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Effects of tree planting geometry on lentil nutritional quality, tree biomass, and economic returns in *Melia dubia*-based agroforestry system in Bundelkhand region of India

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Introduction: Low farm productivity, declining soil fertility, and climatic stress in the semi-arid Bundelkhand region demand sustainable land-use strategies. Integrating *Melia dubia* with lentil-based systems offers potential to enhance soil fertility, resource efficiency, and profitability. However, limited studies have examined how tree spacing influences lentil seed quality, litterfall nutrient dynamics, and carbon sequestration in *M. dubia*-based agroforestry.

Methods: A field experiment was conducted during the 2023–24 Rabi season at the Forestry Research Farm, Rani Lakshmi Bai Central Agricultural University, Jhansi, India. The study employed a split-plot design with three *M. dubia* spacings (5 × 5 m, 5 × 4 m, and 5 × 3 m) and two lentil varieties (IPL 316 and L 4727), along with a sole crop control, replicated thrice. Observations included lentil nutrient composition, litterfall quantity and nutrient content, tree growth, biomass, carbon storage, and economic returns. Statistical analysis was performed using OPSTAT software.

Results: Tree spacing significantly affected lentil nutrient composition, litterfall production, and system productivity. The 5 × 4 m spacing recorded the highest lentil seed protein (26.21%) and nitrogen (4.19%) contents, whereas phosphorus and calcium were maximum under 5 × 3 m spacing (0.45% and 0.58%, respectively). Variety IPL 316 exhibited superior nutrient profiles with higher nitrogen, potassium, calcium, copper, and zinc concentrations compared to L 4727. Denser plantations (5 × 3 m) produced maximum litterfall (1.19 Mg ha⁻¹), with peak nutrient release during January–February, indicating efficient nutrient recycling. Phosphorus and potassium concentrations in litter were also higher under closer spacings. Photosynthetically active radiation (PAR) decreased with increasing tree density, ranging from 652.85 μmol m⁻² s⁻¹ in sole lentil to 135.26

$\mu\text{mol m}^{-2} \text{ s}^{-1}$ under $5 \times 3 \text{ m}$ spacing. The $5 \times 3 \text{ m}$ spacing achieved the highest total biomass (42.7 Mg ha^{-1}), carbon stock (21.32 Mg ha^{-1}), and CO_2 sequestration potential (78.37 Mg ha^{-1}). Economically, the same spacing yielded maximum gross returns (US\$ 4227 ha^{-1}), net returns (US\$ 2783 ha^{-1}), and benefit–cost ratio (2.92).

Conclusion: In conclusion, closer planting geometry of *M. dubia* ($5 \times 3 \text{ m}$) enhanced biomass, carbon storage, and profitability without compromising lentil quality. The integration of lentil under *M. dubia* optimized resource use, nutrient cycling, and carbon sequestration, demonstrating its suitability for sustainable and climate-resilient agroforestry in Bundelkhand.

KEYWORDS

agroforestry, biomass, carbon sequestration, litterfall, net returns, protein content

Introduction

Forests are highly significant to mankind as they make a substantial contribution to enhancing the environment, economy, and society. In a developing country like India, there is a significant need for timber, fuel wood, and tree fodder. This demand is primarily fulfilled by trees located outside of forest areas on agricultural lands (Chakravarty et al., 2019). Forests have a crucial role in preserving ecological balance, serving as habitats for numerous plant and animal species, and safeguarding the soil against water and wind erosion (Liu, 2025; Ponyane et al., 2025). Climate change has recently provided a boost to forests and trees. Around 27 percent of India's population continues to depend on forests for their sustenance through numerous ways (Pandey et al., 2016). The country has a total forest and tree cover of 25.17 percent (Forest Survey of India, 2023). To enhance the extent of forest and tree cover, it is imperative to undertake operations like as reforestation, enrichment planting, and agroforestry (Gupta et al., 2020; Jinger et al., 2023; Singhal et al., 2024).

Agroforestry, which involves the incorporation of trees into agricultural landscapes, has been demonstrated to be a practical and self-sustaining land use system in this area (Ghosh et al., 2014; Gautam et al., 2025). The incorporation of rapidly growing trees on degraded soil in the area can exploit the economic benefits of trees for the rural community (Palsaniya et al., 2010; Jinger et al., 2021; Selvan et al., 2023). It is often considered as a financially viable strategy for mitigating climate change (Lasco et al., 2014; Jinger et al., 2022a). Agroforestry systems capture carbon in both soil and woody biomass. The carbon storage capacity in most agroforestry systems varies based on tree species (Nair et al., 2009; Saleem et al., 2023) and management approaches (Nair, 2012). Agroforestry has been implemented globally for decades, predominantly in tropical and subtropical regions. This is a fledgling concept and technique that combines crop production with the conservation of natural resources, addressing environmental and human needs simultaneously (Kreitzman et al., 2022; Jinger et al., 2022b; Vikas

and Ranjan, 2024). Currently, agroforestry fulfils roughly 50 percent of the fuelwood requirement, two-thirds of the small timber demand, 60 percent of the raw materials necessary for paper pulp, 70–80 percent of the plywood industry's needs, and 9–11 percent of the green fodder demand (Dev et al., 2017). Recently, the total area of agroforestry in India has been reported as approximately 28.427 million hectares, representing 8.65 percent of the nation's total geographical area (Arunachalam et al., 2022). The Bundelkhand region in central India is located in the semi-arid tropical zone. The region's vulnerability to climate change and resource scarcity results in poor crop yields and elevated production risks (Sharma, 2023; Deshmukh et al., 2025). The region experiences a shortage of fodder and fuelwood due to intense biotic pressure on forests, community lands, and a decline in vegetation cover.

