



Research article

The multifunctionality benefits of *Gmelina arborea* agroforestry systems: Insights into productivity, carbon sequestration, microbial ecology and economics in Central India

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Abstract

Agroforestry is increasingly recognized as a sustainable land use system in agriculture. To evaluate its effectiveness in terms of crop productivity, carbon sequestration, soil microbial activity, and economic returns, a study was carried out at Jawaharlal Nehru Krishi Vishwa Vidyalaya, Madhya Pradesh, Central India, during 2021-23. The experiment included eight treatment combinations: *Gmelina arborea* with pigeonpea (T₁), cowpea (T₂), and greengram (T₃); *G. arborea* as a sole crop (T₄); sole cropping of pigeonpea (T₅), cowpea (T₆), and greengram (T₇); and a control of open field having no plant (T₈). The *G. arborea* trees used in the study were 6 years old, spaced at 8.0 × 2.5 m. Crops grown in control conditions generally outperformed those under agroforestry systems in terms of yield. However, in terms of mean annual biomass production, the *G. arborea* + greengram combination produced the highest annual biomass. *G. arborea* + pigeonpea led in annual carbon sequestration, recording 3.082 and 3.088 tonnes per hectare in the first and second years, respectively, but remained at par with *G. arborea* + greengram. *G. arborea* + cowpea treatment supported the highest *rhizobium* counts (41.92 × 10⁷ cfu/g soil in year one and 43.81 × 10⁷ cfu/g soil in year two). Fungal populations were highest under the *G. arborea* + pigeonpea combination, while the *G. arborea* + greengram treatment showed the greatest abundance of bacteria and actinomycetes. The *G. arborea* + cowpea treatment delivered the highest economic returns in both years, though it was statistically on par with the *G. arborea* + greengram system. With regard to the multifunctional benefits point of view, *G. arborea* + greengram were a superior land use system over others tested. Overall, agroforestry systems generated significantly higher multifunctional benefits compared to sole cropping approaches.

Keywords: Agroforestry, Carbon sequestration, Cowpea, Economics, Green gram, Microbial status, Pigeonpea, Productivity

Introduction

Agroforestry, which integrates trees and shrubs with crops and/or livestock on the same land, offers a viable solution to numerous environmental and socio-economic challenges. This land use approach supports climate change mitigation (Ahirwal *et al.* 2022; Rathore *et al.*, 2025), enhances biodiversity, and strengthens the economic resilience of farming communities (Reang *et al.*, 2021; Jeecelee and Sahoo, 2022). It is closely aligned with global sustainability efforts, including the United Nations Sustainable Development Goals (SDGs) like SDG 2: zero hunger (food security through crops), SDG 13: climate action (carbon sequestration), SDG 15: life on

land (biodiversity conservation), SDG 1 and 8 (poverty reduction and economic growth) positioning it as a vital strategy in promoting environmentally sustainable and economically viable agriculture (Devi *et al.*, 2023). A key advantage of agroforestry is its role in addressing climate change (Thong *et al.*, 2023). Trees in these systems sequester carbon by absorbing atmospheric CO₂ through photosynthesis (Nair, 2013; Nath *et al.*, 2022), helping to lower greenhouse gas concentrations. Additionally, they improve soil carbon content, which mitigates the negative impacts of climate change, such as increased soil erosion, degradation, and extreme weather events (Jose, 2009; Devi *et al.*, 2023). Many studies have shown

that traditional agroforestry systems are very rich in tree diversity (Jeecelee and Sahoo, 2022) and domestication of a large variety of multipurpose trees (Jeecelee and Sahoo, 2022; Reang *et al.*, 2021). This diversification reduces financial risk and enhances farm profitability (Broadhead *et al.*, 2003; Sahoo *et al.*, 2012; Sahoo and Singh, 2015).

Agroforestry systems often require fewer chemical inputs, such as synthetic fertilizers and pesticides, which lowers production costs (Leakey *et al.*, 2012). Furthermore, the long-term integration of trees can increase farm resilience to market fluctuations and support sustainable livelihoods (Altieri *et al.*, 2015; Nath *et al.*, 2020; Thangjam *et al.*, 2023). Therefore, they are recognized as a land-use system that enhances both biodiversity and ecosystem services by promoting sustainability, resilience and productivity (Barbhuiya *et al.*, 2016; Devi *et al.*, 2023). The multi-strata system encourages species co-existence, maintaining better ecological balance, enhances local livelihoods and health care (Sahoo, 2009; Jeecelee and Sahoo, 2022). The agroforestry plant components are often rich in nutrients (Sahoo and Rocky, 2019). The high species diversity that performs complementary ecological functions results in higher productivity and sustainability and because of the multifunctional roles, agroforestry systems are preferred by marginalized farmers as an alternative land use in northeast India, where shifting cultivation still is a major land use practice (Singh and Sahoo, 2019; Nath *et al.*, 2020, 2021).

