



RESEARCH ARTICLE

Comparative response of leguminous and non-leguminous tree seedlings to organic amendments in nursery conditions

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Abstract

The successful implementation of agroforestry and afforestation initiatives depends on optimizing the vigor of early-stage seedlings. Despite the widespread use of conventional organic amendments, it is important to compare the effectiveness of contemporary bio-stimulants against standard practices. The study aimed to ascertain the effects of various soil organic amendments on the morphological development and nutritional status of commercially significant leguminous and non-leguminous tree species. A variety of organic amendments, including Cocopeat, Jeevamrutha, Vesicular Arbuscular Mycorrhizae (VAM), Microbial Consortium, and Farm Yard Manure (FYM) as a control, were used to cultivate two species of each leguminous (*Tamarindus indica*, *Pongamia pinnata*) and non-leguminous (*Sapindus mukorossi*, *Gmelina arborea*). Over the course of two years (2022-2023), morphological, nutritional, and soil physicochemical characteristics (Organic carbon (OC), Electrical conductivity (EC), Nitrogen (N), Phosphorus (P), Potassium (K)) were examined. To account for treatment heterogeneity, ANOVA and post hoc tests were used to assess the data. Jeevamrutha showed the highest effectiveness, considerably increasing growth (Legumes-38.48 %, non-legumes-18.50 %) compared to the control, and microbial consortium was the second most effective treatment. EC increased from 175 to 620 $\mu\text{S}/\text{cm}$, while organic carbon increased to 1.16 %, indicating a significant improvement in soil quality. Among the studied species, *P. pinnata* and *G. arborea* exhibited the most favourable response to the organic amendments. These findings demonstrate that Jeevamrutha is a sustainable, high precision alternative to conventional FYM in nursery management. Therefore, implementing these organic strategies into practice may greatly improve the long-term productivity and quality of seedlings in large-scale reforestation and agroforestry initiatives.

Keywords: agroforestry; Jeevamrutha; nutrient bioavailability; organic soil amendments; seedling vigor

Introduction

Globally, tree plantations cover 4 % of the world's forest area, which provide a variety of ecosystem services in addition to timber and other wood-derived products. In India, the national forest and tree cover now stands at 25.17 %, with trees outside forests (TOF) making up a substantial 3.41 % of the total. This demonstrates how important TOF is to grow the nation's green canopy (1). Tree plantations are growing rapidly under the National Mission for a Green India, which aims to improve the quality of forests and ecosystem services. This initiative is essential for preventing soil degradation and maintaining soil health, particularly in ecologically challenged regions like Punjab (2). The rapidly growing human population is exerting immense pressure on natural resources, leading to a shortage of timber and wood-based products. In India, 70-80 % of industrial wood is provided by fast-growing TOF, mostly through specialized agroforestry and farm forestry techniques (3).

To improve output and meet growing demand, the use of synthetic fertilizers increased significantly, a trend rooted in the Green Revolution (4). However, this resulted in reduced efficiency and the emergence of nutrient deficiencies, which posed a threat to

both human health and the environment. Many Indian soils have steadily lost almost all the essential nutrients required by plants (5), thereby necessitating sustainable practices to maintain ecological balance and preserve biodiversity.

Organic farming technique offers a viable alternative to conventional nursery practices by fostering soil biological activity and reducing synthetic inputs. These approaches promote sustainable seedling production in forest nurseries. However, few empirical comparisons among bio-based amendments have been conducted. High-quality potting media provides essential nutrients that enhance root architecture and field establishment (6). A cost-effective way to increase the growth and productivity of different tree species is to formulate a soil mixture especially for nursery applications. Using such organic amendments improves soil quality and creates an atmosphere that is ideal for seedling development (7). Despite being widely used, conventional FYM often releases nutrients slowly and unevenly, particularly for micronutrients. These limitations are addressed by contemporary organic amendments such as Jeevamrutha, cocopeat, VAM, or microbial consortia, while remaining environmentally safe. These flexible, affordable alternatives serve as effective substitutes for FYM, ultimately

improving soil fertility and sustainability.

Jeevamrutha is a fermented bio-stimulant that boosts rhizosphere activity and root development by providing microbial enhancers and growth promoters (8). In the soil, VAM improves mineral uptake by increasing the roots' absorption area and helps plant survival by mitigating stress through symbiosis (9). Cocopeat lowers the bulk density while increasing soil organic carbon and improving water retention (10). By converting bound nutrients to available form, rhizosphere microbial consortia function as biofertilizers, improving nutrient use efficiency (11). Each bio-input has a distinct composition and purpose; thus, they likely affect seedling development through different pathways. Nevertheless, no comprehensive study of their comparative performance under nursery conditions currently exists.

The primary goal in forest nurseries is to produce robust and superior-quality seedlings. However, this objective has been hindered by slow growth and poor seedling quality resulting from insufficient microbial activity and nutrient availability (12). High-quality planting material is crucial for large-scale regeneration, as it preserves soil fertility and ensures superior tree phenotypes (13). This challenge can be addressed by formulating suitable organic amendments for nursery settings. Applying the right quantity of manure accelerates seedlings' growth and development (14). Nurseries may improve both seedling quality and development by focusing on the best organic amendments, which would ultimately lead to successful long-term soil health and large-scale production.