Malabar Neem (*Melia dubia*) is a most promising agroforestry tree which grows in deciduous forests around 600 - 1,800 meters above mean sea level. Cultivating *M. dubia* in an agroforestry system provides an alternative source for the supply of pulp wood and fodder (Chauhan et al., 2018; Akhilraj et al., 2023; Jinger et al., 2024). Spacing in the *M. dubia* in an agroforestry system may differ according to the utility of wood. For pulpwood production, closer spacing of $2 \text{ m} \times 2 \text{ m}$ and $3 \text{ m} \times 2 \text{ m}$ is usually recommended, whereas for plywood production, wider spacing of $5 \text{ m} \times 5 \text{ m}$ and $5 \text{ m} \times 4 \text{ m}$ can be used. For timber purposes, wider spacing of $6 \text{ m} \times 6 \text{ m}$ and $8 \text{ m} \times 8 \text{ m}$ can be used for *M. dubia*-based agroforestry (Sirohi et al., 2018). *Melia dubia* undergoes complete leaf shedding in the winter season. Trees assimilate nutrients for growth and development, with certain amounts of these nutrients translocating into various tree components, from which a substantial quantity is returned to the soil through litterfall (Zheng et al., 2022). Litterfall is a critical element of the nutrient cycle that influences soil health by contributing to soil organic matter, facilitating nutrient exchange, replenishing nutrients, conserving biodiversity, and supporting other ecosystem activities (Awasthi et al., 2022; Jinger et al., 2025). The quantity of nutrients released to the soil via leaf litter

is reliant upon tree spacing, litter quality, and specific nutrient concentrations (Elias et al., 2020; Wang et al., 2021). The supplementary nutrients may enhance soil fertility, and nutrient return data can serve as an indicator to predict the relationship between tree species and nutrient recycling in agroforestry systems, thereby improving productivity and ensuring long-term sustainability (Lal, 2025).

Intercropping pulses with commercial tree species during the early phases of establishment is advantageous as it allows legumes to restore soil fertility and provides farmers with extra income (Ghosh et al., 2007; Kumar et al., 2023; Akchaya et al., 2025). Although shade diminishes the productivity of field crops, it paradoxically improves seed quality (Pohlmann et al., 2024). The nitrogen-fixing capacity of legumes renders them extremely appropriate for integration into low-input cropping systems. India is the world's top producer, consumer, and importer of pulses, accounting for 25% of global production, 27% of global consumption, and 14% of global imports (Ketali et al., 2024). While pulses are cultivated during both the Kharif and Rabi seasons, those grown in the Rabi season make up over 60% of the total production (Bhat et al., 2022). Winter legumes like *Lens culinaris*, with flat, lens-shaped seeds, require little water. The plants are usually short and produce self-pollinating flowers (Semba et al., 2021). Lentil seeds are rich in carbohydrates, protein, energy, fat, fibre, phosphorus, zinc, iron, vitamins, carotene, and antioxidants (Riaz et al., 2024). Lentils are mostly grown as a rainfed crop, requiring cool temperatures during the growth phase and warmer conditions for maturity (Venugopalan et al., 2021). The Bundelkhand region in Uttar Pradesh and Madhya Pradesh is distinguished for its lentil production, accounting for approximately 25% of the national total (Malik et al., 2022). Although agroforestry has been widely promoted as a sustainable land-use practice in semi-arid regions, lentil-based systems in Bundelkhand have received little scientific attention. Most studies in the region have focused on cereal-based or oilseed-based agroforestry models, while lentil; a protein-rich pulse well suited to marginal lands has been underrepresented. Consequently, there is inadequate understanding of how tree spacing and crop variety influence productivity, quality attributes, and carbon sequestration in *Melia dubia*-based agroforestry systems. Despite the recognized potential of *M. dubia*, its influence on litterfall nutrient return, carbon sequestration, and intercrop performance under different spacing regimes in semi-arid Bundelkhand remains underexplored. The current study was designed with objectives considering the potential of *M. dubia* as a commercially significant fast-growing agroforestry tree species and the suitability of lentil cultivation in the semi-arid regions of Bundelkhand viz. to assess how different spacings of *M. dubia* affect lentil quality, tree growth, litterfall dynamics in Bundelkhand's semi-arid conditions along with quantification of biomass and carbon sequestration, and determine the economic viability of the agroforestry system.

