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Research Article

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Growth response of sandalwood (*Santalum album*) seedlings to different potting mixtures and host plants in northwestern India

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ABSTRACT

Santalum album L., a hemiparasitic tree, requires a compatible host association for optimal growth, particularly during the nursery stage. Five primary host species *viz. Alternanthera sessilis* (T_1), *Casuarina* equisetifolia (T_2), *Lawsonia inermis* (T_3), *Mimosa pudica* (T_4), *Cajanus cajan* (T_5), and a control without host (T_6) under two potting mixtures *viz.* S_1 (Soil: Sand: FYM-2:2:1) and S_2 (Soil: FYM-2:1), were selected. The experiment was conducted in a factorial completely randomized design with three replications, each comprising five seedlings. Host seeds/cuttings were introduced when sandalwood seedlings were transplanted into hyco trays from the nursery bed. Key morphological parameters were recorded monthly from 60 days after transplanting, while root traits and seedling quality indices were assessed at the termination of the experiment. Results demonstrated that S_1 significantly enhanced shoot growth and seedling survival, whereas S_2 promoted better root development and improved seedling quality indices. Among the hosts, T_5 showed the highest survival (85%), maximum seedling height (21.03 cm) and root length (34.7 cm), while T_1 recorded the highest shoot and root collar diameter (3.00 mm and 3.99 mm, respectively), number of leaves (15.3), and total dry biomass accumulation (1.97 g). Consequently, T_1 and T_5 had similar DQI values, followed by T_4. However, T_1 recorded the lowest SI, indicating a sturdier seedling. The interaction showed a statistically significant effect on survival rate, root length, and root collar diameter, while it showed non-significant effects for other parameters. Thus, $S_1 + T_5$ or $S_1 + T_1$ combinations are recommended for producing well-balanced, vigorous, and high-quality sandalwood seedlings. Results also highlights that *Alternanthera sessilis*, a non-leguminous species, can serve as an effective alternative to the traditionally used leguminous host *Cajanus cajan*.

INTRODUCTION

Santalum album Linn. commonly referred as Indian sandalwood, East Indian sandalwood, chandan, or *safed* chandan, is highly valued for its aromatic heartwood and essential oil. Among the 17 recognized species within the *Santalum* genus, *S. album* is distinguished by its superior oil content, rich in beneficial sesquiterpenes such as α- and β-santalols. The essential oil yield of *S. album* (6–7%) far exceeds that of *S. spicatum* (2%) and *S. lanceolatum* (1%), making it particularly attractive in global markets. Due to decades of overexploitation, the species has been listed as "vulnerable" by the International Union for Conservation of Nature (Kumar et al. 2019). However, after the liberalization of regulations in 2001 regarding sandalwood cultivation and trade, there has been a surge of interest among various stakeholders in its commercial cultivation. The global sandalwood essential oil market is projected to reach USD 197 million by 2026 (Global Sandalwood Oil Markets Report, 2020). India accounts for approximately 50% of global sandalwood consumption, its heartwood is prized for carving, while its oil is used extensively in attars, perfumes, cosmetics, medicinal products, and flavored tobacco (Chavan et al. 2024). India initiated large-scale commercial cultivation around 2014, reaching approximately 20,725 ha of plantations by 2015 (Pallavi 2015). The natural distribution of *S. album* spans an estimated 9,000 km², with about 90% of this area concentrated in Karnataka, Tamil Nadu, Madhya Pradesh, and select regions of Kerala. Smaller populations also exist in semi-arid areas of Maharashtra, Telangana, and parts of Uttar Pradesh (Madhuvanti et al. 2024). Recently, commercial plantations have been expanding into non-traditional areas such as Andhra Pradesh, Telangana, Maharashtra, Gujarat, Assam, and Punjab (Durai et al. 2022).