In light of the above, this study assesses the relative efficacy of different organic amendments versus conventional FYM, including Microbial consortium, VAM, Cocopeat, and Jeevamrutha. The main objective is to evaluate their effects on the morphological development and nutritional properties of soil for selected leguminous and non-leguminous tree species within a nursery setting. Native species like *Tamarindus indica* L., *Pongamia pinnata* (L.), *Sapindus mukorossi* Gaertn. nd *Gmelina arborea* Roxb. Ex. Sm. are included in the research. The aim is to identify the most effective organic treatments for sustainable nursery production.

Materials and Methods

Experimental site and design

The experiment was conducted at the Research Farm, Department of Forestry and Natural Resources, Punjab Agricultural University, Ludhiana. Growth and nutritional analysis were carried out at the

Department of Botany, Department of Soil Science and Department of Forestry and Natural Resources respectively. Two major leguminous species, viz., *Tamarindus indica* and *Pongamia pinnata* and two non-leguminous spp, viz., *Sapindus mukorossi* and *Gmelina arborea*, were selected for the investigation. The seeds were sown on raised beds (2 × 4 m). Seed germination commenced after 14-16 days, and 6-week-old seedlings at the six to seven-leaf stage, exhibiting uniform size and vigor, were selected and transplanted into uniform polybags (20 × 18 cm) in mid-July. The experiment comprised five different organic treatments (Table 1) with three replications, each containing 10 seedlings per replication for each species. The seedlings were maintained at a spacing of 40 × 30 cm for two consecutive years (2022 and 2023). The initial characteristics of the soil were also analyzed prior to the commencement of the experiment and after mixing with the soil (Table 2). For statistical analysis, each seedling within a replication was considered an independent functional replicate to account for intra-treatment variation. Data obtained from both years were pooled and averaged for analysis.

The effect of different treatments was evaluated by recording observations on various growth and nutrient parameters, viz., plant height, total biomass and nutrient analysis (N, P and K). To assess the periodic changes induced by the application of organic amendments on the morphological and nutritional status of the studied tree seedlings, observations were recorded at three and six months after transplantation during each consecutive year. These observation periods were selected to prevent the root system from emerging from the transplanted polybags.

Growth parameters

Plant height of the seedlings was measured from the root tip to the apex of the apical bud using a measuring tape. Dry biomass was recorded at both observation intervals using independent plant samples, as the measurements required destructive harvesting of the entire plants. An electronic balance was used to weigh the biomass after plant samples had been completely dried in a hot-air oven.

Plant nutrient estimation

The total nitrogen (N) content was estimated using the Kjeldahl method (15). the. For the determination of P and K, plant samples were digested using a diacid mixture (Nitric acid and perchloric acid). Pcontent was estimated using the Vanadomolybdenophosphoric reagent method (16). The flame photometer was used to determine

Table 1. Detail description of treatments

Treatments	Application	Composition
C (Control)	Soil and FYM were mixed	1:0.25
T ₁ (Cocopeat)	Soil and cocopeat were mixed	1: 0.25
T ₂ (Jeevamrutha)	400mL of Jeevamrutha was applied every 2 weeks near the root zone per plant when the soil was wet.	10 kg- cow dung, 10 L cow urine, 2 kg- jaggery, 2 kg- pulse flour and a handful of soil and the total volume was made up to 200 L (25).
T ₃ (VAM)	4g VAM per kg of soil was added	VAM: Mycorrhizal spores of <i>Glomus mosseae</i> , <i>Glomus intraradices</i>
T ₄ (Microbial consortium)	4g consortium per kg of soil was added	Microbial consortium composition: <i>Azotobacter crocucum</i> , <i>Bacillus subtilis</i> and <i>Pseudomonas</i> sp.

Table 2. Characteristics of the organic material used

Treatment /Soil properties	Control (C)	Cocopeat (T ₁)	Jeevamrutha (T ₂)	VAM (T ₃)	Microbial consortium (T ₄)
pH	7.65	8.11	7.75	7.78	7.67
EC (dS/cm)	0.105	0.134	0.268	0.179	0.196
OC (%)	0.34	0.41	0.87	0.53	0.66
Available N (kg/ha ⁻¹)	32.12±0.06	53.12±0.14	87.99±0.10	68.81±0.08	77.04±0.11
Available P (kg/ha ⁻¹)	20.10±0.00	22.13±0.00	38.90±0.00	27.58±0.00	32.87±0.00
Available K (kg/ha ⁻¹)	55.67±0.06	78.12±0.10	132.11±0.06	89.20±0.05	92.33±0.08

the K content (17). All nutrient contents were expressed on a dry matter basis.

Soil nutrient estimation

Soil pH was determined in a soil-to-water suspension using a digital pH meter (17). EC of the soil samples was assessed using a conductivity bridge after equilibration of the soil-water (1:2) suspension for 24 hr. Organic carbon content was determined using Walkley and Blacks' method (18).

Macro nutrients, such as available N in the soil, were determined using the alkaline potassium permanganate method (19). Available P was estimated using the Kruse method (20), and the extract was measured at 660 nm; the P content was calculated from the standard curve. Available K in the soil was determined using neutral ammonia acetate (21).