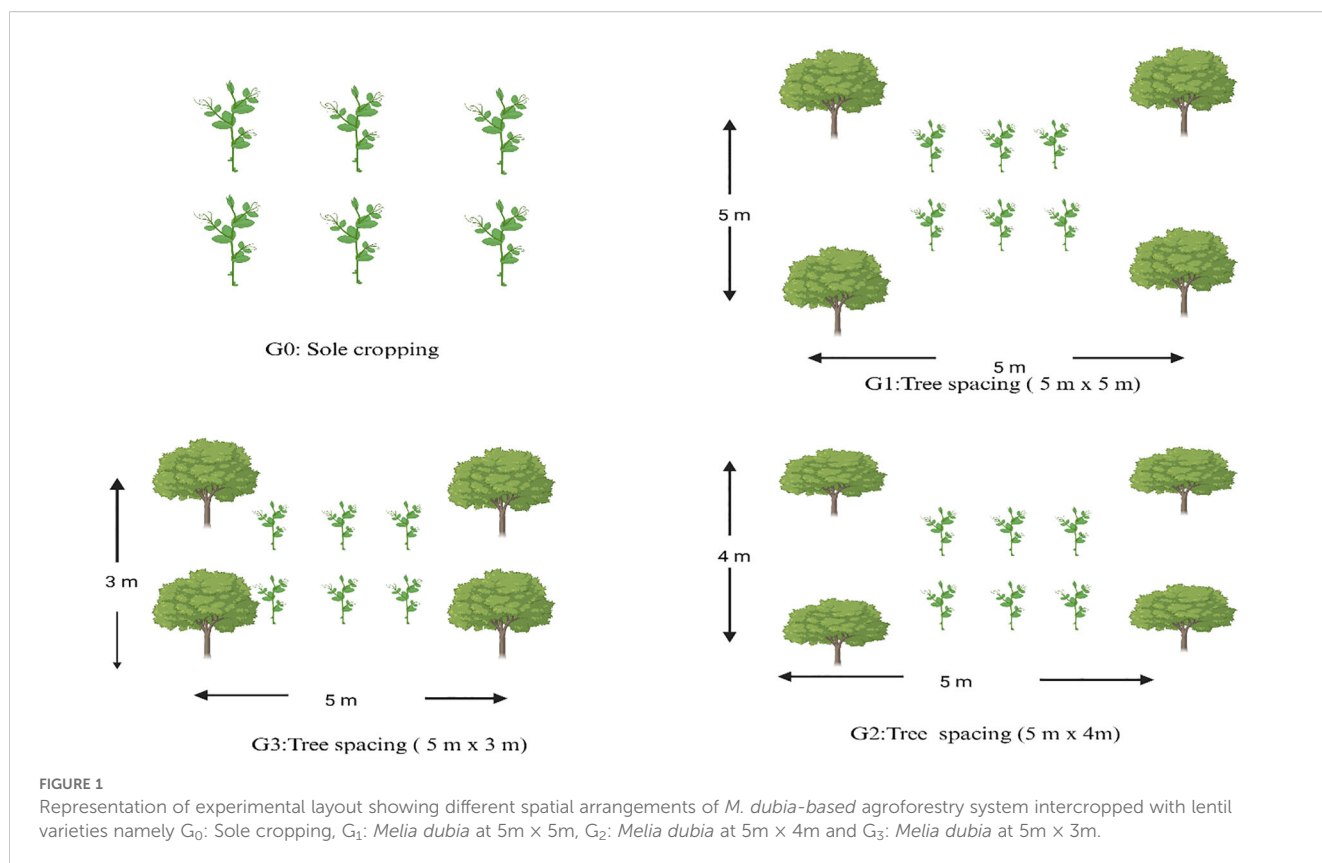
Materials and methods

Experimental site

The experiment was carried out in Rabi 2023 in field H-12 in the *M. dubia* plantation located at the Forestry Research Farm, Bhojla, under the Rani Lakshmi Bai Central Agricultural University, Jhansi (U.P.). The experimental site is situated at an elevation of 284 meters above sea level, positioned at 25.517457° N latitude and 78.561147° E longitude. Jhansi exhibits an annual average temperature of 25.80°C and an average precipitation of approximately 870 mm (Ram et al., 2025). The soil at the experimental site is classified as sandy loam in texture with a pH of 6.9, low in organic carbon content (0.45%), available nitrogen (182 kg ha⁻¹), available phosphorus (9.3 kg ha⁻¹), and available potassium (176 kg ha⁻¹).

Experimental details

The research employed a split-plot design using *M. dubia* arranged at 5m × 5m (G₁), 5m × 4m (G₂), and 5m × 3m (G₃) as main plots (Figure 1). Three spacings of *M. dubia* were evaluated against sole cropping (G₀). During the experimental period, two lentil varieties were employed as the subplots, namely V₁ (IPL 316) and V₂ (L 4727), and replicated three times under *M. dubia* (Figure 2). These two varieties are low-water-requiring and are recommended for use in the Bundelkhand region. Lentil was sown at a spacing of 30 cm × 10 cm and a seed rate of 40 kg ha⁻¹. For *M. dubia*, no additional fertilization, irrigation, or pest control was applied during the experimental period beyond the standard plantation practices followed at the research farm. For *Lens culinaris*, recommended agronomic practices were followed for sowing and weeding, chemical fertilizers, and irrigation were applied. Fertilizer was applied to the lentil crop at the rate of 20 kg N ha⁻¹, 40 kg P₂₅ ha⁻¹, 20 kg K₂O ha⁻¹, and 20 kg S ha⁻¹ at the time of sowing. Intercultural operations were conducted when necessary, and the lentil crop was harvested in March. *M. dubia* was planted in July 2020, and the trees were three years old at the time of the lentil intercropping experiment conducted during Rabi 2023. Litterfall, tree growth, biomass, and carbon sequestration data were recorded over a continuous three-year period (2020–2023), beginning from the year of plantation establishment. However, the lentil intercropping experiment, including crop quality analysis, was conducted only during Rabi 2023 under the established *M. dubia* stand. For estimation of litterfall and its nutrient concentrations, the months were treated as subplots. Tree growth and biomass parameters were estimated under different treatments using a Randomized Block Design, with observations recorded at two intervals i.e. before sowing and after harvesting of lentil in order to assess the seasonal influence of intercrop management on tree performance.



Nutrient analysis of lentil

Reliable sampling is crucial for acquiring dependable plant analysis outcomes. For nutrient quality analysis, three replications were maintained by compositing seeds obtained from nine randomly selected lentil plants at harvest in each treatment plot. Mechanical grinding of the seeds was conducted and utilized for chemical analysis according to the standard methodology (Jackson, 1973; AOAC, 1990). To determine the total nitrogen in the litterfall, a specified weight of the sample was digested in strong sulfuric acid (H_2SO_4). The sample was digested in a diacid mixture of HNO_3 and HClO_4 in a 3:1 ratio for the measurement of other nutrients. Nitrogen (N) in the digest was quantified using distillation utilizing a Kjeldahl apparatus with a boric acid indicator solution. The phosphorus (P) level in the digest was quantified using the vanadomolybdate phosphoric yellow colour method within a nitric acid medium. The concentrations of potassium (K) and calcium (Ca) in the digest were measured using a flame photometer. The amounts of iron (Fe), copper (Cu), and zinc (Zn) were determined using an atomic absorption spectrophotometer.

Litterfall analysis

Leaf litter was collected from the trees from the onset of litterfall in November until the trees were entirely devoid of leaves in

February across a three-year growth period. Three replications were employed for each treatment. Four metal litter traps measuring 1 m × 1 m × 10 cm were placed in each replication for each spacing. Leaf litterfall was obtained from these traps in paper bags during the leaf-shedding phase of *M. dubia* at biweekly intervals, and the quantities from two intervals were combined to get monthly litterfall values. The freshly weighed samples included a representative 50 g from each replication for subsequent analysis. The typical samples were subjected to oven drying at 70° C until a constant weight was achieved to determine the dry weight of litterfall (Mg ha^{-1}). Subsequently, the dried samples were crushed with an electric grinder equipped with stainless steel blades and sieved through a 2 mm mesh. The concentration of several nutrients was assessed according to the standard protocol on a monthly basis. The identical procedures employed for estimating nutrient contents in litterfall were also used for nutritional analysis in lentil seeds. The data were statistically analyzed using a split-plot design, with tree spacings as the main plot and months as the subplots.

