants inoculated with the same species exhibited 35% colonization. The micro-propagated plants also demonstrated more prominent sporulation, which positively correlated with the number of vesicles and arbuscules, indicating higher mycorrhizal activity in the micro-propagated plants.

3.2. Growth Parameters

Growth improvements were evident in all AM fungal-inoculated plants when compared to the control group. Plants inoculated with *Glomus mosseae* (T2) exhibited the highest plant height throughout the study, reaching a maximum height of 112 cm at 12 months. Both *Glomus fasciculatum* (T3) and *Glomus leptotichum* (T4) showed significant height increases, substantially outperforming the control group. This growth pattern was statistically validated through ANOVA and F-tests, which revealed significant differences at the 1% and 5% levels (see Table 2, Figure 1). The growth progression of *Dalbergia latifolia* over the study period is further illustrated in Figure 2.

Table 2: Growth Parameters of *Dalbergia latifolia* Under Different Arbuscular Mycorrhizal Fungi Treatments at Different Time Intervals

Parameter	T1 (Control)	T2 (*Glomus mosseae*)	T3 (*Glomus fasciculatum*)	T4 (*Glomus leptotichum*)
3 Months				
Plant Height (cm)	21.66 ± 0.577b	29.66 ± 2.082a	32.66 ± 5.508a	27.66 ± 0.577a
Average Leaf Length (cm)	2.83 ± 0.289b	3.53 ± 0.058a	3.63 ± 0.231a	3.53 ± 0.115a
Average Leaf Width (mm)	1.93 ± 0.115b	3.07 ± 0.379a	3.00 ± 0.000a	3.00 ± 0.000a
Shoot Length (cm)	11.9 ± 0.1b	16.00 ± 1.00a	16.33 ± 0.577a	16.00 ± 0.577a
Shoot Width (mm)	0.25 ± 0.006c	0.40 ± 0.10ab	0.43 ± 0.058a	0.30 ± 0.00bc
Root Length (cm)	9.83 ± 0.29c	11.67 ± 0.58b	13.33 ± 0.58a	10.33 ± 0.58c
Root Width (cm)	0.243 ± 0.012b	0.433 ± 0.058a	0.50 ± 0.10a	0.433 ± 0.058a
Number of Nodules	30.33 ± 0.577b	64.00 ± 1.00a	63.33 ± 0.577a	62.67 ± 0.577a
Total Chlorophyll Content (SPAD)	29.00 ± 1.00d	37.33 ± 0.577b	33.33 ± 0.577c	45.00 ± 1.00a

Table 2 (Cont.)