Biological activities, including alkaline phosphatase (AKP), Dehydrogenase (DHA) and total microbial count (TMC), were measured (22–24).

Statistical analysis

The experimental data, including growth, biochemical and nutrient parameters, were statistically analyzed using two-way ANOVA in SPSS version 16. Before analysis, the data were subjected to the Shapiro-Wilk and Levenes' test to verify the assumptions of normality and homogeneity of variance respectively. Tukeys' HSD

(Honestly Significant Difference) post-hoc test was applied to compare means at a 5 % significance level ($p \leq 0.05$).

The statistical results, including the F-statistic, degrees of freedom and exact p-values are reported to ensure transparency and scientific rigor (Supplementary Table 1–4). Standard errors of the calculated means were determined using Microsoft Excel 2016.

Results

Effect of organic treatments on morphological parameters

The response to the organic amendments was consistent across both years; therefore, pooled data were used for the present analysis. Three and six months after transplantation, Jeevamrutha (T_2) exhibited the highest growth across all tree species (Fig. 1). Among the leguminous species, *T. indica* showed a 38.48 % increase in plant height, whereas *G. arborea* recorded an 18.50 % increase among the non-leguminous species under T_2 treatment by the end of the experiment.

Plant biomass in the T_2 treatment was significantly higher ($p < 0.05$) than that in the other treatments and control. Under Jeevamrutha, microbial consortium, VAM and cocopeat treatment, the biomass of *P. pinnata* increased by 14.18 %, 13.98 %, 8.61 % and 3.45 % respectively.

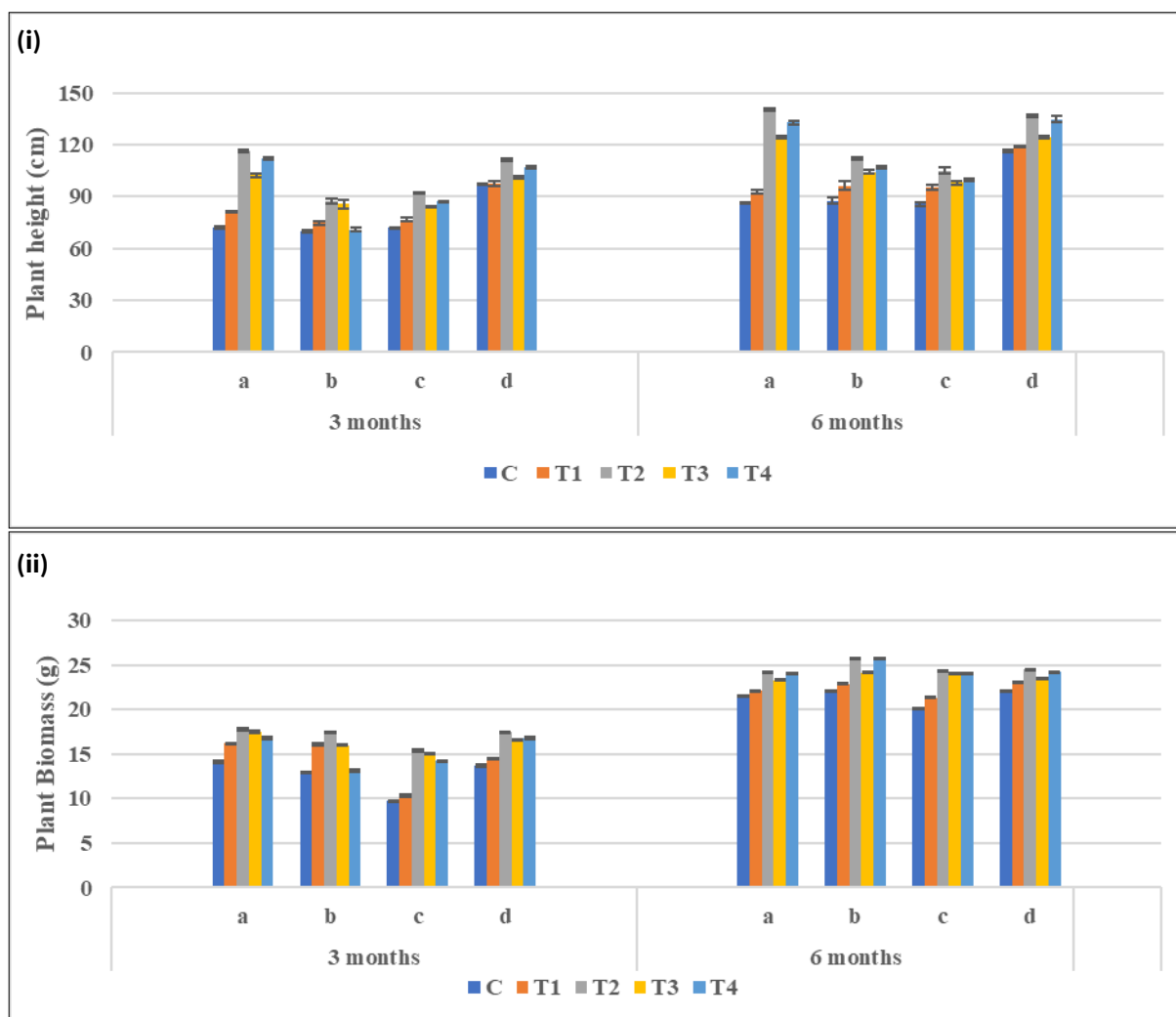


Fig.1. Effect of organic treatments on i) plant height (cm), ii) total biomass (g)

(a- *Tamarindus indica*, b- *Pongamia pinnata*, c- *Sapindus mukorossi*, d- *Gmelina arborea*, C- Control, T1- Cocopeat, T2- Jeevamrutha, T3- VAM, and T4- Microbial consortium).