Gmelina arborea Roxb. ex Sm. (commonly known as gamar or white teak) is a fast-growing multipurpose tree widely used in agroforestry systems across tropical and subtropical regions, including India (Kumar *et al.*, 2017; Swamy *et al.*, 2003). *Gmelina*-based agroforestry systems are used as model agroforestry systems in central and eastern India for obtaining several ecological, economic and social benefits (Newaj *et al.*, 2007). The straight growth, manageable canopy and compatibility with many intercrops such as pigeon pea (*Cajanus cajan* (L.) Millsp), greengram (*Vigna radiata* (L.) R.Wilczek) and cowpea (*Vigna unguiculata* (L.) Walp.) make it easy to integrate into farming systems and ensure diversified production and enhance farmers' resilience against market and climate shocks (Tamang *et al.*, 2021). Further, these systems align with India's National Agroforestry Policy (2014) and SDGs on sustainable land use, climate action and poverty reduction (Rizvi *et al.*, 2011; Yadav, 2010). Studies carried out on this system report that *Gmelina arborea* is productive for wood/fuel and beneficial for carbon sequestration (Swamy and Puri, 2005) while allowing productive understory crops if spacing or management are appropriate (Vanlalhluna and Sahoo, 2008). Some past studies have demonstrated that these systems have good carbon stock potential (Swamy *et al.*, 2003; Swamy and Puri, 2005). However, there is a knowledge gap on the annual rate of biomass production, annual

carbon sequestration, economic return, quantification of soil health in terms of population of *rhizobium*, fungi, bacteria and actinomycetes in soil under *G. arborea*-based agroforestry systems.

The objective of the present study was to quantify the multifunctional benefits comprising economic, ecological and soil health aspects of *Gmelina arborea* based agroforestry systems. The work was focused on a fast growing timber species such as *G. arborea* with three remunerative pulse crops as intercrops like pigeonpea, cowpea, and greengram to boost farm incomes, enhance soil health, and contribute to greater carbon sequestration in central Indian conditions.

Materials and Methods

Study area: The present study was carried out during 2021–22 and 2022–23 at Jawaharlal Nehru Krishi Vishwa Vidyalaya (JNKVV), located in Jabalpur, Madhya Pradesh, central India. The experimental site is situated between latitudes 22°49' and 24°08' N and longitudes 78°21' and 80°58' E, at an elevation of 412 m above mean sea level. The region experiences a tropical semi-humid climate, characterized by hot, dry summers and cool, dry winters. The average annual rainfall is approximately 1350 mm, most of which occurs between mid-June and the end of September. The average maximum temperature during May–June ranges between 40 and 42°C, while the average minimum temperature during December–January falls between 5.3 and 6.1°C.

Experimental design: The trials consisted of eight treatments as shown in Table 1. *G. arborea* trees were 6-year in the first year of experimentation and 7-year old in the second year of experimentation and planted at 8.0 × 2.5 m spacing. The experiments were conducted under RBD with 5 replications over 2 years with identical treatments and layout. There were 40 plots, including 20 plots with trees and 5 open plots without plants. Each plot size was 80 m², hence the experimental area was 3200 m² containing 80 experimental trees of *G. arborea* and the area per treatment was 400 m². The physico-chemical properties of the soil of the experimental field at the beginning of the experiment are given in Table 2.

The recommended quantity of nutrients *viz.*, nitrogen, phosphorus, and potash (20:40:20 NPK Kg ha⁻¹) were given as a basal application through urea, single super phosphate, and muriate of potash, respectively. Before sowing of different agricultural crops, the seeds were treated with carbendazim @ 2-3 g per kg of seed to protect the seed against soil-borne diseases and *rhizobium* culture @ 2-3g per kg of seed for better establishment.

Sowing of different crops, namely pigeonpea (*Cajanus cajan* (L.) Millsp), greengram (*Vigna radiata* (L.) R.Wilczek) and cowpea (*Vigna unguiculata* (L.) Walp.) was carried out

Table 1. The treatments used in the present study

Treatment	Crop composition
T ₁	<i>G. arborea</i> + Pigeonpea
T ₂	<i>G. arborea</i> + Cowpea
T ₃	<i>G. arborea</i> + Greengram
T ₄	<i>G. arborea</i> (Sole crop)
T ₅	Pigeonpea (Sole crop)
T ₆	Cowpea(Sole crop)
T ₇	Green gram (Sole crop)
T ₈	Control (open blank land)

Table 2. Physico-chemical properties of the soil of the experimental field

S. No.	Particular	Analytical values	Category
A. Mechanical composition			
1.	Sand %	22.92	Sandy clay loam
2.	Silt %	21.31	
3.	Clay %	55.77	
B. Chemical composition			
1.	Organic carbon %	0.50	Medium
2.	Available N (kg/ha)	240.0	Low
3.	Available P (kg/ha)	15.6	Medium
4.	Available K (kg/ha)	226.0	Medium
5.	Soil pH	5.83	Acidic
6.	Electrical conductivity (dS/m)	0.13	High

manually on June 28, 2021, for the first season, and June 27, 2022, for the second season. The planting distances used were 40 × 20 cm for pigeonpea (variety TJT 501), 45 × 15 cm for cowpea (variety Madhur), and 30 × 10 cm for greengram (variety TJM 37). The weeds were removed from all plots at 30 to 35 days after sowing by manual weeding to keep the plots free from weed infestation. In the first year, greengram, cowpea, and pigeonpea were harvested on September 10, September 20, and December 10, 2021, respectively, once the pods had fully ripened and turned yellow. In the second year, harvesting occurred on September 8 for greengram, September 18 for cowpea, and December 8, 2022, for pigeonpea.