PAR

The data for PAR was taken with the help of the Lux meter two times a week in three slots, i.e., morning, afternoon, and evening. The Lux reading was converted into ($\mu\text{mol m}^{-2} \text{s}^{-1}$) by the following formula, $\text{PAR} = \text{Lux} \times 0.0185 \mu\text{mol m}^{-2} \text{s}^{-1}$.



FIGURE 2

View of *M. dubia* plantation before sowing of lentil (a) and during the lentil crop growth period (b).

Tree growth, biomass, and carbon assessment

Tree height (m) was recorded using a Ravi Altimeter for each tree before sowing and after harvesting the intercrops. Girth at breast height (GBH) was measured at 1.37 meters above the ground using a measuring tape. Crown spread was assessed in both the north-south and east-west directions using ground-based measurements, both for trees under agroforestry systems and those in pure stands. Biomass estimation was performed by calculating above-ground biomass (AGB) using the pan-tropical allometric equation developed by [Chave et al. \(2014\)](#): $AGB = 0.0673 \times (WD \times DBH^2 \times H)^{0.975}$, where wood density (WD) of 3-year-old *M. dubia* was 0.468 g cm^{-3} as reported by [Saravanan et al. \(2014\)](#). Below-ground biomass (BGB) was estimated by multiplying AGB by a root-to-shoot ratio of 0.26 ([Ravindranath and Ostwald, 2008](#)), and total biomass was the sum of AGB and BGB. Carbon storage was determined by multiplying the total biomass by a carbon fraction of 0.5, based on the assumption that 50 percent of dry biomass constitutes carbon ([MacDicken, 1997](#)). Subsequently, the carbon dioxide (CO_2) sequestration potential was calculated by

multiplying the carbon stock by a conversion factor of 3.67 ([Howard et al., 2014](#)), representing the molecular weight ratio of CO_2 to carbon.

Economic analysis

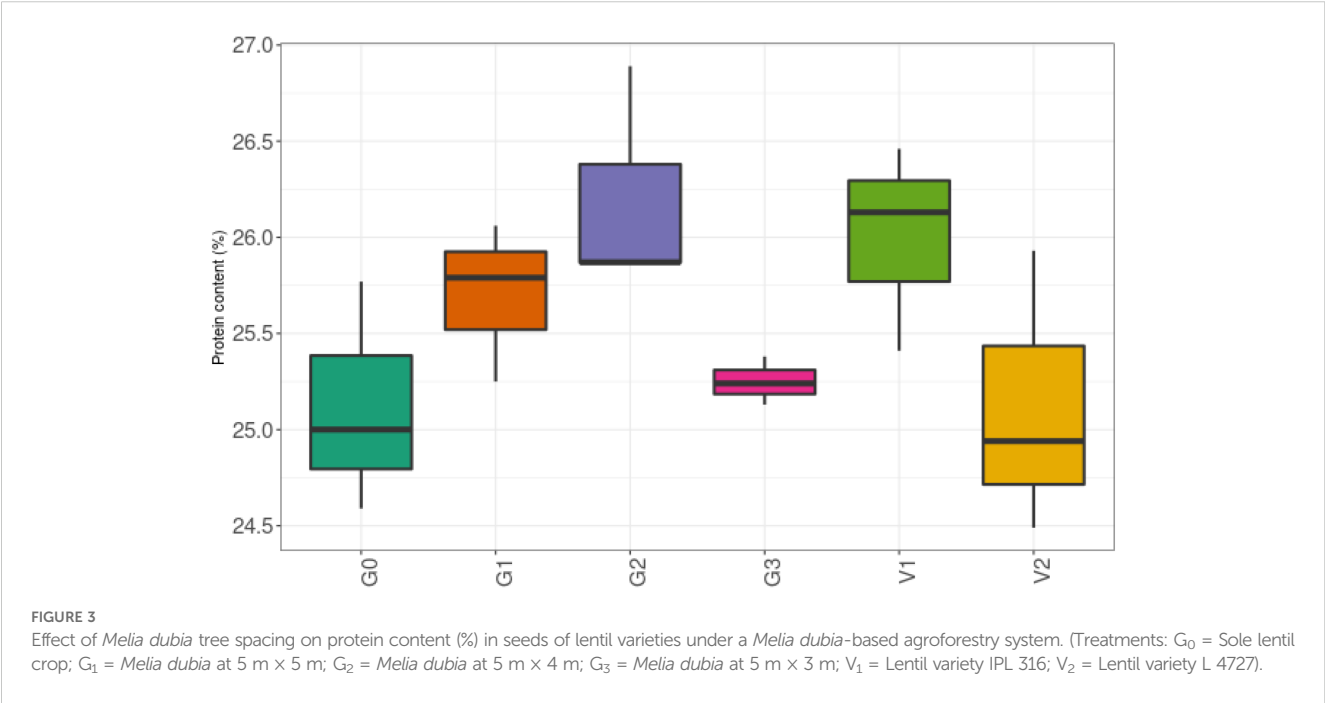
The costs related to the cultivation of lentil and *M. dubia* trees were evaluated based on the net cultivated area per hectare. The labour and mechanical power necessary for operations, including ploughing, harrowing, weeding, and harvesting, together with the costs associated with seeds and farmyard manure, were computed on a per-hectare basis utilizing the prevailing rates at the experimental farm. Returns were calculated on a per-hectare basis, considering the market selling prices of the cultivated crops. The total returns from *M. dubia* were assessed by evaluating the above-ground volume. Net returns were calculated by deducting total costs from gross returns and reported in US dollars. Net returns were calculated using formula of [Bhatia et al. \(2024\)](#).

Net Returns ($\text{US\$ ha}^{-1}$) = Gross Returns ($\text{US\$ ha}^{-1}$) – Cost of Cultivation ($\text{US\$ ha}^{-1}$)

TABLE 1 Effect of *M. dubia* tree spacing on nutrient content in the seeds of lentil varieties.