Effect of organic treatments on nutrients in the whole plant

Jeevamrutha (T₂) resulted in the highest accumulation of macronutrients (N, P and K) in all species at both observation intervals (Table 3, 4 and 5). The plant NPK content followed the decreasing order of T₂>T₄>T₃>T₁>C. By the end of the experiment, *P. pinnata* exhibited the highest macronutrient content among the leguminous species. At the same time, *G. arborea* outperformed the other non-leguminous species.

Effect of organic treatments on pH, EC, OC and soil nutrients

The organic treatments exerted an alkaline effect on the soil, with pH values ranging from 8.30 to 8.80. EC ranged from 175 to 595 $\mu\text{S}/\text{cm}$; with Jeevamrutha recording the highest EC across all species (Fig. 2). Jeevamrutha (T₂) also resulted in the highest OC content in both legumes (1.28 %) and non-legumes (1.10 %), followed by microbial consortium, VAM and cocopeat treatment. On the other hand, the control recorded the lowest OC values among all species. Soil pH, EC and OC were measured at the end of the experiment.

At the termination of the experiment, T₂ maintained the maximum available NPK (Table 6, 7 and 8). Specifically, available nitrogen increased by 32.18 % compared to initial levels (Table 2). Available P reached a maximum of 87.32 kg/ha⁻¹ in legumes and 72.13 kg/ha⁻¹ in non-legumes. Similarly, T₂ yielded the highest available K content, reaching 296.24 kg/ha⁻¹ in legumes and 249.08 kg/ha⁻¹ in non-legumes.

Furthermore, Jeevamrutha enhanced soil biological activities more effectively than all other treatments and the control, including AKP, DHA and TMC (Table 9).

Discussion

Jeevamrutha (T₂) outperformed conventional FYM and other amendments across all examined parameters, indicating that its fermented liquid composition speeds up nutrient mobilization. This readily available carbon substrates present in Jeevamrutha enhance microbial proliferation and enzymatic activity, thereby increasing the rate of organic matter decomposition and nutrient mineralization. The comparatively superior performance of Jeevamrutha over the microbial consortium may be due to its composite nature, which not only serves as a source of beneficial microorganisms but also acts as a carrier of readily available organic substrates and nutrients. These components improve nutrient mineralization and availability to plants through rapid microbial growth, enhanced enzymatic activity and stimulation of native soil microflora (25).

Jeevamrutha functions as a powerful bio-stimulant compared to solid amendments, wherein cow urine offers easy accessibility of N and growth-promoting factors, while cow dung provides a concentrated microbial inoculum (26). This synergy probably has a priming effect in the rhizosphere, speeding up the organ development and increasing leaf area, which ultimately enhances the photosynthetic efficiency (27, 28).

Table 3. Nitrogen (%) in composite sample

Parameter	Sp./T	Month	Leguminous species		Non-leguminous species	
			<i>Tamarindus indica</i>	<i>Pongamia pinnata</i>	<i>Sapindus mukorossi</i>	<i>Gmelina arborea</i>
Nitrogen (%) composite sample	C	6	1.75 ^{±0.02}	1.98 ^{gh} ±0.01	1.57 ^{jk} ±0.01	1.73 ^{ghi} ±0.01
		3	1.63 ^{ijk} ±0.04	1.74 ^{hij} ±0.04	1.46 ^{kl} ±0.04	1.47 ^{ikl} ±0.03
	T ₁	6	1.90 ^{hi} ±0.01	2.06 ^{efg} ±0.00	1.72 ^{hi} ±0.02	1.86 ^{efg} ±0.02
		3	1.73 ^{hij} ±0.05	1.86 ^{efg} ±0.03	1.56 ^{ijk} ±0.02	1.59 ^{hijk} ±0.05
	T ₂	6	2.39 ^b ±0.03	2.60 ^a ±0.01	2.27 ^{ab} ±0.02	2.38 ^a ±0.01
		3	2.36 ^b ±0.04	2.64 ^a ±0.03	2.22 ^b ±0.04	2.39 ^a ±0.04
	T ₃	6	1.97 ^{gh} ±0.01	2.39 ^b ±0.00	1.89 ^{ef} ±0.00	2.07 ^{cd} ±0.02
		3	1.79 ^{gh} ±0.02	2.03 ^{de} ±0.03	1.67 ^{ghi} ±0.04	1.82 ^{ef} ±0.05
	T ₄	6	2.09 ^{ef} ±0.02	2.36 ^b ±0.01	1.96 ^{de} ±0.02	2.12 ^c ±0.02
		3	1.87 ^{gh} ±0.04	2.18 ^{cd} ±0.02	1.75 ^{fg} ±0.03	1.96 ^d ±0.04