Estimation of grain yield, total tree and crop biomass: Grain yield per hectare was calculated by multiplying the yield from the net plot by a standard conversion factor, and results were expressed in quintals per hectare. The total biomass of *Gmelina arborea* trees, including both above- and below-ground portions, was estimated using the formula proposed by Swamy et al. (2003):

$$Y = a + bD,$$

where Y is the total biomass in kilograms, a = -2.421, b = 4.2551, and D represents the diameter at breast height (DBH) in centimeters. The mean annual biomass production was then obtained by dividing the total biomass by the age of the trees for each year of the study. Crop biomass was determined by uprooting sample plants and recording the dry weight of all plant parts. The system's total annual biomass production was calculated by summing the mean annual tree biomass with the seasonal crop biomass. Carbon sequestration in both crops and trees was estimated by applying a standard conversion factor of 0.5 to the biomass, following IPCC (2006) guidelines, and expressed in tonnes per hectare.

Soil sampling and microbial population analyses:

Soil samples were collected from each plot at 0 to 45 cm depth during crop harvest to assess microbial populations. The microbial analysis was performed using the serial dilution and spread plate method. For enumeration of *rhizobium*, bacteria, actinomycetes, and fungi, 10 g of soil were placed in flasks containing 90 mL of distilled water and shaken for 20 minutes to form a soil suspension. This suspension was serially diluted up to 10⁻⁸ to prepare solutions suitable for microbial population assessment.

The microbial load was calculated using the following formula and expressed as CFU

$$\text{CFU/g} = \frac{\text{No. of colony} \times \text{Inverse of dilution taken}}{\text{Volume of inoculum taken}}$$

Plating was done aseptically by transferring 1-mL of the appropriate dilution (ranging from 10⁻¹ to 10⁻⁸) into sterile Petri dishes, depending on the type of microorganism being quantified. Sterilized and centrifuged nutrient agar medium was then poured into each dish, which was gently swirled to ensure uniform distribution and allowed to cool. Each dilution was plated in triplicate to ensure accuracy. Specific media were used for the growth and identification of different microbial groups, including Caseinate Agar Medium for actinomycetes (Vijaykumar et al., 2009), Thornton's medium for total bacterial count (Thornton, 1992), Rose Bengal Streptomycin medium for fungi (Martin, 1950), and YEM (Yeast Extract Mannitol) medium for *Rhizobium* (Al-Mujahidy et al., 2013).

Economic analysis of agroforestry systems: The cultivation cost for each land-use system was estimated based on the various inputs required to grow crops and establish *Gmelina arborea* plantations on a per-hectare basis. Revenue from the different treatments was calculated using the Minimum Support Price for grains and the prevailing farm rate prices for stover and timber (Table 3).

Table 3. Minimum Support Price for grains and the prevailing farm rate for stover and timber (fuelwood)

Crop/tree	Price of year 1 (Rs/q)			Price of year 2 (Rs/q)		
	Grain	Stover	Fuel wood	Grain	Stover	Fuel wood
<i>Pigeonpea</i>	6300	100	-	6600	110	-
<i>Cowpea</i>	7275	100	-	7755	110	-
<i>Green gram</i>	7275	100	-	7755	110	-
<i>G. arborea</i>	-	-	1000			1100

The total income generated from grain yield, stover, and *G. arborea* wood was considered the Gross Monetary Return (GMR) per hectare. The annual wood value was derived from the average yearly biomass output. To determine the Net Monetary Return (NMR) per hectare for each land-use system, the respective cultivation cost was deducted from the corresponding GMR.

Data analyses: The data were analyzed following a pooled analysis of variance (ANOVA) over years, treating *treatment* as a fixed effect, *year* as a fixed effect, and *Blocks nested within year* as random effects. The interaction between *Treatment × Year (T×Y)* was explicitly included in the model. Prior to pooling, the homogeneity of error variances across years was tested and found to be non-significant, justifying the use of pooled analysis. In the pooled ANOVA, treatment effects were tested against the pooled error mean square, while *Year* and *T×Y* effects were tested against their respective appropriate error terms as per standard procedures for multi-year RBD experiments. The non-significant year effect observed for several variables indicates consistency of responses across years rather than an omission or mis-specification of the model. Importantly, the *T×Y* interaction was also non-significant for these variables, further supporting the stability of treatment effects across years and validating the pooled interpretation. For variables where *T×Y* interaction was significant, treatment means were interpreted separately by year.

Correlation between net monetary return and annual carbon sequestration was carried out (Pearson, 1920).

$$r = \frac{\sum xy - \frac{\sum x \sum y}{n}}{\sqrt{\sum x^2 - \frac{(\sum x)^2}{n}} \sqrt{\sum y^2 - \frac{(\sum y)^2}{n}}}$$

Where, x = Net monetary return; y = Annual carbon sequestration; n = Number of observations; Association among soil microbes was estimated by using Kendall's Coefficient of Concordance (W) (Kendall and Babington Smith, 1939).

$$W = \frac{\sum Ri^2 - \frac{(\sum Ri)^2}{N}}{\frac{k^2}{12} N(N^2 - 1)}$$

Where, K= Different microbes; $\sum Ri$ = Sum of each landuse systems; N= Number of observations

Hierarchical cluster analysis based on the Euclidean distance and average linkage was used to cluster different land use systems with respect to the population of four microbes (Malika *et al.*, 2014). Also the Principal Component Analysis (PCA) technique was followed in data analysis for knowing microbial variation (Abdi and Williams, 2010). The sample size taken for Kendall's Coefficient of Concordance (W) and PCA analysis is 8.