Sandalwood is an evergreen, facultative hemiparasitic tree that establishes root associations with host plants to augment its uptake of water and essential nutrients. Sandalwood requires a sequential host association strategy encompassing three stages: primary (nursery) hosts, intermediate hosts (during transplantation), and secondary (field) hosts. In addition to nutritional support, hosts also confer physical benefits, including protection against abiotic stressors such as solar radiation, wind, and herbivory, and may act as a source of organic compounds including amino acids (Rocha et al. 2022). The parasitic nature of sandalwood was first reported by Scott (1871), with subsequent studies indicating that approximately 70% of seedlings initiate haustorial connections within the first month post-germination (Nagaveni and Srimathi, 1985). Early host association in nursery conditions is critical for improving seedling vigor, which directly influences long-term survival and field performance (Fox, 2000; Tennakoon and Cameron, 2006). Root exudates from compatible hosts, particularly strigolactones, are known to induce haustorium formation (Rocha et al. 2015). In the presence of a suitable host, the haustorium undergoes morphological development into a bell-shaped structure that facilitates vascular connectivity and the bidirectional transfer of nutrients. In the absence of host roots, however, haustorial structures remain rudimentary and subsequently degenerate. Nutrient acquisition through host associations provides sandalwood with critical elements such as nitrogen, phosphorus, potassium, and magnesium (Hiremath et al. 2024). Sandalwood exhibits a broad host range, the underlying physiological and biochemical mechanisms that govern host compatibility and parasitic success remain incompletely understood.

Despite its ecological adaptability, sandalwood cultivation in India remains constrained by the absence of standardized silvicultural protocols (Doddabasawa and Chittapur, 2021; Srikantaprasad et al. 2022). Among the critical determinants of successful establishment, seedling traits shaped largely by plant-soil interactions play a pivotal role in governing plant fitness, vigor, and persistence. The choice of nursery substrate is especially crucial, as it mediates the supply of water, oxygen, and essential nutrients, while also providing mechanical support to the developing root system (Liu et al. 2009). Traditionally, Indian nurseries employ a potting mix of soil, sand, and farmyard manure in a 2:1:1 ratio (Rai, 1990), whereas studies in Timor have reported better seedling performance in native, unamended soils (Fox et al. 1990), suggesting the importance of regional adaptation. In addition to substrate composition, the selection of compatible primary host species is integral to optimizing early growth in this hemiparasitic species. Previous studies have explored a range of potential nursery hosts, including *Alternanthera sessilis* (Durai, 2022; Mohapatra et al. 2018), *Casuarina* (Sahoo et al. 2021), *Lawsonia inermis*, *Mimosa pudica* (Chakrabarty, 2021; Mohapatra et al. 2018), *Cajanus cajan* (Annapurna, 2007; Sahu et al. 2021; Chakrabarty, 2021), and host-free control conditions (Doddabasawa and Chakrabarty, 2021), each with varying levels of compatibility and resource contribution. This study was therefore designed to evaluate the interactive effects of two potting media and five primary host species on the nursery performance of *Santalum album* seedlings under Punjab's agro-climatic conditions. The objective is to identify optimal combinations that enhance early growth, physiological quality, and survival, thereby contributing to the development of reliable and region-specific nursery protocols to support sustainable sandalwood cultivation.

MATERIAL AND METHODS

Site Description: The experiment was conducted during the year 2023 at the main research area of the Department of Forestry and Natural Resources, Punjab Agricultural University, Ludhiana, India. The study site is located at an elevation of 247 meters above mean sea level, at 30° 45' N latitude and 75° 40' E longitude, in the central region of Punjab. The climate of the area is characterized as sub-tropical to tropical, with prolonged dry periods extending from late September to early June, and a distinct monsoon season from July to September. May and June are the hottest months, while December and January are the coldest. Frost occurrence is rare. The average annual rainfall is approximately 704 mm, with 75–80% of the precipitation occurring between July and September.