Treatments	N (%)	P (%)	K (%)	Ca (%)	Fe (mg 100 g ⁻¹)	Cu (mg 100 g ⁻¹)	Zn (mg 100 g ⁻¹)
Tree spacings							
G ₀	4.02	0.41	0.70	0.42	6.3	2.42	3.62
G ₁	4.11	0.42	0.77	0.45	6.75	2.50	3.93
G ₂	4.19	0.43	0.77	0.47	6.8	2.55	3.98
G ₃	4.04	0.45	0.75	0.44	6.73	2.56	3.93
CD _{0.05}	0.11	0.02	0.03	0.02	0.12	0.06	0.21
Lentil varieties							
V ₁	4.16	0.42	0.79	0.46	6.71	2.59	3.92
V ₂	4.02	0.44	0.71	0.43	6.58	2.42	3.81
CD _{0.05}	0.09	0.01	0.02	0.01	NS	0.05	0.06
Interaction							
CD _{0.05}	NS	NS	NS	NS	NS	NS	NS

G₀, Sole lentil crop; G₁, *Melia dubia* at 5 m × 5 m; G₂, *Melia dubia* at 5 m × 4 m; G₃, *Melia dubia* at 5 m × 3 m; V₁, Lentil variety IPL 316; V₂, Lentil variety L 4727. NS, Non-significant at p ≤ 0.05.



Similarly, Benefit Cost Ratio of the gross returns per dollar invested was calculated as

B: C Ratio = Gross returns (US\$ ha⁻¹)/Cost of Cultivation (US\$ ha⁻¹).

Statistical analysis

Data on lentil nutritional quality, litterfall characteristics, and economic returns were analysed using analysis of variance (ANOVA) for a split-plot design, with tree spacings (G₀–G₃) as main plots and lentil varieties (V₁ and V₂) as sub-plots. Data on tree growth, biomass, and carbon sequestration were analysed using a

Completely Randomized Block Design (CRBD). The significance of differences was tested at the 5% probability level using **OPSTAT statistical software**.

Results and discussions

Nutrient contents in lentil seed

The nutrient content of lentil seed was significantly influenced by tree spacings and varieties was recorded and is presented in

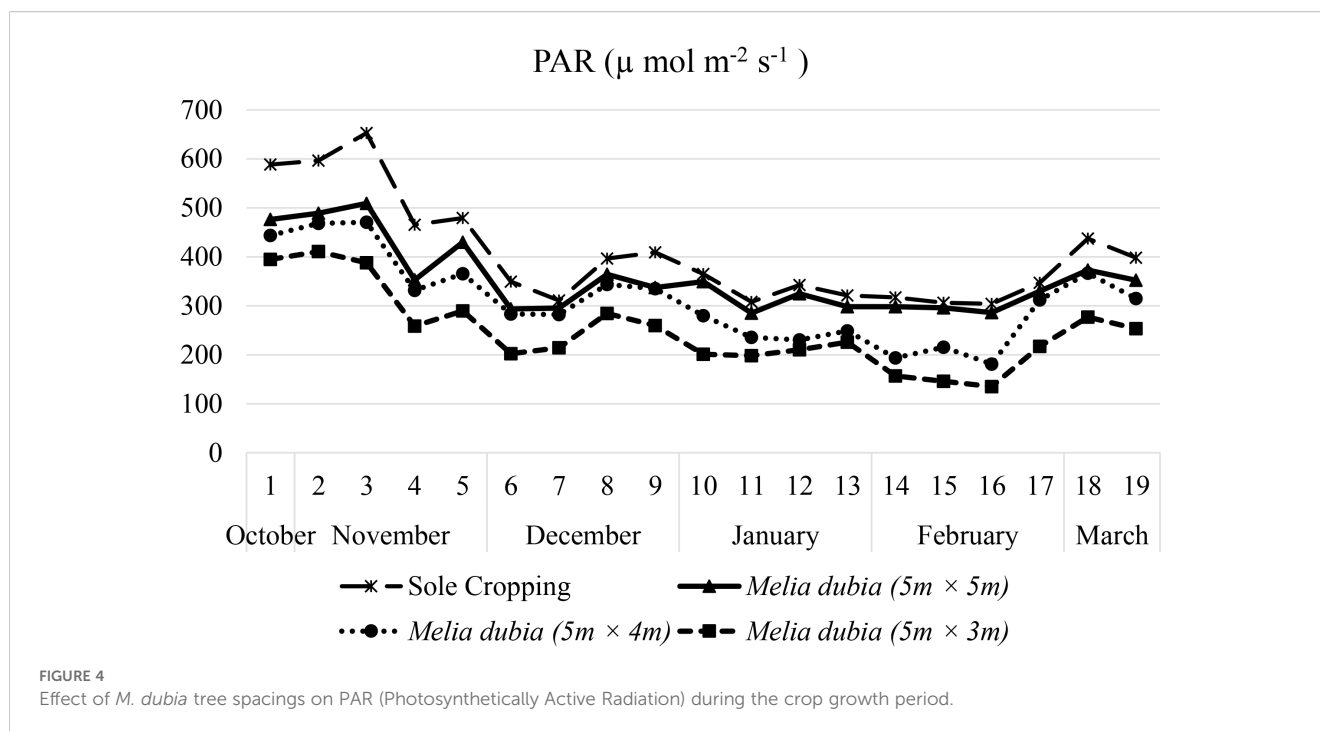
TABLE 2 Production and nutrient concentrations in leaf litterfall of *M. dubia* plantations under different spacings.