Results and Discussion

Productivity of G. arborea based agroforestry systems:

The overall productivity of agroforestry systems was influenced by the yield of both seasonal crops and the tree component (Table 4). Significant differences in grain yield were observed among the treatments in both years. In the first year, yields ranged from 7.02 to 9.04 q/ha, while in the second year, they varied between 6.94 and 9.26 q/ha. These variations can be attributed to differences in genetic characteristics, plant size, and crop duration. Among the treatments, sole pigeonpea and sole cowpea recorded significantly higher yields compared to the others, which may be due to the larger plant size of pigeonpea and the higher grain count per pod in cowpea. Yields were generally higher under open-field conditions than under agroforestry systems, likely due to the absence of shade. In contrast, greengram grown in association with *Gmelina arborea* recorded the lowest yields, attributed to the dense canopy and resultant shading effect from the trees. Spacing and management are critical determinants of crop productivity in agroforestry systems (Vanlalhluna and Sahoo, 2008; 2010; de Castro Santiago *et al.*, 2023). When appropriately designed these factors improve crop productivity while maintaining ecological sustainability and overall system resilience (Ahlawat *et al.* 2019; Kanwal *et al.* 2022).

Significant differences were also observed in the mean annual biomass production of *G. arborea* trees across various land-use systems during both years of the study (Table 4). Among the treatments, the *G. arborea* + greengram combination (T₃) recorded the highest biomass production in both years, significantly

Table 4. Grain yield, mean annual tree biomass production and annual carbon sequestration under different treatments/ agroforestry systems

Treatment/ system	Grain yield (t/ha)			Mean annual biomass production (q/ha)			Total (tree + crop) annual carbon sequestration (t/ha)		
	Year 1 (6-year- old)	Year 2 (7-year- old)	Pooled Mean (T)	Year 1 (6-year- old)	Year 2 (7-year-old)	Pooled mean (T)	Year 1 (6-year- old)	Year 2 (7-year- old)	Pooled mean (T)
T ₁	8.02 ^{bcd}	7.88 ^{bcde}	7.95 ^{bc}	24.01 ^c	24.17 ^c	24.08 ^c	3.082 ^a	3.088 ^a	3.085 ^a
T ₂	7.58 ^{cde}	7.42 ^{de}	7.50 ^{cd}	27.13 ^b	27.39 ^b	27.25 ^b	2.879 ^a	2.884 ^a	2.881 ^b
T ₃	7.02 ^e	6.94 ^e	6.98 ^d	29.97 ^a	30.31 ^a	30.13 ^a	2.904 ^a	2.908 ^a	2.906 ^{ab}
T ₄	-	-	-	23.58 ^c	23.62 ^c	23.60 ^c	1.179 ^d	1.181 ^d	1.180 ^e
T ₅	9.04 ^a	9.26 ^a	9.15 ^a	-	-	-	2.093 ^b	2.155 ^b	2.124 ^c
T ₆	8.42 ^{abc}	8.62 ^{ab}	8.52 ^{ab}	-	-	-	1.678 ^c	1.745 ^c	1.711 ^d
T ₇	7.64 ^{cde}	7.82 ^{bcde}	7.73 ^c	-	-	-	1.491 ^c	1.534 ^c	1.512 ^d
Mean (Y)	7.95 ^a	7.99 ^a	-	26.17 ^a	26.36 ^a	-	2.186 ^a	2.213 ^a	-
SEM for Treatment (T) = 0.24; CD _(0.05) for Treatment (T) = 0.68				SEM for Treatment (T) = 0.57; CD _(0.05) for Treatment (T) = 1.66			SEM for Treatment = 0.071; CD _(0.05) for Treatment = 0.203		
SEM for Year (Y) = -; CD _(0.05) for Year (Y) = N.S.				SEM for Year (Y) = -; CD _(0.05) for Year (Y) = N.S.			SEM for year = -; CD _(0.05) for Year = N.S.		
SEM for T x Y interaction = 0.34; CD _(0.05) for T x Y interaction = 0.96				SEM for T x Y interaction = 0.81; CD _(0.05) for T x Y action = 2.34			SEM for Treatment x Year = 0.101; CD _(0.05) for Treatment x Year = 0.287		

Treatment keys as in Table 1; *Values having same letter are not significantly different; -no tree for these treatments

outperforming the other systems. These differences in biomass accumulation are primarily linked to variations in tree growth parameters such as height, diameter at breast height (DBH), and crown spread. T₃ exhibited superior growth in these parameters, which directly contributed to its higher biomass output. In contrast, T₄ produced the lowest biomass due to its relatively poor growth in height, DBH, and crown dimensions. Interestingly, trees under agroforestry systems generally yielded higher biomass than those in sole tree plantations. This can be attributed to the beneficial effects of nutrient inputs and cultural practices applied to the intercrops, which may have indirectly supported better tree growth (Kaul and Panwar, 2008; Umrao et al., 2010). Thus, it may be said that agroforestry offers a balanced approach for higher biomass storage with agricultural productivity, livelihood security and biodiversity conservation (Devi et al., 2013; Chavan et al. 2022).