Planting material and seed treatment: Sandalwood seeds were sourced from the Institute of Wood Science and Technology, Bengaluru. To overcome seed dormancy and promote germination, the dried seeds were soaked in a 500 ppm gibberellic acid (GA_3) solution, as suggested by Vira and Smith (1996). The solution was prepared by dissolving 1 gram of GA_3 in a few drops of ethanol in a glass beaker, followed by dilution to 2 liters with distilled water and thorough mixing. Seeds were sown in the first fortnight of March under a green net shed.

Experimental design: Two potting mixtures were evaluated: S_1 (Soil: Sand: FYM-2:2:1) and S_2 (Soil:FYM-2:1). Five potential primary host species were tested as treatments: *Alternanthera sessilis* (T_1), *Casuarina* (T_2), *Lawsonia inermis* (T_3), *Mimosa pudica* (T_4), *Cajanus cajan* (T_5), and a control without host (T_6). The experiment was laid out in a factorial completely randomized block design with three replications. Each treatment within a replication comprised five individually potted sandalwood seedlings.

Observations of growth and biomass parameters:

Seedling height (cm): Measured from the soil surface in the polythene bag to the shoot tip using a measuring scale.

Collar diameter (mm): Recorded at the collar region using a vernier caliper.

Number of leaves: Fully opened mature leaves were counted visually.

Root length (cm): Measured after carefully washing the roots.

Root and shoot fresh biomass (g): Weighed using an electronic balance immediately after separation of shoots and root portions.

Root and shoot dry biomass (g): The root and shoot portions were oven-dried separately at 60°C until constant weight was achieved, then weighed using an electronic balance.

Total dry biomass (g): Calculated as the sum of root dry weight and shoot dry weight.

Qualitative indices

Sturdiness quotient (SQ): Calculated by dividing seedling height (cm) by collar diameter (mm), as described by Roller (1977).

Quality index (QI): Computed using the method proposed by Dickson et al. (1960), integrating height, collar diameter, and biomass data to assess overall seedling quality.

Statistical analysis

The mean data recorded on various growth and physiological parameters were subjected to statistical analysis as per the method laid down for factorial completely randomized block design by using CPCS1 software.

RESULTS AND DISCUSSION

Survival

Survival percentage, a critical morphological trait reflecting early establishment success, was assessed at the end of the experiment and it was significantly influenced by both the nursery host species and the potting mixture (Fig. 1). Among the two potting media, S_1 resulted in 8.22% higher survival compared S_2; however, the difference was statistically non-significant. In contrast, the influence of host species on survival was statistically significant, and their interaction with the potting media also showed a positive effect, underscoring the importance of optimizing both factors to achieve maximum seedling survival. Among the treatments, maximum survival was recorded in T_5 (85%) in both S_1 and S_2 indicating its strong potential to support sandalwood establishment. This mean survival was statistically at par with T_1 (77.5%) and T_4 (72.5%) whereas survival were poor in T_3 and T_6.

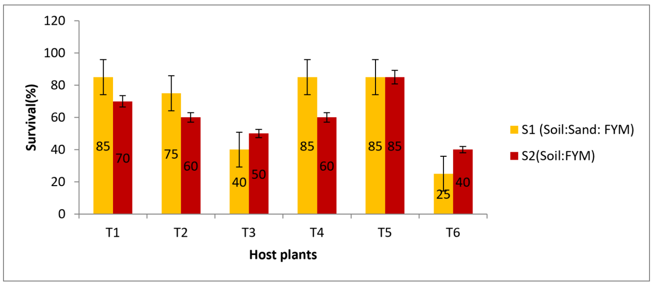

Figure 1: Effect of potting mixture and host plants on survival percentage of sandalwood seedlings Bars represent the mean value; error bars indicate ±SE

Leguminous species such as *Cajanus cajan* and *Mimosa pudica* were well-documented for their ability to facilitate early haustorial development in *Santalum album*, thereby improving nutrient acquisition and promoting seedling vigor and survival (Radomiljac, 1998). Annapurna (2002) reported that substrates composed exclusively of sand, soil, or organic matter was inadequate

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Table 1: Effect of potting mixture and host plants on collar diameter and number of leaves of sandalwood