Treatments	Litterfall (Mg ha ⁻¹ month ⁻¹)	N (%)	P (%)	K (%)	Ca (%)	Fe (mg 100g ⁻¹)	Cu (mg 100g ⁻¹)	Zn (mg 100g ⁻¹)
Tree spacings								
G ₁	0.99	0.89	0.15	0.77	0.51	98.3	3.29	10.98
G ₂	1.07	0.9	0.16	0.8	0.54	99.45	3.41	11.12
G ₃	1.19	0.91	0.17	0.8	0.58	99.56	3.49	11.26
CD _{0.05}	0.02	NS	0.01	0.02	0.02	NS	0.06	NS
Months								
November	0.93	0.90	0.14	0.77	0.51	87.99	2.62	10.74
December	1.05	0.92	0.18	0.8	0.56	88.09	2.75	11.02
January	1.13	0.92	0.16	0.83	0.58	115.59	5.31	11.44
February	1.21	0.88	0.15	0.76	0.53	104.74	2.90	11.28
CD _{0.05}	0.03	0.02	0.01	0.02	0.02	2.3	0.07	0.29
Interaction								
CD _{0.05}	NS	NS	NS	NS	NS	NS	NS	NS

G₀, Sole lentil crop; G₁, *Melia dubia* at 5 m × 5 m; G₂, *Melia dubia* at 5 m × 4 m; G₃, *Melia dubia* at 5 m × 3 m; V₁, Lentil variety IPL 316; V₂, Lentil variety L 4727.
NS, Non-significant at p ≤ 0.05.

Table 1. Among different tree spacings, 5m × 4m (G₂) recorded significantly higher nutrients, viz. protein content (Figure 3), nitrogen, and calcium, i.e., 26.21%, 4.19%, and 0.47% which was at par with 5m × 5m (G₁) (25.7%, 4.11%, and 0.45%). Iron and Zinc were also significantly higher in 5m × 4m (G₂) (6.8 mg 100g⁻¹, 3.98 mg 100g⁻¹), which was at par with 5m × 5m (G₁) (6.75 mg 100g⁻¹, 3.93 mg 100g⁻¹) and 5m × 3m (G₃) (6.73 mg 100g⁻¹, 3.93 mg 100g⁻¹), respectively. Phosphorus was significantly higher in 5m × 3m (G₃) (0.45%), which was at par with 5m × 4m (G₂) (0.43%). The potassium was significantly higher in 5m × 5m (G₁) (0.77%) and 5m × 4m (G₂) (0.77%), which was at par with 5m × 3m (G₃) (0.75%). The copper content was significantly higher in 5m × 3m (G₃) (2.56 mg 100g⁻¹), which was at par with 5m × 4m (G₂) (2.55 mg 100g⁻¹) and 5m × 5m (G₁) (2.5 mg 100g⁻¹). The lentil variety IPL 316 (V₁) exhibited the most significant nutrient content among the tested varieties, viz. protein content, nitrogen, potassium, calcium, copper, and zinc, i.e., 26.01%, 4.16%, 0.79%, 0.46%, 2.59 mg 100g⁻¹, 3.92 mg 100g⁻¹) respectively. The phosphorus content was significantly higher in L 4727 (V₂), viz., 0.44%. There was no significant difference of lentil varieties on iron content in lentil seeds. The nutrient composition of lentil seeds is significantly affected by tree spacing and genetic potential in agroforestry systems, as it influences the microclimate, resource availability, and plant competition (Amassaghrou et al., 2023). The elevated phosphorus concentrations observed in high density *Melia dubia* plots may be attributed to nutrient sourcing from deeper soil layers facilitated by extensive root systems, which enhance vertical nutrient translocation. The favourable C:N ratio in lentils, coupled with their nitrogen-fixing ability, likely contributed to improved soil fertility and enhanced biomass

accumulation of *M. dubia* under intercropped conditions. This symbiotic nitrogen input may have supported tree growth in denser spacings by alleviating competition for soil nitrogen. In agroforestry systems, wider spacings generally provide superior light availability, less root competition, and enhanced access to soil nutrients for the intercrop, thus improving nutrient uptake and accumulation in seeds (Keprate et al., 2024). Conversely, reduced spacings may result in shade and underground competition, thus diminishing nutrient availability to plants and consequently decreasing seed nutritional content. Consequently, altering tree spacing is essential for improving intercrop yield and raising the nutritional quality of seeds, impacting both food security and the sustainability of soil fertility (Kumar et al., 2023). The relation between tree spacing and lentil variety is crucial in shaping the ultimate seed nutritional composition, and improving productivity in agroforestry systems. Zaki et al. (2017) reported that protein content and other quality parameters of pea seed were enhanced under *Sesbania sesban*-based alley cropping as compared to pea sole cropping. Painkra et al. (2023) revealed the enhancement of quality parameters of intercrops under peach-based agroforestry in the Chhattisgarh region. Dhewa et al. (2017) also observed an increase in protein content and other nutrients of green gram under *Tectona grandis* as compared with sole cropping of green gram. Sharma et al. (2023) studied the biochemical analysis, which demonstrated that the levels of total soluble protein were significantly elevated in the seeds of soybean cultivated under Aonla compared to the sole crop. Qiao et al. (2020) reported the increase in protein content of wheat under apricot based agroforestry, but the nutrients like nitrogen and phosphorus were reduced.



Litterfall and its nutrient concentration

Significant variations were observed in the litterfall and its nutrient concentrations under different tree spacings (Table 2). The significantly higher leaf litterfall was observed in 5m × 3m (G_3) (1.19 Mg ha^{-1}), which was followed by tree spacing 5m × 4m (G_2) (1.07 Mg ha^{-1}) and 5m × 5m (G_1) (0.99 Mg ha^{-1}). There was no significant effect of tree spacing on nutrient content in nitrogen, iron, and zinc. Phosphorus content was significantly higher in 5m × 3m (G_3) (0.17%), which was at par with 5m × 4m (G_2) (0.16%). Potassium content was significantly higher in 5m × 3m (G_3) (0.8%) and 5m × 4m (G_2) (0.8%), while calcium and copper were found significantly higher in 5m × 3m (G_3) (0.58%, $3.49 \text{ mg } 100\text{g}^{-1}$). Among the four months, the significantly higher leaf litterfall was observed in February (1.21 Mg ha^{-1}), whereas the lowest was observed in November (0.93 Mg ha^{-1}). The nitrogen content was significantly higher in December (0.92%) and January (0.92%), which was at par with November (0.9%). Phosphorus content was significantly higher in December (0.18%), whereas potassium, iron, and copper content were significantly higher in January (0.83%, $115.59 \text{ mg } 100\text{g}^{-1}$, $5.31 \text{ mg } 100\text{g}^{-1}$). Calcium was having significant differences among different months and was highest in January (0.58%) which was at par with December (0.56%), while zinc was significantly higher in January ($11.44 \text{ mg } 100\text{g}^{-1}$) which was at par with February ($11.28 \text{ mg } 100\text{g}^{-1}$). Litterfall and its nutrient composition are profoundly affected by tree spacing and seasonal variations in agroforestry systems, as space influences canopy structure, leaf density, and therefore the volume of biomass deposited into the soil (Bhardwaj et al., 2024). The higher litterfall observed under closer *M. dubia* spacing may arise from intensified