Carbon sequestration of *G. arborea* based agroforestry systems: The data on total annual carbon sequestration by the three intercrops and *G. arborea* trees (Table 4) showed significant variation across the treatments in both years. In the first year (when the trees were six years old), carbon sequestration ranged from 1.179 to 3.082 t/ha. The *G. arborea* + pigeonpea combination (T₁) recorded the highest sequestration, which was statistically at par with T₃. In contrast, the sole *G. arborea*

treatment (T₄) sequestered the least amount of carbon, and the difference was statistically significant. A similar pattern was observed in the second year (with seven-year-old trees), where carbon sequestration ranged from 1.181 to 3.088 t/ha. The pooled mean values across treatments over the two years ranged from 1.180 to 3.085 t/ha. Among all treatments, T₁ consistently recorded the highest carbon sequestration, while T₄ continued to record the lowest. The pooled data followed the trend: T₁ > T₃ > T₂ > T₅ > T₆ > T₇ > T₄. However, when comparing the mean annual carbon sequestration across both years (regardless of treatment), no significant year-to-year variation was observed. This stability may be attributed to variations in biomass accumulation by trees and crops under different land-use systems. The superior performance of the *G. arborea* + pigeonpea system (T₁) in terms of carbon sequestration is likely due to the longer duration and better compatibility of pigeonpea with the tree component. Nevertheless, T₁ remained statistically comparable to T₂ and T₃ in both years. Overall, agroforestry treatments (T₁, T₂, and T₃) consistently showed higher annual carbon sequestration compared to the sole crop and sole tree systems. Similarly, long rotation trees are found to have higher carbon stock and carbon-related financial benefits (Gera et al., 2011; Yadav, 2010). Higher soil organic carbon has been reported by several workers in agroforestry systems than sole cropping (Tripathi et al., 2024) due to the presence of trees and perennial biomass in the former contributing

Table 5. Microbial population at 0 to 45 cm soil depth in *Gmelina arborea* based agroforestry systems under different treatments

Treatment	<i>Rhizobium</i> (x 10 ⁷ cfu g ⁻¹ soil)			Fungi (x 10 ⁴ cfu g ⁻¹ soil)			Bacteria (x 10 ⁷ cfu g ⁻¹ soil)			Actinomycetes (x 10 ⁵ cfu g ⁻¹ soil)		
	Year 1	Year 2	Pooled mean	Year 1	Year 2	Pooled mean	Year 1	Year 2	Pooled mean	Year 1	Year 2	Pooled mean
	T ₁	34.71 ^e	36.60 ^{de}	35.66 ^c	10.03 ^a	9.74 ^a	9.88 ^a	23.34 ^{cd}	24.23 ^c	23.79 ^c	21.91 ^c	23.11 ^c
T ₂	41.92 ^{ab}	43.81 ^a	42.86 ^a	8.80 ^b	8.29 ^{bc}	5.55 ^b	27.13 ^b	28.13 ^{bb}	27.63 ^b	25.86 ^b	27.15 ^{ab}	26.51 ^b
T ₃	39.83 ^{bc}	41.99 ^{ab}	40.91 ^b	8.07 ^c	7.71 ^{cd}	7.89 ^c	29.00 ^{ab}	30.61 ^a	29.82 ^a	27.44 ^{ab}	28.90 ^a	28.17 ^a
T ₄	23.61 ^{gh}	25.07 ^g	24.34 ^e	4.39 ^j	4.11 ⁱ	4.25 ^g	20.43 ^{ef}	21.29 ^{de}	20.87 ^d	19.15 ^d	18.74 ^d	19.44 ^d
T ₅	30.81 ^f	31.63 ^f	31.22 ^d	7.09 ^{de}	6.52 ^{fg}	6.85 ^d	15.69 ^j	15.85 ^{hi}	15.77 ^f	13.47 ^f	13.57 ^f	13.51 ^g
T ₆	35.37 ^e	37.64 ^{cd}	36.50 ^c	6.59 ^{ef}	6.15 ^g	6.37 ^e	18.07 ^{gh}	18.37 ^{fg}	18.22 ^c	14.91 ^{ef}	14.81 ^{ef}	14.86 ^f
T ₇	35.01 ^e	36.83 ^{de}	35.42 ^c	5.91 ^{gh}	5.27 ^h	5.59 ^f	19.61 ^{efg}	19.87 ^{efg}	19.74 ^{de}	16.47 ^e	16.22 ^e	16.35 ^e
T ₈	21.32 ⁱ	21.91 ^{hi}	21.61 ^f	4.24 ^j	3.75 ⁱ	4.00 ^g	12.12 ^j	12.26 ^j	12.1 ^g	9.89 ^g	10.13 ^g	10.01 ^h
SEM for pooled Treatment (T) = 0.57 ; CD _(0.05) for pooled Treatment (T) = 1.58												
SEM for Year (Y) = 0.80; CD _(0.05) for Year (Y) = 2.23												
SEM for Y x T = 1.38 ; CD _(0.05) for Y x T = 3.87												
SEM for Y x T interaction = 0.40 ; CD _(0.05) for T x Y interaction = 1.12												
SEM for Y x T interaction = 1.09; CD _(0.05) for Y x T x d interaction = 3.03												

Treatment keys as in Table 1; *Values having same letter are not significantly different

more organic matter (leaf litter, roots) which accumulates carbon in soil. This is yet another reason for higher carbon sequestration in integrated systems than sole cropping.