Treatments	Collar diameter (mm)					Number of leaves				
	Days after transplanting									
	60	90	120	150	180	60	90	120	150	180
Potting mixture										
S1	1.46	1.88	2.03	2.4	2.63	10.17	12.01	11.54	12.09	13.06
S2	1.29	1.67	1.78	2.18	2.41	7.87	7.88	6.35	6.81	9.94
CD(p=0.05)	0.16	0.16	0.22	0.18	0.16	0.89	1.89	1.87	2.32	2.35
Host plants										
T1	1.49	1.86	2.01	2.69	3.00	8.61	12.26	12.66	13.08	15.38
T2	1.49	1.88	1.99	2.33	2.46	8.29	8.71	9.23	8.91	11.72
T3	1.31	1.54	1.75	2.01	2.18	9.21	8.92	7.58	8.99	9.79
T4	1.52	2.1	2.31	2.64	2.72	10	11.39	10.92	12.32	14.22
T5	1.43	1.82	1.88	2.38	2.92	10	9.46	9.84	10.21	12.41
T6	1.05	1.41	1.5	1.71	1.84	7.58	8.95	4.31	4.22	5.51
CD(p=0.05)	0.29	0.2	0.39	0.31	0.28	NS	NS	3.24	4.02	4.08

for optimal seedling development, often resulting in poor physiological performance. The study concluded that a balanced medium integrating all three components was essential to ensure adequate aeration, moisture retention, and nutrient availability. Further, Annapurna *et al.* (2007) observed significant improvements in both growth and survival of sandalwood seedlings when grown in a suitable potting medium, reporting survival rates of up to 80% at 180 days after transplanting. Conversely, Sahu et al. (2021) observed an 89.07% survival when sandalwood seedlings were associated with the non-leguminous *Alternanthera sessilis*, suggesting that even non-leguminous species can effectively support sandalwood establishment under appropriate nursery conditions.

Seedlings growth parameters

The growth parameters: plant height (cm) (Fig. 2), collar diameter (mm), and number of leaves of sandalwood seedlings were recorded at 60, 90, 120, 150, and 180 days after transplanting (DAT) (Table 1). A progressive increase in all growth parameters was observed. Seedlings grown in the S1 consistently outperformed S2 and varied significantly among both potting mixtures. The collar diameter increased from 1.46 mm to 2.63 mm, height from 12.80 cm to 20.20 cm, while the number of leaves varied from 10.17 to 13.06. The enhanced performance of seedlings in S1 may be attributed to better nutrient availability and moisture retention, both of which are critical during early seedling establishment.

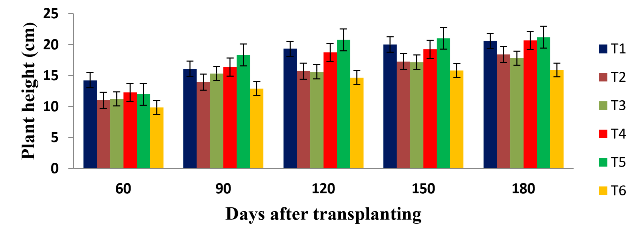

Figure 2: (a and b) Effect of potting mixture and host treatments on plant height (cm) of sandalwood