Parameter	T1 (Control)	T2 (*Glomus mosseae*)	T3 (*Glomus fasciculatum*)	T4 (*Glomus leptotichum*)
6 Months				
Plant Height (cm)	28.86 ± 0.321b	42.00 ± 1.00a	40.67 ± 1.155a	40.33 ± 0.577a
Average Leaf Length (cm)	3.90 ± 0.10b	5.03 ± 0.208a	4.10 ± 0.173b	4.10 ± 0.173b
Average Leaf Width (mm)	3.70 ± 0.265b	4.47 ± 0.153a	3.47 ± 0.473b	3.47 ± 0.473b
Shoot Length (cm)	15.90 ± 0.10b	16.33 ± 0.577b	20.67 ± 2.082a	16.00 ± 1.732b
Shoot Width (mm)	0.32 ± 0.023b	0.40 ± 0.00a	0.43 ± 0.058a	0.30 ± 0.00b
Root Length (cm)	13.07 ± 0.208c	25.67 ± 0.58b	29.67 ± 1.16a	25.67 ± 0.577b
Root Width (cm)	0.33 ± 0.017b	0.367 ± 0.058b	0.53 ± 0.153a	0.433 ± 0.058ab
Number of Nodules	79.67 ± 5.508c	135.67 ± 6.028a	101.67 ± 7.37b	86.67 ± 6.807c
Total Chlorophyll Content (SPAD)	39.67 ± 1.528c	46.33 ± 0.577b	45.67 ± 0.577b	51.33 ± 0.577a
9 Months				
Plant Height (cm)	41.67 ± 0.577c	70.33 ± 1.528b	73.67 ± 2.082a	73.00 ± 1.00ab
Average Leaf Length (cm)	4.86 ± 0.078b	5.03 ± 0.058a	5.00 ± 0.00a	4.97 ± 0.058a
Average Leaf Width (mm)	4.02 ± 0.012b	4.13 ± 0.153b	4.27 ± 0.153b	4.63 ± 0.231a
Shoot Length (cm)	25.73 ± 0.058c	45.33 ± 4.041a	43.33 ± 1.53b	37.67 ± 3.215b
Shoot Width (mm)	0.53 ± 0.058b	0.73 ± 0.058a	0.60 ± 0.00b	0.57 ± 0.058b
Root Length (cm)	16.20 ± 0.10c	26.33 ± 0.58b	29.67 ± 1.55a	26.00 ± 1.732b
Root Width (cm)	0.48 ± 0.029b	0.50 ± 0.00b	0.60 ± 0.00a	0.67 ± 0.058a
Number of Nodules	81.67 ± 4.72b	103.33 ± 2.082a	96.67 ± 6.028a	101.67 ± 4.359a
Total Chlorophyll Content (SPAD)	32.00 ± 2.64d	60.33 ± 0.577a	51.00 ± 1.00b	45.33 ± 0.577c
12 Months				
Plant Height (cm)	60.50 ± 0.10b	112.00 ± 4.00a	109.00 ± 4.36a	108.00 ± 2.65a
Average Leaf Length (cm)	4.05 ± 0.006c	4.90 ± 0.656b	6.43 ± 0.404a	6.73 ± 0.153a
Average Leaf Width (mm)	3.55 ± 0.017d	3.97 ± 0.153c	5.10 ± 0.10a	4.30 ± 0.20b
Shoot Length (cm)	37.47 ± 0.379c	76.00 ± 3.00a	67.00 ± 1.732b	69.00 ± 3.00b
Shoot Width (mm)	0.48 ± 0.008b	0.77 ± 0.153a	0.87 ± 0.058a	0.87 ± 0.058a
Root Length (cm)	24.37 ± 0.321d	35.33 ± 2.082c	45.67 ± 0.577a	42.33 ± 0.577b
Root Width (cm)	0.43 ± 0.058b	0.73 ± 0.058a	0.80 ± 0.00a	0.77 ± 0.058a
Number of Nodules	85.00 ± 5.00c	136.00 ± 4.58a	128.00 ± 2.65b	129.33 ± 5.69ab
Total Chlorophyll Content (SPAD)	38.00 ± 3.00c	57.00 ± 1.00a	45.33 ± 0.577b	43.00 ± 1.00c

Note: Data represent the mean ± standard deviation. Means followed by different letters (a,b,c) within the same row indicate significant differences among treatments at $p < 0.05$, as determined by Duncan's Multiple Range Test. Values sharing the same letter are not significantly different from each other.