Soil microbial population of *G. arborea* based agroforestry systems: The population of *rhizobium* varied significantly across different treatments during both years of the study, as shown in Table 5. The *Gmelina arborea* + cowpea system recorded the highest *Rhizobium* population, which was significantly greater than in other treatments. This can be attributed to cowpea's strong ability to support *Rhizobium* proliferation compared to the other crops studied. Similar findings were reported by Kebede et al. (2021), who highlighted cowpea as an effective host for *Rhizobium* species. Additionally, Agudelo et al. (2023) emphasized that host-rhizobia compatibility plays a key role in shaping *Rhizobium* community structure and population levels. Overall, agroforestry systems supported higher *Rhizobium* populations than sole cropping systems. This may be due to the more favorable microclimatic and soil conditions in agroforestry setups, including moderated soil temperatures and improved organic matter levels. Across all treatments, *Rhizobium* populations declined with increasing soil depth, likely due to a reduction in root density and decreased availability of organic substrates in deeper layers. Kebede et al. (2021) also noted that *Rhizobium* populations in cowpea rhizospheres are influenced by previous land use and inherent soil characteristics.

Fungal populations showed considerable variation across treatments (Table 5). In both years of the study, the *G. arborea* + pigeonpea system (T₁) exhibited significantly higher fungal populations compared to other treatments, regardless of soil depth. Treatments involving tree–crop combinations consistently supported higher fungal populations than sole cropping systems, which aligns with the observations made by Singh et al. (2018). A general decline in fungal populations was noted with increasing soil depth across all treatments. This trend may be attributed to the reduction in available nutrients and energy sources required for fungal metabolism in deeper soil layers. Similar results were reported by Silva-Parra et al. (2017). Among the treatments, T₁ was followed by T₂ and T₃ in terms of fungal abundance at all depths, likely due to the greater availability of organic matter in these systems compared to sole crop treatments. Lauber et al. (2013) also found that fungal populations are typically more abundant in forested soils than in agricultural lands, as root exudates from trees provide a rich source of carbon, which serves as a preferential energy source for fungi. Radhakrishnan and Varadharajan (2016) further supported this view, noting the beneficial role of tree root secretions in promoting fungal growth.

The bacterial population in soil varied significantly

across different land-use systems (Table 5). Among the treatments, the *Gmelina arborea* + greengram system (T₃) recorded the highest bacterial population, while the control plot exhibited the lowest. These findings are consistent with the results reported by Singh et al. (2018), who observed enhanced bacterial activity under agroforestry systems. A noticeable decline in bacterial population was observed with increasing soil depth across all treatments. This may be attributed to the decreasing influence of root exudates and greater distance from the rhizosphere. Specifically, T₃ might have enhanced bacterial abundance due to the higher release of amino acids through greengram root exudation, as suggested by Kent and Triplett (2002). Similar observations on the depth-wise reduction in bacterial populations across land-use systems have been reported by Silva-Parra et al. (2017) and Radhakrishnan and Varadharajan (2016). The actinomycetes population in soil was also significantly influenced by the different land-use systems during both years of the study (Table 5). The highest population was observed in the *G. arborea* + greengram system (T₃), followed by *G. arborea* + cowpea (T₂) and *G. arborea* + pigeonpea (T₁). In contrast, systems involving sole cropping showed markedly lower populations, with the control plots (no crop) registering the minimum values. These differences in actinomycete populations may be attributed to variations in soil conditions such as nutrient availability, oxygen levels, temperature, and mineral content, as highlighted by Silvia et al. (2005). The T₃ treatment likely provided a more favorable microenvironment for actinomycetes proliferation due to improved soil biota conditions. As with bacteria, actinomycete populations declined with increasing soil depth, likely due to reduced availability of nutrients and oxygen. These results are in agreement with the findings of Radhakrishnan and Varadharajan (2016).

Microbial population analysis: The integrated multivariate analysis combining principal component analysis, hierarchical cluster analysis, and inter- and intra-cluster distance metrics provided a comprehensive understanding of soil microbial population dynamics across different systems. The Kendall's coefficient of concordance (W) was 0.75, which indicates a strong positive association among the four microbes, such as *rhizobium*, fungi, bacteria and actinomycetes at p value = 0.004 with respect to 8 land use systems. The hierarchical cluster analysis based on Euclidean distance and average linkage categorized the 8 land use systems into 4 clusters with respect to 4 characters such as population of rhizobium, fungi, bacteria and actinomycetes (Fig 1). Cluster I includes T₁, T₂, T₃, where tree and crop were combined. Cluster II includes T₄ (sole tree), Cluster III includes T₅, T₆, T₇ (sole crop) and Cluster V includes T₈ (control plot having no tree and no crop).