competition and accelerated nutrient translocation, leading to increased leaf turnover. However, leaves shed in these conditions are often lower in nutrient concentration, suggesting that quantity of litterfall may not always correspond to nutrient quality. The quantity and timing of litterfall are directly affected by tree spacing; closer spacings lead to denser canopies and increased litterfall during peak months, whereas wider spacings may decrease total litterfall. The nutrient-dense litter, especially regarding nitrogen (N), phosphorus (P), and potassium (K), is essential for restoring soil fertility and facilitating intercrop development (Fahad et al., 2022). Therefore, regulating tree spacing is crucial for enhancing biomass production and sustaining balanced nutrient input into the soil via litterfall, thereby ensuring the agroforestry system's sustainability. In *M. dubia*-based agroforestry systems, litterfall generally reaches its peak during the dry season, typically from December to March, when leaf senescence is most apparent due to moisture stress and physiological cycles. Gupta et al. (2010) found the higher leaf litter production in the *Albizia lebbek*-based agroforestry system without any pruning regimes, with more addition of nutrients. Kumar et al. (2021) revealed that the highest litterfall was noted in closer spacing than wider spacing, along with different nutrient concentrations in leaf litterfall in *Eucalyptus tereticornis*-based agroforestry. Gawali (2014) found that litterfall was significantly higher in closer spacing of 4m × 4m than wider spacings in *Ceiba pentandra*-based agroforestry. Singh et al. (2007); Singh (2009), and Singh et al. (2024) studied the litterfall content, nutrient concentrations in different spacings and different months of Poplar-based agroforestry in Punjab, wherein the highest litterfall was observed in closer spacing. Singh et al. (2023) reported a pattern of nutrient dynamics through

litterfall in *M. composita* plantation with different espacements under agroforestry, with the highest litterfall in closer spacing in December month with the highest nutrient contents.

Photosynthetically active radiation

The data in Figure 4 showed clear variations in the photosynthetically active radiation (PAR) received by the crop across several agroforestry system treatments. The photosynthetically active radiation (PAR) values varied between 304.09 and 652.85 $\mu\text{mol m}^{-2} \text{s}^{-1}$ in the G_0 (*Lens culinaris* sole cropping) and between 135.26 and 509.22 $\mu\text{mol m}^{-2} \text{s}^{-1}$ in the intercropped treatments (G_1 , G_2 , and G_3) during the October 2023 to March 2024 crop growth period. A decrease in light availability resulting from the presence of *M. dubia* trees was consistently seen in the intercropped treatments, as evidenced by lower PAR values compared to the sole cropping. Among tree spacings, 5 m $\times$ 3 m (G_3) exhibited the lowest PAR values, with values ranging from 135.26 to 410.68 $\mu\text{mol m}^{-2} \text{s}^{-1}$. The results emphasise the shading impact caused by *M. dubia* trees in the agroforestry system, leading to decreased light availability for the intercropped lentil crop. The diminishing pattern in PAR values as tree density increases highlights the need to take into account light availability during the establishment of agroforestry systems that include lentil or comparable pulse crops. Reduced PAR values under denser tree spacing not only limit photosynthesis but also alter the red:far-red phytochrome ratio, a key light quality signal regulating crop morphology and resource allocation under shaded environments (Smith, 2000). This change in light quality may explain variations in seed nutrient quality and growth responses of lentil under *M. dubia* spacing regimes. To achieve a satisfactory balance between tree benefits and agricultural yield in such environments, it is essential to optimize tree spacing and canopy management (Handiso et al., 2024). The shading caused by *M. dubia* leaves reduces the intensity of light, which in turn becomes a limiting factor in the decrease in yield of intercrops cultivated under *M. dubia*. Because of the shadowed conditions prevalent under block plantation, the data on PAR were higher in open conditions than under *M. dubia*. Gill et al. (2009) reported similar findings in the case of *M. dubia*, where there was a decrease in PAR under intercropping. Furthermore, several studies have examined the effects of various light conditions on crops in temperate agroforestry systems, including durum wheat and apple (Moretti et al., 2020). Peng et al. (2009) reported a significant reduction in photosynthetically active radiation (PAR) in a 4-year-old plantation of walnut and plum-based agroforestry spaced at 5 m $\times$ 3 m when intercropped with soybean maize. The effects of tree competition significantly reduced PAR in Neem-based agroforestry intercropped with black gram as compared to sole cropping (Pandey et al., 2010). Comparable results were also reported by Mukherjee and Sarkar (2016) in *Acacia auriculiformis*, *Casuarina equisetifolia*, *Dalbergia sissoo*, *Glyricidia sepium*, *Albizia lebbek*, *Gmelina arborea*, and *Eucalyptus hybrid* when intercropped with the tea crop in the eastern region of India.