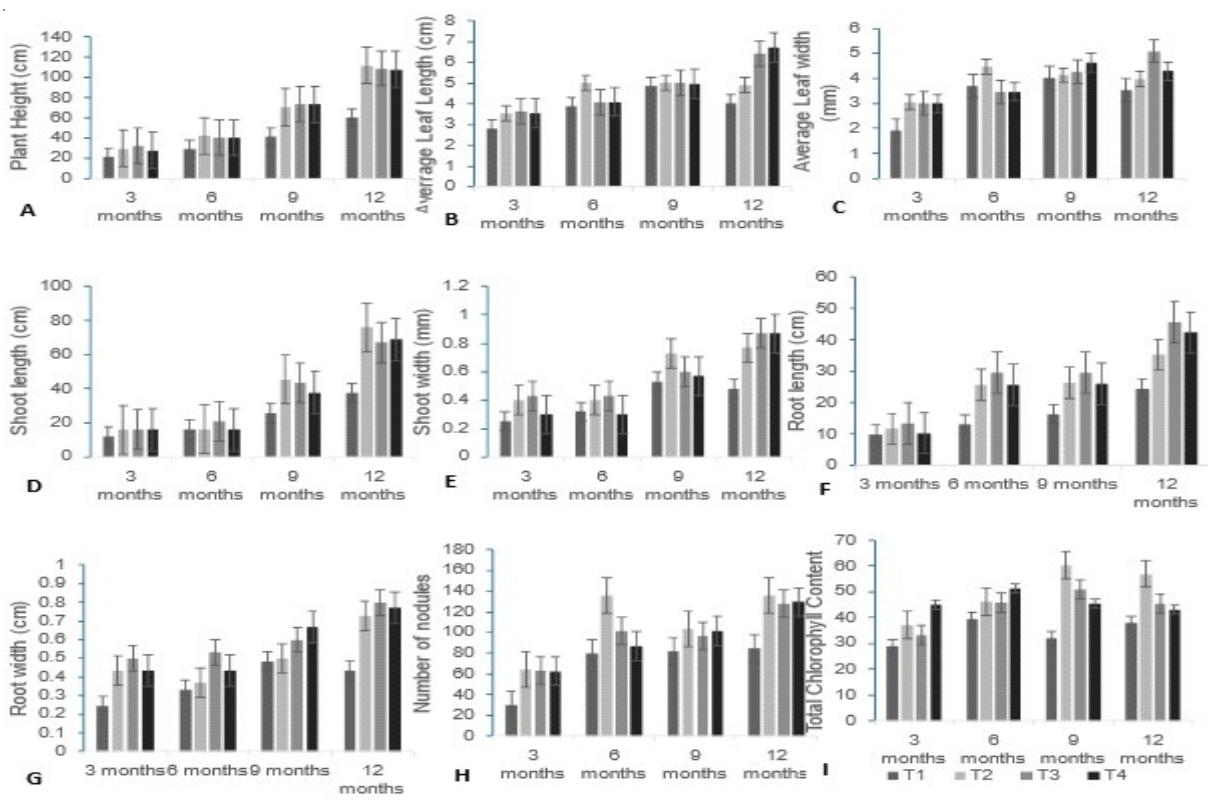

Figure 1: Growth and Physiological Responses of *Dalbergia latifolia* Under Different AM Fundal Treatment (T1, T2, T3 and T4) Over a 12-Month Period

Note: (A) Plant Height, (B) Average Leaf Length, (C) Average Leaf Width, (D) Shoot Length, (E) Shoot Width, (F) Root Length, (G) Root Width, (H) Number of Nodules and (I) Total Chlorophyll Content; Error bars represent standard deviations.

Figure 2: Growth and Progressive of *Dalbergia latifolia* at Different Time Intervals: (A) 3 Months; (B) 6 Months; (C) 9 Months and (D) 12 Months

Note: Treatments incude T1 (Control: *D. latitfolia* without AM fundal inoculation, T2: *D. latitfolia* inoculated with *Glomus mosseae*, T3: *D. latitfolia* inoculated with *Glomus fasciculatum* and T4: *D. latitfolia* inoculated with *Glomus leptotichum*.

Figure 2 (Cont.)

3.3. Leaf Parameters

Leaf length and width improved significantly under AM fungal inoculation. At the end of the study, *G. leptotichum* (T4) recorded the longest leaves (6.73 cm), followed by *G. fasciculatum* (T3) at 6.43 cm. *G. mosseae* (T2) exhibited the widest leaves at earlier stages (3 and 6 months), but *G. fasciculatum* (T3) achieved the largest leaf width (5.1 mm) by 12 months.

a. Shoot Growth

Shoot length showed a similar upward trend. At 3 months, plants inoculated with *G. fasciculatum* (T3) had the longest shoots (16.33 cm). However, by 9 and 12 months, *G. mosseae* (T2) exhibited the highest shoot length, reaching 76 cm by 12 months, followed by *G. fasciculatum* (T3) and *G. leptotichum* (T4). Shoot width also increased, with *G. fasciculatum* (T3) and *G. leptotichum* (T4) achieving the largest shoot width (0.87 mm) by the end of the study.

b. Root Growth

Root length and root width were significantly greater in AM-inoculated plants compared to the control group. *G. fasciculatum* (T3) plants exhibited the longest roots, followed by *G. leptotichum* (T4) and *G. mosseae* (T2), while the control plants consistently displayed the shortest roots. The improvement in root development was also reflected in root width, with *G. fasciculatum* (T3) and *G. leptotichum* (T4) showing significant increases in root diameter.

c. Root Nodulation

Root nodulation was significantly influenced by AM fungal inoculation. *G. mosseae* (T2) consistently produced the highest number of nodules, followed by *G. fasciculatum* (T3) and *G. leptotichum* (T4), while the control group exhibited the fewest nodules. This suggests enhanced nitrogen fixation in AM-inoculated plants.

d. Chlorophyll Content

Chlorophyll content, an indicator of photosynthetic efficiency, was significantly higher in AM fungal-inoculated plants at all time intervals. *G. mosseae* (T2) exhibited the highest chlorophyll content, peaking at 60.33 at 9 months and maintaining a value of 57 at 12 months. Both *G. fasciculatum* (T3) and *G. leptotichum* (T4) showed significant increases

in chlorophyll content compared to the control group, which consistently displayed the lowest chlorophyll content throughout the study.