Table 4. Phosphorus (%) in composite sample

Parameter	Sp./T	Month	Leguminous species		Non-leguminous species	
			<i>Tamarindus indica</i>	<i>Pongamia pinnata</i>	<i>Sapindus mukorossi</i>	<i>Gmelina arborea</i>
Phosphorus (%) composite sample	C	6	0.39 ^{de} ±0.00	0.39 ^e ±0.00	0.29 ^f ±0.00	0.36 ^{def} ±0.00
		3	0.30 ^{±0.00}	0.33 ^{fg} ±0.00	0.24 ^g ±0.00	0.25 ^g ±0.00
	T ₁	6	0.39 ^g ±0.00	0.39 ^g ±0.00	0.33 ^{gh} ±0.00	0.36 ^{def} ±0.00
		3	0.33 ^{gh} ±0.00	0.34 ^f ±0.00	0.25 ^g ±0.00	0.29 ^d ±0.00
	T ₂	6	0.42 ^b ±0.00	0.43 ^a ±0.00	0.38 ^{bcd} ±0.00	0.39 ^{abc} ±0.00
		3	0.40 ^b ±0.00	0.43 ^a ±0.01	0.37 ^b ±0.00	0.37 ^b ±0.01
	T ₃	6	0.41 ^{bc} ±0.00	0.43 ^a ±0.00	0.35 ^{ef} ±0.00	0.30 ^{ab} ±0.00
		3	0.36 ^d ±0.00	0.40 ^b ±0.01	0.30 ^d ±0.00	0.40 ^d ±0.00
	T ₄	6	0.41 ^c ±0.00	0.43 ^a ±0.00	0.37 ^{cde} ±0.00	0.34 ^{cde} ±0.00
		3	0.36 ^d ±0.00	0.40 ^b ±0.00	0.30 ^d ±0.00	0.37 ^c ±0.00

Table 5. Potassium (%) in composite sample

Parameter	Sp./T	Month	Leguminous species		Non-leguminous species	
			<i>Tamarindus indica</i>	<i>Pongamia pinnata</i>	<i>Sapindus mukorossi</i>	<i>Gmelina arborea</i>
Potassium (%) composite sample	C	6	3.02 ^{hi} ±0.05	3.06 ^{hi} ±0.04	2.79 ^j ±0.07	2.96 ^{def} ±0.09
		3	2.12 ^h ±0.15	2.29 ^{gh} ±0.05	1.89 ^h ±0.20	2.16 ^{gh} ±0.10
	T ₁	6	3.36 ^{efg} ±0.04	3.46 ^{defg} ±0.04	3.16 ^{bcd} ±0.04	3.69 ^{abcd} ±0.23
		3	2.59 ^{efgh} ±0.14	2.99 ^{def} ±0.15	2.49 ^{defg} ±0.15	2.52 ^{cdefg} ±0.05
	T ₂	6	3.59 ^{abcde} ±0.04	3.86 ^a ±0.02	3.86 ^a ±0.05	4.02 ^a ±0.07
		3	3.59 ^{abc} ±0.11	3.96 ^a ±0.20	3.16 ^{ab} ±0.17	3.29 ^{ab} ±0.15
	T ₃	6	3.29 ^{fgh} ±0.02	3.52 ^{cdefg} ±0.02	3.59 ^{abcde} ±0.05	3.72 ^{abc} ±0.05
		3	2.49 ^{fgh} ±0.15	2.76 ^{efg} ±0.37	2.86 ^{abcde} ±0.10	3.06 ^{abc} ±0.20
	T ₄	6	3.56 ^{bcd} ±0.05	3.72 ^{abcd} ±0.04	3.62 ^{abcde} ±0.34	3.71 ^{abc} ±0.08
		3	3.09 ^{cde} ±0.13	3.32 ^{bcd} ±0.11	3.06 ^{abc} ±0.10	3.02 ^{abcd} ±0.14