Among the nursery host treatments, statistically significant differences were observed in the vegetative growth of sandalwood seedlings at 180 DAT, highlighting the pivotal role of host species in influencing early seedling vigor. The tallest seedlings were recorded in T5 (21.03 cm), which was statistically at par with T1 (20.02 cm), followed by T4 (19.23 cm). In contrast, the control treatment T_6 (without host) recorded the lowest seedling height (15.90 cm). Compared to the control, T_5, T_1, and T_4 showed 32.3%, 25.9%, and 20.9% higher seedling heights, respectively, demonstrating the significant advantage of suitable host associations during the nursery phase. The mean seedling height across treatments at 180 DAT ranged between 15.9 and 21.03 cm. These findings align with earlier reports by Annapurna et al. (2007) and Radomiljac (1998), which emphasized that the formation of functional haustoria during early growth stages—particularly with leguminous or fast-growing herbaceous hosts enhances nutrient uptake and biomass accumulation. Similarly, Gomez and Adnayana (2017), in a nursery trial, reported that sandalwood seedlings attained taller average height with *Cajanus cajan*, compared with *A. sessilis*, reinforcing the superior early growth supported by the leguminous host. However, recent studies also underscore the potential of non-leguminous hosts. Sahu et al. (2021) observed that *A. sessilis* significantly improved seedling height and survival, demonstrating its effectiveness as a primary host. Additionally, Durai (2022) highlighted *A. sessilis* as highly effective in promoting rapid seedling establishment, attributed to its fine root system and early haustorial compatibility. These studies corroborate the present findings, reaffirming that host-assisted nutrient acquisition is critical for early seedling performance and future field establishment in sandalwood cultivation and that both leguminous and select non-leguminous hosts can serve this purpose effectively.

The maximum collar diameter was recorded in T_1 (3.00 mm), which was statistically at par with T_5 (2.92 mm), followed by T_4 (2.72 mm). In contrast, the minimum collar diameter was observed in the control treatment T_6 (1.84 mm). Compared to the control, T_1, T_5, and T_4 exhibited 63.0%, 58.7%, and 47.8% higher collar diameters, respectively, indicating the significant contribution of compatible host species to early stem development in sandalwood seedlings. This suggests that both leguminous and compatible herbaceous hosts facilitate better radial stem growth. Tennakoon and Cameron (2006) reported that successful host associations enhance the vascular connection between sandalwood and its host, facilitating the transfer of water, minerals, and amino acids required for rapid cambial activity and secondary growth. Durai (2022) and Sahu et al. (2021) emphasized that even non-leguminous hosts like *Alternanthera* can support vigorous collar thickening due to their ability to establish early root contact and foster efficient haustorial connections. Subasinghe et al. (2011) evaluated six host species and found *Desmodium triflorum* to be effective for increasing height, while *Mimosa pudica* contributed significantly to collar diameter and leaf whorl development.

Leaf development, an important indicator of photosynthetic capacity and overall seedling health, was also most pronounced in T_1 (15.38 leaves), followed by T_4 (14.22), and T_5 (12.41). The control treatment had only 5.51 leaves at 180 DAT. The mean leaf number ranged from 5.51 to 15.38**,** again reinforcing the critical role of nursery hosts in foliage development and plant vigor. Leaf number variations show the importance of host association in enhancing early canopy development and plant vigor in sandalwood. As the experiment progressed, variations in leaf number were noted, likely due to seasonal fluctuations that affect physiological activity. The rise in temperature and changes in photoperiod appeared to stimulate vegetative growth, underscoring the role of environmental factors in modulating plant development. According to Radomiljac (1998) and Tennakoon and Cameron (2006), successful host-parasite interactions promote nutrient translocation, which directly influences chlorophyll production, leaf number and leaf expansion. Hosts like *Alternanthera* and *Mimosa*, with fine, fibrous root systems, are particularly effective in establishing early haustorial contact, enabling efficient nutrient uptake essential for active leaf development (Sahu et al. 2021; Durai, 2022).

The interaction between soil media and host plants was found to be significant, indicating a combined influence on the early growth stages of sandalwood seedlings. However, for collar diameter and leaf number, the interaction between soil media and host species remained non-significant across all observation intervals, suggesting that these two factors contribute independently to these traits. Fast-growing host species were found to promote greater seedling height, while a broader collar diameter generally indicated better seedling vigor and health. Annapurna et al. (2007) highlighted the critical role of host species in enhancing sandalwood seedling performance, reporting positive effects on height, collar diameter, total dry weight, and overall seedling quality. Similarly, Durai et al. (2022) and Srikantaprasad et al. (2021) observed that *A. sessilis* significantly improved both height and collar diameter in comparison to seedlings grown without a host. Balasubramanian et al. (2018) studied that cocultivation with *A. sessilis* and *Sesbania grandiflora* enhanced seedling performance, suggesting a synergistic effect from multiple hosts.