4. Discussion

This study highlights the significant role of arbuscular mycorrhizal (AM) fungi in enhancing the growth of *Dalbergia latifolia*, aligning with similar observations in other medicinal plants. Arpana and Bagyaraj (2007) found that AM fungi improved the growth of Kalmegh under phosphorus fertilization, emphasizing the fungi's role in enhancing nutrient availability. Similarly, the increased nutrient uptake and chlorophyll content observed in this study reflect Zuccarini's (2007) findings, where mycorrhizal infection boosted nutrient absorption and chlorophyll levels in lettuce under saline conditions. The improvement in root development of *Dalbergia latifolia* following AM fungal inoculation aligns with findings in other species. Chiramel *et al.* (2006) reported significant root growth improvements in *Andrographis paniculata* upon AM fungal inoculation, suggesting that mycorrhizal fungi enhance root architecture, crucial for optimizing nutrient and water uptake, particularly in challenging soil conditions. Our study further deepens the understanding of AM fungi's role in nutrient uptake, supporting the results of Rajeshkannan *et al.* (2013), who demonstrated enhanced growth and nutrient absorption in *D. latifolia* under tropical conditions with bioinoculants. The positive influence of AM fungi on soil properties has been widely documented. Syam Prasad *et al.* (2020) showed that these fungi improve soil physico-chemical properties, promoting healthier plants. Similarly, Wahab *et al.* (2023) confirmed that AM fungi regulate plant growth and productivity, particularly under biotic and abiotic stress, consistent with the present findings. Beyond plant health, AM fungi offer ecological benefits by improving soil structure and nutrient cycling. Martin and Heijden (2024) emphasized the role of mycorrhizal symbiosis in enhancing nutrient cycling and soil structure, making it a critical element in sustainable agricultural practices. These benefits indicate that AM fungi could play a crucial role in the restoration of degraded soils, providing long-term ecological benefits. Another key finding from this study is the potential of AM fungi to aid in the conservation of *D. latifolia*. By incorporating AM fungi, the regeneration and growth of this species could be enhanced, further strengthening conservation efforts, as emphasized by Arunkumar *et al*. (2021) and Sasidharan et al. (2020). Integrating AM fungi into agroforestry systems can enhance productivity and maintain ecological balance, meeting the growing global demand for sustainable agricultural practices.

5. Conclusion

This study underscores the critical role of arbuscular mycorrhizal (AM) fungi in promoting the growth and development of *Dalbergia latifolia*. Inoculation with AM fungi, particularly *Glomus mosseae*, *Glomus fasciculatum*, and *Glomus leptotichum*, resulted in substantial improvements in plant height, leaf size, shoot length, and root development. Among the fungi tested, *G. mosseae* exhibited the best performance in terms of plant height and chlorophyll content, highlighting its potential to enhance the overall health and productivity of *D. latifolia*. *G. fasciculatum* demonstrated the highest root colonization, indicating its effectiveness in establishing a strong mycorrhizal symbiosis. These findings emphasize the importance of AM fungi in improving nutrient uptake, supporting root and shoot growth, and enhancing photosynthetic efficiency. The results position AM fungi as a sustainable method for promoting the growth of *D. latifolia*, a species of significant ecological and economic value. Moving forward, research should focus on optimizing AM fungal inoculation techniques for large-scale plantation management to support sustainable forestry practices and the conservation of this valuable species, while fostering ecological balance in agroforestry systems.

Acknowledgment

The authors would like to express their appreciation to the Director, Group Coordinator (Research), and Head of the Silviculture and Forest Management Division at IWST, Bengaluru, for their continued support. We also acknowledge the financial assistance from CAMPA, Government of India, for AICRP-28 on *Dalbergia latifolia* Roxb. Our sincere thanks go to Prof. D.H. Tejavathi (retired, from Bangalore University) for her valuable guidance and support.

Author Contributions

Conception and design of the research: TNM and BSM; acquisition of data: BSM; analysis and interpretation of data: TNM and BSM; statistical analysis: BSM; drafting the manuscript: TNM and BSM; all authors have read and agreed to the published version of the manuscript.

Funding

This study was funded by the CAMPA, MoEF&CC, Government of India, Research grant for AICRP 28 *Dalbergia latifolia* Roxb.

Data Availability Statement

The raw data supporting the conclusions of this article will be made available by the authors upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Cite this article as: Manohara T.N. and Balakrishna S.M. (2025). Synergistic Effects of a Mycorrhizal Consortium on Growth, Morphophysiological Traits, and Nodulation Efficiency in *Dalbergia latifolia*: Implications for Sustainable Forestry and Industry Applications. *International Journal of Agricultural Sciences and Technology*, 5(1), 12-22. doi: 10.51483/IJAGST.5.1.2025.12-22.