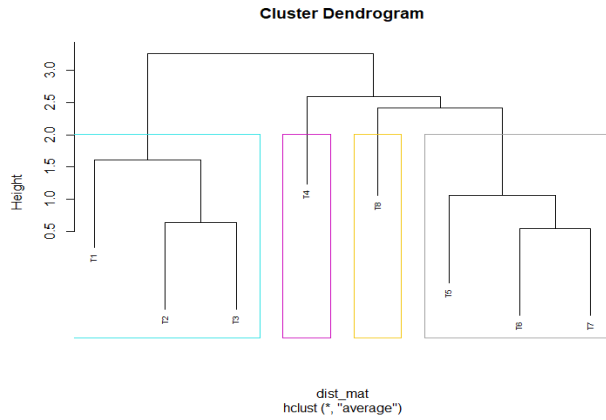


Fig 1. Cluster dendrogram on the basis of four microbial population

Matrix of inter- and intra-cluster distance

	C I	C II	C III	C IV
C I	1.29			
C II	3.25	0		
C III	2.75	2.50	0.89	
C IV	4.80	2.87	2.42	0

The dendrogram was used as an integrative multivariate tool to assess overall similarity among land-use systems based on multiple variables simultaneously. The clustering pattern—sole crop and agroforestry systems forming distinct clusters with sole tree and empty field positioned intermediately—is ecologically meaningful and aligns with established theory, thereby confirming the robustness of the selected variables and the appropriateness of the clustering approach rather than indicating redundancy. The diagonal values represent the intra-cluster distance and were found to be highest in Cluster I. The off-diagonal values represent the inter-cluster distance and were found to be highest between clusters I and IV. The principal component analysis showed that the first principal component (PC1) explained 75.4% of the total variance with a high eigenvalue (3.016), indicating that overall microbial abundance was the dominant factor governing variability among systems, while the second principal component (PC2) accounted for 18.7% of the variance and reflected differences in microbial community composition by separating fungal and rhizobial populations from bacterial and actinomycete groups. Together, PC1 and PC2 explained 94.1% of the total variability, confirming that the two-dimensional PCA biplot adequately represented the major patterns in microbial distribution (Fig 2). Overall, the strong concordance among PCA, clustering, and distance metrics highlights the decisive role of system characteristics in shaping soil microbial population structure and demonstrates the effectiveness

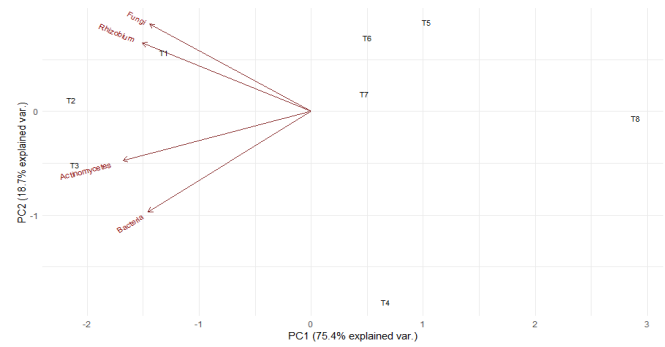


Fig 2. Principal component analysis figure of microbial population in different systems

of the multivariate approach in capturing biologically meaningful variation.

Economics of *Gmelina arborea*-based land use systems: The production cost during the first year (when the trees were six years old) and the second year (at seven years old) showed notable variation across different land-use systems, as summarized in Table 6. Costs ranged from Rs. 10,000 to Rs. 35,000 per hectare in the first year and from Rs. 11,000 to Rs. 38,000 per hectare in the second year. The *Gmelina arborea* + arhar system (T₁) incurred the highest expenses, although it was statistically comparable to the costs in *G. arborea* + cowpea (T₂) and *G. arborea* + greengram (T₃) systems. The relatively greater cost associated with T₁ can be attributed to the longer growing period of pigeonpea, which demands increased operational inputs. Conversely, the cost of maintaining the sole *G. arborea* plantation was the lowest, as the trees were already established and required minimal maintenance during their sixth and seventh years. Systems combining trees and crops involved higher costs compared to sole crop systems, reflecting the combined expenses for both components. In general, the studies have found that wide spacing between tree rows enhanced crop productivity by reducing competition and improving solar radiation penetration, whereas narrower spacing increased tree-crop competition leading to reduced crop yields (Prasad *et al.*, 2010), thus the gross return, net monetary benefits and benefit-cost ratio from an agroforestry system would depend on planting design and tree-crop combination (Huxley and van Houten, 1997; Tomar and Bhatt, 2004; Nayak *et al.* 2014; Kumar *et al.*, 2024; Ulman and Patel, 2025). Similarly, other researchers (Kumar *et al.*, 2017; Ramesh *et al.*, 2023) have found that trees in agrisilvicultural systems performed better growth than sole stands and their studies have found higher crop yields and financial returns in integrated systems than sole crop stands.

Significant differences were observed in the gross monetary return (GMR) across various land-use systems during both years of the study (Table 6). In the first

Table 6. Economics (Rs/ha) in *G.arborea* based land use systems in Central India