Root and biomass attributes

The findings presented in Table 2 reveal significant differences ($p \le 0.05$) in key root parameters, namely root length and root collar diameter, among the various treatments. In contrast, dry matter accumulation exhibited non-significant variation with respect to potting media and their interactions. Seedlings grown in the S_2 medium recorded the longest average root length (29.1 cm), significantly greater than those in S_1 (24.6 cm). Among the host treatments, T5 exhibited the maximum mean root length (34.69 cm), followed by T1 (32.94 cm), while T6 recorded the lowest (18.94 cm). These observations indicate that specific combinations of hosts and potting media can markedly influence root development. Root elongation is a crucial early indicator of seedling vigor, promoting efficient water and nutrient uptake and enhancing establishment success in the field (Grossnickle, 2005). Treatments promoting longer root growth are therefore beneficial for successful field transplantation by improving anchorage, stress resilience and overall seedling establishment. However, longer roots are not the only determinant of effective host interaction.

Rodomiljac (1998) emphasized the benefits of

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Table 2: Effect of potting mixture and host plants on root collar diameter and root length of sandalwood after six months of transplanting

Treatments	Root collar diameter (mm)			Root length (cm)		
	S1	S2	Mean	S1	S2	Mean
T1	3.98	4.00	3.99	30.75	35.13	32.94
T2	3.51	3.76	3.63	27.25	26.50	26.88
T3	2.87	2.86	2.86	23.25	24.75	24.00
T4	3.69	3.30	3.49	18.25	27.00	22.63
T5	3.12	3.21	3.16	24.88	44.50	34.69
T6	1.83	1.29	1.56	21.00	16.88	18.94
Mean	3.16	3.07		24.23	29.13	
CD(p=0.05)	Potting mixture-NS, Host plants 0.24, Potting mixture x Host plants -0.34			Potting mixture-2.79, Host plants-4.84, Potting mixture x Host plants -6.85		

shallow-rooted leguminous or herbaceous host species, which share the rooting zone with sandalwood without competing excessively for below-ground resources, thereby promoting early seedling development. The growth and vigor of sandalwood seedlings are also closely influenced by the choice of potting medium and host species. Further, Mohapatra *et al.* (2018) reported that root system architecture and nutrient dynamics in hemiparasitic species like sandalwood are significantly affected by nursery inputs. The effect of potting mixture on root collar diameter was non-significant, while the difference among treatments was significant. The highest root collar diameter was observed in T1 (3.99 mm), followed by T2 (3.63 mm) and T4 (3.49 mm), indicating better seedling vigour under these combinations. In contrast, the lowest collar diameter was recorded in T6 (1.56 mm). Although the overall mean values of collar diameter under potting mixtures S1 (3.16 mm) and S2 (3.07 mm) were not significantly different. An increased diameter indicates greater seedling robustness and suggests better vascular development and structural strength (Bose et al. 2022), both of which are crucial for survival under field stress conditions. The interaction between soil media and host was statistically significant, suggesting that both factors influence each other and collectively contribute to improved seedling growth performance. The significant interactions between potting mixture and host plants were also observed for root length and root collar diameter, indicating that specific combinations (e.g., T1 and T5) are more favourable for root development. These findings highlight the critical role of host species and substrate combinations in enhancing early growth parameters of sandalwood seedlings in nursery conditions.

The shoot dry weight was marginally higher in S_2 (1.01 g) compared to S_1 (0.69 g), while root dry weight also had a slight increase in S_2 (0.61 g) relative to S_1 (0.57 g) (Table 3). Despite these numerical differences, the variation in total dry biomass between the two potting media was statistically non-significant, indicating that both substrates were comparably effective in supporting overall dry matter accumulation. However, the distinct allocation patterns between shoot and root components suggest subtle differences in resource partitioning attributable to the media composition. Regarding host treatments, the highest shoot dry weight was recorded in T_1 (1.15 g), followed by T_4 (1.06 g), whereas T_6 had the lowest accumulation (0.16 g). Although these differences were not statistically significant, the observed trend underscores the potential influence of host species on promoting above-ground biomass. Annapurna *et al.* (2006) highlighted the pivotal role of compatible host species in enhancing shoot biomass, plant height, and leaf area in sandalwood seedlings, thereby improving photosynthetic efficiency and early vigor.