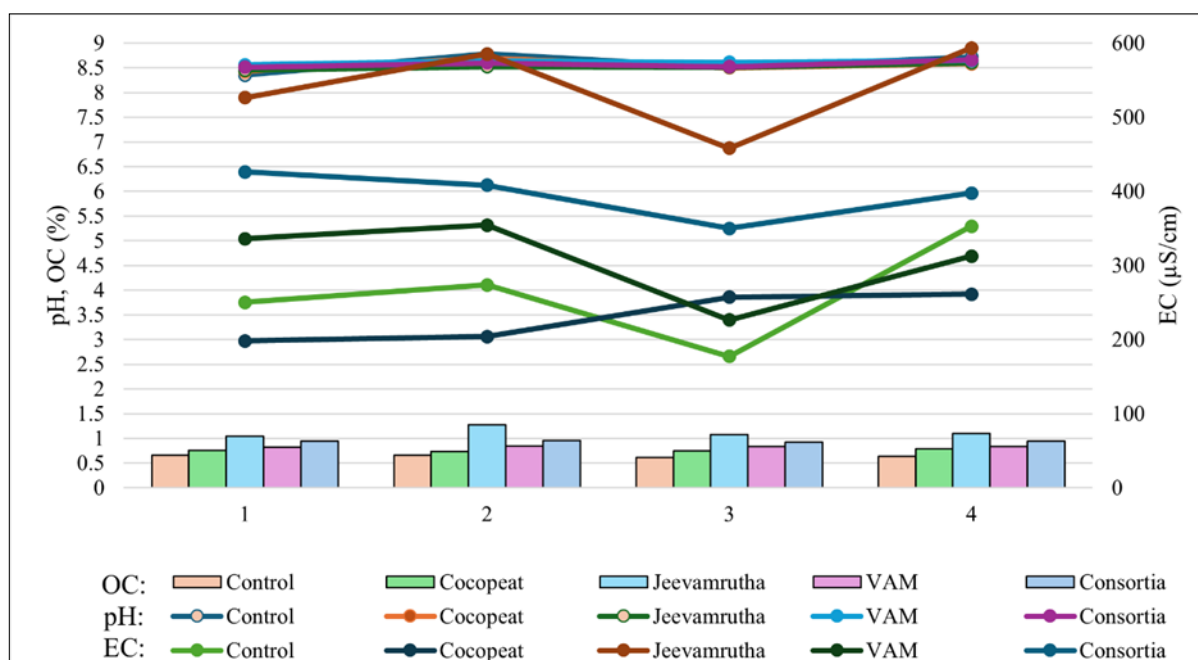


Fig. 2. Effect of organic treatments at the end of the experiment on pH, EC and OCo of soil.

(a- *Tamarindus indica*, b- *Pongamia pinnata*, c- *Sapindus mukorossi*, d- *Gmelina arborea*, C- Control, T1- Cocopeat, T2- Jeevamrutha, T3- VAM, and T4- Microbial consortium).

Table 6. Available nitrogen in soil (kg/ha^{-1})

Parameter	Sp./T	Month	Leguminous species		Non-leguminous species	
			<i>Tamarindus indica</i>	<i>Pongamia pinnata</i>	<i>Sapindus mukorossi</i>	<i>Gmelina arborea</i>
Nitrogen (kg/ha^{-1}) soil sample	C	6	79.97 ^{def} ±0.35	104.70 ^{bcd} ±0.86	88.50 ^{bc} ±0.50	55.61 ^c ±0.21
		3	112.87 ^{ghi} ±0.10	133.78 ^{defghi} ±0.21	121.96 ^{def} ±0.21	101.06 [±] 0.18
	T ₁	6	130.15 ^{abc} ±0.36	143.60 ^{ab} ±0.72	98.34 ^{bc} ±0.72	102.11 ^b ±0.32
		3	158.86 ^{bcd} ±0.13	183.95 ^{abc} ±0.12	126.14 ^{cde} ±0.22	138.69 ^{cde} ±0.23
	T ₂	6	146.67 ^{ab} ±0.72	138.31 ^{ab} ±0.58	183.95 ^a ±0.25	167.29 ^a ±0.25
		3	189.22 ^{ab} ±0.08	189.18 ^{ab} ±0.10	209.04 ^a ±0.14	183.95 ^{ab} ±0.16
	T ₃	6	116.70 ^{abcde} ±0.60	120.88 ^{abcd} ±0.72	82.46 ^{bc} ±0.25	84.04 ^{bc} ±0.27
		3	150.50 ^{bcd} ±0.05	158.86 ^{bcd} ±0.08	123.78 ^{cde} ±0.20	111.23 ^{ef} ±0.14
	T ₄	6	113.60 ^{abcde} ±0.72	128.33 ^{abc} ±0.82	110.88 ^b ±0.25	85.79 ^{bc} ±0.72
		3	204.86 ^a ±0.18	171.41 ^{abcd} ±0.08	145.47 ^{bcd} ±0.17	148.86 ^{bcd} ±0.11

Table 7. Available phosphorus in soil (kg/ha^{-1})

Parameter	Sp./T	Month	Leguminous species		Non-leguminous species	
			<i>Tamarindus indica</i>	<i>Pongamia pinnata</i>	<i>Sapindus mukorossi</i>	<i>Gmelina arborea</i>
Phosphorus (kg/ha^{-1}) soil sample	C	6	28.35 ^h ±0.68	20.26 [±] 0.39	10.11 [±] 0.50	15.26 ^{ij} ±0.38
		3	32.25 ^{kl} ±0.05	45.20 [±] 0.01	22.53 ^{ij} ±0.05	38.41 [±] 0.11
	T ₁	6	46.22 ^e ±0.40	65.15 ^{abc} ±0.53	20.87 ^{hi} ±0.66	35.18 ^{efgh} ±0.87
		3	50.51 ^h ±0.06	81.57 ^{bc} ±0.05	33.09 ^{hi} ±0.06	52.71 ^h ±0.13
	T ₂	6	60.18 ^{bc} ±0.46	87.32 ^a ±0.46	48.56 ^{de} ±0.78	72.13 ^{ab} ±0.41
		3	85.20 ^{abc} ±0.08	89.55 ^a ±0.06	60.46 ^{bcd} ±0.05	73.68 ^d ±0.17
	T ₃	6	59.138 ^{bcd} ±0.56	51.21 ^{bcd} ±0.67	50.05 ^{hi} ±0.72	62.35 ^b ±0.29
		3	75.13 ^{cd} ±0.10	77.81 ^{bcd} ±0.03	33.85 ^{cde} ±0.05	87.68 ^{ab} ±0.14
	T ₄	6	42.15 ^{ef} ±0.74	32.75 ^{gh} ±0.23	42.35 ^{ij} ±0.41	50.22 ^{cde} ±0.07
		3	58.47 ^{fgh} ±0.03	68.68 ^e ±0.08	37.15 ^{efg} ±0.06	62.52 ^{ef} ±0.11