Treatment/ system	Cost of production			Gross monetary return			Net monetary return		
	Year 1	Year 2	Pooled mean	Year 1	Year 2	Pooled mean	Year 1	Year 2	Pooled mean
T ₁	35000 ^a	38000 ^a	36500 ^a	77824 ^{bc}	81883 ^{ab}	79853 ^b	42824 ^{cd}	43883 ^{bcd}	43353 ^b
T ₂	34000 ^a	37000 ^a	35500 ^a	85126 ^{ab}	90506 ^a	87816 ^a	51126 ^a	53506 ^a	52316 ^a
T ₃	34000 ^a	37000 ^a	35500 ^a	83605 ^{ab}	89957 ^a	86781 ^{ab}	49605 ^{ab}	52957 ^a	51281 ^a
T ₄	10000 ^c	11000 ^c	10500 ^c	23583 ^f	25980 ^f	24781 ^d	13583 ^f	14980 ^f	14281 ^d
T ₅	25000 ^b	27000 ^b	26000 ^b	60608 ^{de}	65256 ^{de}	62932 ^c	35608 ^e	38256 ^{de}	36932 ^c
T ₆	24000 ^b	26000 ^b	25000 ^b	64397 ^{de}	70441 ^{cd}	67419 ^c	40397 ^{cde}	44441 ^{bc}	42419 ^b
T ₇	24000 ^b	26000 ^b	25000 ^b	58305 ^e	63726 ^{de}	61015 ^c	34305 ^e	37726 ^{de}	36015 ^c
Mean (Y)	26571 ^b	28857 ^a		64778 ^b	69678 ^a		38207 ^b	40821 ^a	
SEM for Treatment = 1253 ; CD _(0.05) for Treatment = 3562				SEM for Treatment = 2620 ;CD _(0.05) for Treatment = 7449			SEM for Treatment = 1624 ;CD _(0.05) for Treatment = 4619		
SEM for Year = 669 ; CD _(0.05) for Year = 1904				SEM for Year = 1400 ;CD _(0.05) for Year = 3982			SEM for Year = 868; CD _(0.05) for Year = 2469		
SEM for Treatment x Year = 1771; CD _(0.05) for Treatment x Year =5037				SEM for Treatment x Year = 3705 ; CD _(0.05) for Treatment x Year =10535			SEM for Treatment x Year = 2297; CD _(0.05) for Treatment x Year = 6532		

Treatment keys as in Table 1; *Values having same letter are not significantly different.

year (2021), GMR ranged from Rs. 23,583 to Rs. 85,126 per hectare, while in the second year (2022), it varied between Rs. 25,980 and Rs. 81,883 per hectare. These variations were primarily influenced by differences in crop and tree yields as well as the market prices of the respective produce. The *Gmelina arborea* + cowpea system (T₂) recorded the highest GMR, statistically comparable to the *G. arborea* + greengram system (T₃). This similarity is likely due to comparable grain prices and yields from both crops and associated tree biomass. Agroforestry systems consistently generated higher gross returns than their corresponding sole cropping systems, benefiting from the combined output of trees and intercrops managed on the same land unit.

Net monetary return (NMR) is a key indicator for evaluating the economic viability of any plant-based land-use system. During both years of the study, NMR showed significant variation among the different treatments (Table 6). In the first year, when the *Gmelina arborea* trees were six years old, NMR ranged from Rs. 13,583 to Rs. 51,126 per hectare. In the second year, with seven-year-old trees, the values varied between Rs. 14,980 and Rs. 53,506 per hectare. Across both years, the *G. arborea* + cowpea system (T₂) recorded the highest NMR, statistically comparable to the *G. arborea* + greengram system (T₃). These findings suggest that T₂ and T₃ are economically the most promising among the seven land-use systems evaluated, likely due to their higher gross monetary returns as outlined in Table 6. Sole cropping systems consistently yielded significantly lower returns compared to agroforestry systems, which benefit from the combined economic output of both trees and crops.

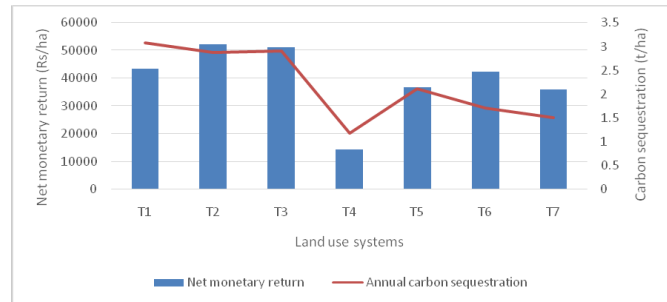


Fig 3. Net monetary return and total (tree + crop) annual carbon sequestration

Integrating fodder trees like *Ficus infectoria*, *Acacia nilotica*, *Morus alba* and *Leucaena leucocephala* on degraded, non-arable land in the semi-arid Central India have found good return from the silvipastoral systems (Kumar et al, 2017) and therefore a well-designed system can not only provide better economic return but also better ecosystem stability (Chauhan et al., 2015; Ramesh et al., 2023). In the present study, T₂ and T₃ attained better biomass production and higher economic return thus increasing overall land use efficiency compared to other treatments.

Correlation between net monetary return and annual carbon sequestration: The integration of economic and ecological benefits underscores the sustainability of agroforestry systems compared to sole cropping systems. In this study, the Pearson product-moment correlation coefficient (r) between net monetary return and annual carbon sequestration was calculated to be 0.81, with a corresponding t-value of 3.06 and a p-value

of 0.028. This indicates a strong positive correlation at the 5% significance level. The relationship is also illustrated in Figure 3. These findings highlight that agroforestry systems offer superior economic and environmental advantages relative to sole cropping systems.

Conclusion

Gmelina arborea-based agroforestry systems recorded significantly higher overall productivity, carbon sequestration, soil microbial status and net monetary return in comparison to sole cropping systems. Further, the *G. arborea* + greengram system was observed to be superior, closely followed by the *G. arborea* + cowpea system from an economic and ecological point of view. It suggests that growing leguminous crops such as greengram, cowpea and pigeonpea with remunerative trees under an agroforestry system is more beneficial than sole crop and sole tree cultivating in central Indian semi-humid like conditions.

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