Conversely, root dry weight was significantly affected by host species. Treatment T_5 recorded the highest root biomass (1.04 g), followed by T_1 (0.82 g), both of which significantly surpassed T_6 (0.10 g). These findings indicate that suitable hosts can substantially enhance below-ground development, likely through more effective haustorial connections and improved resource acquisition. In support, Mohapatra et al. (2018) reported that host association plays a critical role in modulating root system architecture and nutrient uptake dynamics, which are essential for sustained seedling performance. The total dry biomass was maximum in T_1 (1.97 g), closely followed by T_5 (1.95 g), suggesting that these host treatments provided the most favorable conditions for overall biomass accumulation. Similarly, Balasubramanian et al. (2018), demonstrated that co-cultivation of sandalwood with *A. sessilis* and *Sesbania grandiflora* significantly, enhanced seedling vigor and dry matter content. The superior performance observed in T_1 and T_5 may be attributed to enhanced physiological compatibility and nutrient synergies between the sandalwood seedlings and their respective hosts.

Table 3: Shoot, root and total dry weight of sandalwood plants at the termination of experiment

Treatments	Shoot Dry weight (g)	Root dry weight (g)	Total dry weight (g)
Potting mixture			
S1	0.69	0.57	1.27
S2	1.01	0.61	1.62
CD(p=0.05)	NS	NS	NS
Host plants			
T1	1.15	0.82	1.97
T2	0.89	0.63	1.51
T3	0.95	0.52	1.47
T4	1.06	0.43	1.50
T5	0.92	1.04	1.95
T6	0.16	0.1	0.26
CD (p=0.05)	0.61	0.36	0.81

Table 4: Quality indices of *sandalwood* plants six months after transplanting

Quality Parameters	Dickson quality index	Sturdiness quotient
Potting mixture		
S1	0.14	7.95
S2	0.18	7.60
CD (p=0.05)	NS	NS
Host plants		
T1	0.23	6.89
T2	0.19	7.60
T3	0.16	8.46
T4	0.14	7.61
T5	0.23	7.32
T6	0.03	8.76
CD (p=0.05)	0.10	0.82

Sturdiness quotient (SQ) and Dickson quality index (DQI)

The quality of sandalwood seedlings, as evaluated by the Dickson Quality Index (DQI) and Sturdiness Quotient (SQ), was predominantly influenced by host species rather than potting media (Table 4). The DQI, composite metric integrating morphological parameters such as height, collar diameter, and biomass partitioning, is widely recognized as a robust indicator of seedling vigor, providing a more comprehensive assessment than individual traits such as shoot length or stem diameter (Binotto et al., 2010). Although the interaction between potting medium and host species did not result in statistically significant differences for either parameter, treatment-specific responses revealed meaningful trends. Seedlings grown in S_2 exhibited a marginally higher DQI (0.18) than those grown in S_1 (0.14), indicating a modest improvement in overall seedling quality. Although this difference was not statistically significant, the observed trend suggests that S_2 may provide a more favorable environment for balanced growth and biomass allocation. Higher DQI values generally indicate seedlings with superior structural balance and vigor, traits that are desirable for successful outplanting and field establishment.

Among the host species, the highest DQI values were recorded in T_1 and T_5 (0.23), followed closely by T_2 (0.19), suggesting that these hosts substantially enhanced seedling morphological quality. In contrast, seedlings grown under T_6 exhibited a markedly lower DQI (0.03), highlighting the critical role of host presence in promoting seedling vigor during early development. Balasubramanian et al. (2018) reported that compatible hosts such as *Alternanthera sessilis* and *Sesbania grandiflora* significantly improved seedling quality through enhanced haustorial connections and nutrient uptake. Furthermore, Bose et al. (2022) emphasized that higher DQI values are closely associated with improved field performance, including greater survival and establishment potential.