Jeevamruthas' fermented liquid is rich in vital amino acids and growth-promoting compounds, providing a metabolic advantage to the seedlings (29). This biochemical composition greatly increases the nutrient-absorption zone for the seedling by directly promoting the development of the root system and improving the uptake efficiency of the plant. Although the microbial consortium had similar outcomes to Jeevamrutha in a particular character, such as plant height, possibly due to enhanced P solubilization and mobilization (30). This effect is still more limited in scope compared to Jeevamruthas' broad-spectrum bio-stimulatory impact.

Interestingly, VAM exhibited lower effectiveness under nursery conditions despite the favorable performance of the

microbial consortium. This difference may be attributed to host dependency and the temporal lag associated with mycorrhizal colonization, which may not respond as rapidly as the immediate nutrient availability provided by fermented liquid amendments. Furthermore, VAM infection rates can occasionally be suppressed by high initial nutrient availability in the nursery (31,32). Moreover, the short-term duration of the nursery experiment may not have provided sufficient time for effective root colonization and establishment of symbiosis.

A synergistic process of nitrogen mobilization is further supported by the enhanced nutrient status observed in both the soil and the seedlings. Jeevamrutha substantially improves the soils' metabolic capacity by introducing a microbial inoculum into the

Table 8. Available potassium in soil (kg/ha⁻¹)

Parameter	Sp./T	Month	Leguminous species		Non-leguminous species	
			<i>Tamarindus indica</i>	<i>Pongamia pinnata</i>	<i>Sapindus mukorossi</i>	<i>Gmelina arborea</i>
Potassium (kg/ha ⁻¹) soil sample	C	6	152.07 ^h ±0.32	165.06 ^{gh} ±0.33	108.73 ^{gh} ±0.29	96.18 ^h ±0.94
		3	207.44 ^{jk} ±0.05	202.18 ^k ±0.16	167.49 ^g ±0.14	128.01 ^j ±0.11
	T ₁	6	170.32 ^{feh} ±0.28	199.17 ^{cd} ±0.18	165.26 ^{cd} ±0.34	107.61 ^h ±0.43
		3	222.27 ^{ijk} ±0.09	238.59 ^{ghi} ±0.20	188.98 ^{de} ±0.17	161.92 ^{gh} ±0.16
	T ₂	6	256.33 ^b ±0.53	296.24 ^a ±0.47	249.08 ^a ±0.78	234.00 ^{ab} ±0.76
		3	258.11 ^{cdef} ±0.10	283.64 ^b ±0.05	260.36 ^a ±0.20	230.76 ^b ±0.20
	T ₃	6	181.90 ^{def} ±0.26	209.82 ^c ±0.49	174.63 ^c ±0.86	125.90 ^{fg} ±0.22
		3	242.28 ^{efghi} ±0.12	274.56 ^{bc} ±0.15	231.30 ^b ±0.21	192.85 ^b ±0.28
	T ₄	6	173.11 ^{efgh} ±0.13	178.91 ^{defg} ±0.58	164.29 ^{cd} ±0.61	138.25 ^{ef} ±0.16
		3	232.36 ^{ghi} ±0.18	271.90 ^{bcd} ±0.10	214.97 ^c ±0.10	182.57 ^{ef} ±0.08

Table 9. Effect of organic treatments on biological activity in the soil of tree seedlings

Parameter	Sp./T	Leguminous species		Non-leguminous species	
		<i>Tamarindus indica</i>	<i>Pongamia pinnata</i>	<i>Sapindus mukorossi</i>	<i>Gmelina arborea</i>
DHA (µg TPF g ⁻¹ soil h ⁻¹)	C	3.42 ^{fg} ±0.05	1.22 ⁱ ±0.10	2.82 ^{ghi} ±0.06	2.64 ^{hi} ±0.08
	T ₁	3.86 ^g ±0.09	2.77 ^{gh} ±0.11	3.15 ^{fg} ±0.06	2.91 ^{gh} ±0.03
	T ₂	5.33 ^b ±0.13	4.43 ^{cd} ±0.08	5.57 ^a ±0.13	4.37 ^{bc} ±0.15
	T ₃	4.53 ^{cd} ±0.07	3.13 ^{fg} ±0.05	3.88 ^d ±0.05	3.21 ^{ef} ±0.10
	T ₄	5.09 ^{bc} ±0.10	2.87 ^g ±0.04	4.23 ^{cd} ±0.03	3.49 ^e ±0.12
AKP (µg PNP g ⁻¹ soil h ⁻¹)	C	29.40 ^{cdef} ±0.03	17.63 ^f ±0.06	30.83 ^{def} ±0.03	14.43 ⁱ ±0.04
	T ₁	32.98 ^{bcd} ±0.05	28.23 ^{def} ±0.06	32.56 ^{def} ±0.03	34.33 ^{cde} ±0.02
	T ₂	41.63 ^{bcd} ±0.08	44.68 ^{ab} ±0.05	58.40 ^a ±0.08	48.80 ^b ±0.09
	T ₃	36.20 ^{bcd} ±0.04	29.07 ^{cdef} ±0.03	34.05 ^{de} ±0.03	34.96 ^{cd} ±0.06
	T ₄	40.06 ^{bcd} ±0.06	42.33 ^{bcd} ±0.02	36.83 ^{cd} ±0.02	35.83 ^{cd} ±0.07
TMC (CFU g ⁻¹ soil)	C	69.33 ^{hi} ±0.04	81.33 ^g ±0.02	51.00 ^k ±0.08	78.66 ^{ghi} ±0.09
	T ₁	80.33 ^g ±0.05	92.33 ^{ef} ±0.06	62.00 ^{jk} ±0.08	89.66 ^{defg} ±0.04
	T ₂	102.33 ^{cd} ±0.07	114.33 ^{ab} ±0.07	84.00 ^{gh} ±0.06	111.67 ^{ab} ±0.06
	T ₃	87.33 ^{fg} ±0.03	99.33 ^{cde} ±0.07	69.00 ^{ij} ±0.03	96.66 ^{cdef} ±0.05
	T ₄	93.33 ^{def} ±0.08	85.67 ^{fg} ±0.04	75.00 ^{hij} ±0.09	102.67 ^{bcd} ±0.06

rhizosphere (29). The increased biological activities observed in the soil under Jeevamrutha treatment indicate intensified microbially mediated nutrient transformations, which play a crucial role in converting complex nutrient forms into the available form for plants.

However, a reduction in available macronutrient content was observed during the second observation interval compared to the first, primarily due to progressive nutrient uptake by plants, resulting in depletion of soil nutrient reserves and increased accumulation within plant tissues (33). Nevertheless, the relatively low nitrogen levels observed in some samples or treatments suggest that additional processes, including volatilization, leaching and microbial immobilization, also influence nutrient dynamics, especially in nurseries with regular irrigation (34,35). Moreover, changes in microbial activity and substrate availability may lead to a decline in measurable nitrogen (36,37,38). These findings demonstrate that the availability of nutrients is governed by a dynamic balance between uptake by plant and soil microbial processes rather than by a single mechanism (39).

The positive association between soil organic carbon and enzymatic activity reported in the literature highlights an important practical implication: the availability of high-quality organic substrates is closely linked with the biological fertility of nursery soils. In contrast, soil pH exhibited a non-significant effect among treatments, suggesting that the applied organic amendments exerted only a limited influence on soil pH during the experimental period. This may be attributed to the soils' buffering capacity, which prevents changes in pH despite external influences (40–42).

However, compared with the control, treated soils showed increased organic carbon content, likely due to the addition of organic substances and increased microbial activity, thereby contributing to carbon accumulation and improved soil structure. These results are consistent with previous research showing

minimal short-term changes in soil pH but considerable increase in soil organic carbon following the application of organic addition (43, 44).

In the conclusion, the present study demonstrates that managing the microbial-enzymatic relationship is more important than relying solely on conventional nutrient inputs when switching from conventional to fermented liquid organic inputs. Such action can substantially enhance the rate of nutrient cycling and, in turn, speed up nursery production cycles (45).

Conclusion

Tree seedlings responded differently to the various organic amendments applied during the experiment. The results indicate that organic amendments, particularly Jeevamrutha, were more effective than conventional FYM in enhancing seedling growth and quality under nursery conditions. These findings suggest that liquid organic amendments may be more effective than solid manure in improving soil characteristics and nutrient availability, thereby promoting better plant performance.

The observed differences among species are likely to be due to variation in their genetic makeup, nutritional requirements and evolutionary adaptations, all of which may influence plants interactions with soil biota. The superior performance of Jeevamrutha may be linked to its potential to accelerate nutrient transformation and uptake through enhanced microbial activity.

According to the findings, Jeevamrutha has demonstrated its potential as a reliable organic amendment, showing consistent effectiveness across all examined species. Although the results are promising, further evaluation of these treatments under varied field conditions would strengthen their practical applicability and support their use in a large-scale nursery plantation system.

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Authors' contributions

HK participated in data curation, investigation and writing the original draft, RS provided supervision, conceptualization and participated in carrying out methodology, AS participated in writing, reviewing and editing of the draft, ST participated in providing resources, writing, reviewing and editing of the draft. All authors have read and approved the final manuscript.

Compliance with ethical standards

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During the preparation of this work, HK and AS used ChatGPT to improve the language of the manuscript. After using this tool, the authors thoroughly reviewed and edited the content as needed and take full responsibility for the final version of the publication.

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