The SQ serves as an important indicator of mechanical stability and resistance to lodging. Lower SQ values are desirable because they indicate seedlings with thicker stems relative to their height—an important characteristic of well-balanced and structurally robust transplants (Grossnickle and MacDonald, 2018). Among the treatments, T_1 recorded the lowest and most desirable SQ value (6.89), followed by T_5 (7.32), whereas the highest and least desirable value was observed in T_6 (8.76). These results suggest that the absence of a host leads to disproportionate shoot elongation relative to stem thickening, thereby reducing mechanical stability. Although differences in SQ between potting media were not statistically significant, S_2 again demonstrated slightly better performance (7.60) than S_1 (7.95), mirroring the trend observed for DQI. The consistently superior performance of T_1 and T_5 across both indices suggests that these host species promote improved biomass allocation, enhanced morphological balance, and potentially more efficient haustorial integration, all of which are critical for optimal nursery-stage development.

Practical nursery observations further corroborated these findings, revealing host-specific advantages and limitations under Punjab conditions. *Alternanthera sessilis* emerged as the most practical and sustainable host because of its non-thorny growth habit, ease of management, and consistent support for vigorous shoot proliferation. In contrast, *Casuarina* spp., despite their rapid growth, developed coarse root systems with limited surface-level fibrous roots. *Lawsonia inermis* exhibited poor synchrony with the early growth requirements of sandalwood because of its slow initial development. *Mimosa pudica*, although effective in promoting biomass accumulation, was thorny and exhibited invasive tendencies, thereby complicating routine nursery operations. *Cajanus cajan* improved root development and seedling survival; however, its high susceptibility to aphid and pod borer infestations under local conditions reduced its reliability as a consistent nursery host.

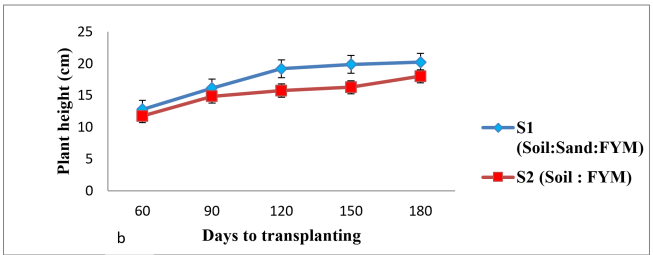

Figure 3: Bars represent the mean value; error bars indicate ±SE

CONCLUSION

It may be concluded that both potting medium and host species significantly influence the early growth and quality of *sandalwood* seedlings. Among the combinations tested, S_1 (Soil:Sand:FYM-2:2:1 paired with either *Cajanus cajan* (T_5) or *Alternanthera sessilis* (T_1) resulted in higher survival rates, superior shoot growth, and improved overall seedling vigor. Although potting medium S_2 (Soil: FYM- 2:1) promoted slightly better root development, its overall performance in supporting shoot growth, and leaf development was comparatively lower than S_1. Thus, S_1+ T_5 or S_1 + T_1 combinations are recommended for producing well-balanced, vigorous, and high-quality sandalwood seedlings. Results also highlights that *Alternanthera sessilis*, a non-leguminous species, can serve as an effective alternative to the traditionally used leguminous host *Cajanus cajan*.

COMPLIANCE WITH ETHICAL STANDARDS

This article does not contain any research involving people as objects of research.

CONFLICT OF INTEREST

No conflict of interest exists among the authors of the research paper.

AUTHOR CONTRIBUTIONS

All authors have made substantial contributions: the conception and design of the study (NK, BS, RIS, HK), acquisition of data or analysis (HK, NK, BS,) and interpretation of data (HK, AS), drafting the article (HK, NK, BS).

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