Tree growth parameters

Perusal of data (Table 3) showed that there was no significant effect on tree growth parameters. The highest final height (8.49 m) was recorded in G_3V_1 , which had the initial height of 8.2 m. G_1V_1 recorded the highest final GBH (48.88 cm), which started with an initial GBH of 42.41 cm. G_3V_1 had the highest initial crown spread of 5.19 m and final crown spread of 5.73 m. The intercropped treatments in all spacings exhibited superior growth characteristics compared to sole trees indicating that reduction in the distance between trees and cultivating them together with lentil varieties contributed to the increase in height and non-significant changes in the girth of *M. dubia* trees in a very short span of time. The results revealed favourable impacts of intercropping on the growth of trees in the agroforestry systems. A possible cause for this result may be the complementarity between the tree and the crop. The finding was consistent with other research by Ashalatha et al. (2015) and Ali et al. (2023) that the height of the *M. dubia* tree was higher when it was grown alongside the agricultural crops in comparison to sole *M. dubia* trees. A similar trend was observed by Nandal and Kumar (2010) that the tree height of *M. dubia* was higher under an intercropped field than pure stand of *M. dubia*. Similar findings were obtained by Thakur et al. (2019) that the highest girth was observed in *M. composita*-based silvimedical system spaced at 3 m $\times$ 3 m compared to pure stands of *M. dubia* spaced at 2 m $\times$ 2 m. Several scientific studies have reported the advantageous impacts of intercropping on the girth of trees in *M. dubia*-based agroforestry systems (Mohanty et al., 2019). Prasad et al. (2010) observed that the growth attributes like height and diameter increased under different spatial arrangements of Eucalyptus-based agroforestry as compared to sole stands of Eucalyptus. Singh and Kumar (2014) found that a greater distance between trees in agroforestry systems led to a wider spread of the tree crown in poplar-based agroforestry. These findings align with the research conducted by Singh et al. (2017), which showed that intercropping with leguminous crops enhanced the development and enlargement of tree crowns of poplar in Uttar Pradesh.

Biomass and carbon estimation

Significant differences were observed among treatments for biomass estimation (Table 3). Before sowing, the significantly higher above ground biomass, below ground biomass and total biomass were recorded under G_3V_1 (24.51 Mg ha⁻¹, 6.37 Mg ha⁻¹, 30.88 Mg ha⁻¹), which was at par with G_3V_2 (24.45 Mg ha⁻¹, 6.35 Mg ha⁻¹, 30.8 Mg ha⁻¹), and G_3 (24.26 Mg ha⁻¹, 6.31 Mg ha⁻¹, 30.57 Mg ha⁻¹) while the lowest was under G_1 (14.97 Mg ha⁻¹, 3.89 Mg ha⁻¹, 18.86 Mg ha⁻¹). After harvest, biomass values increased markedly, with G_3V_2 showing the highest above ground biomass, below ground biomass and total biomass (33.89 Mg ha⁻¹, 8.81 Mg ha⁻¹, 42.7 Mg ha⁻¹), which was at par with G_3V_1 (33.08 Mg ha⁻¹, 8.6 Mg ha⁻¹, 41.68 Mg ha⁻¹) and G_3 (31.8 Mg ha⁻¹, 8.26 Mg ha⁻¹, 40.06 Mg ha⁻¹). There were significant differences observed for Carbon storage and CO₂ sequestration potential. Before sowing, the highest Carbon storage and CO₂ sequestration potential was recorded

TABLE 3 Growth, biomass, and carbon sequestration attributes of *M. dubia* under lentil intercropping in an agroforestry system.

Treatments	Tree height (m)	Girth at breast height (cm)	Crown spread (m)	Above-ground biomass (Mg ha ⁻¹)	Below-ground biomass (Mg ha ⁻¹)	Carbon storage (Mg ha ⁻¹)	CO ₂ sequestration potential (Mg ha ⁻¹)
Before sowing							
G ₁ V ₁ (AFS)	7.77	42.41	5.19	15.16	3.94	9.55	35.06
G ₁ V ₂ (AFS)	7.9	42.42	5.08	15.52	4.03	9.78	35.89
G ₁ (Sole tree)	7.72	42.01	5.01	14.97	3.89	9.43	34.63
G ₂ V ₁ (AFS)	7.94	41.96	4.95	18.93	4.92	11.93	43.77
G ₂ V ₂ (AFS)	7.95	41.94	4.97	19.09	4.96	12.02	44.15
G ₂ (Sole tree)	7.89	41.88	4.76	18.91	4.91	11.91	43.72
G ₃ V ₁ (AFS)	8.2	41.32	4.48	24.51	6.37	15.44	56.68
G ₃ V ₂ (AFS)	8.16	40.68	4.51	24.45	6.35	15.41	56.54
G ₃ (Sole tree)	8.05	40.07	4.36	24.26	6.31	15.28	56.1
S. Em.±	0.35	1.76	0.2	1.69	0.44	1.07	3.92
CD _{0.05}	NS	NS	NS	5.09	1.32	3.21	11.77
After harvest							
G ₁ V ₁ (AFS)	7.99	48.88	5.73	20.52	5.34	12.93	47.46
G ₁ V ₂ (AFS)	8.11	48.86	5.68	21.02	5.46	13.25	48.61
G ₁ (Sole tree)	7.90	48.39	5.53	19.88	5.17	12.52	45.96
G ₂ V ₁ (AFS)	8.16	48.13	5.41	25.4	6.61	16.01	58.74
G ₂ V ₂ (AFS)	8.18	48.16	5.38	25.69	6.68	16.18	59.34
G ₂ (Sole tree)	8.1	48.01	5.12	25.36	6.59	15.98	58.65
G ₃ V ₁ (AFS)	8.49	47.29	4.94	33.08	8.6	20.84	76.48
G ₃ V ₂ (AFS)	8.44	46.64	4.92	33.89	8.81	21.35	78.37
G ₃ (Sole tree)	8.29	46.01	4.68	31.8	8.26	20.03	73.52
S. Em.±	0.36	1.88	0.21	2.29	0.59	1.44	5.3
CD _{0.05}	NS	NS	NS	6.87	1.78	4.33	15.89

G₁V₁, *Melia dubia* at 5m × 5m + Lentil variety IPL 316; G₁V₂, *Melia dubia* at 5m × 5m + Lentil variety L 4727; G₁, *Melia dubia* at 5m × 5m sole tree; G₂V₁, *Melia dubia* at 5m × 4m + Lentil variety IPL 316; G₂V₂, *Melia dubia* at 5m × 4m + Lentil variety L 4727; G₂, *Melia dubia* at 5m × 4m sole tree; G₃V₁, *Melia dubia* at 5m × 3m + Lentil variety IPL 316; G₃V₂, *Melia dubia* at 5m × 3m + Lentil variety L 4727; G₃, *Melia dubia* at 5m × 3m sole tree.
NS, Non-significant at p ≤ 0.05.

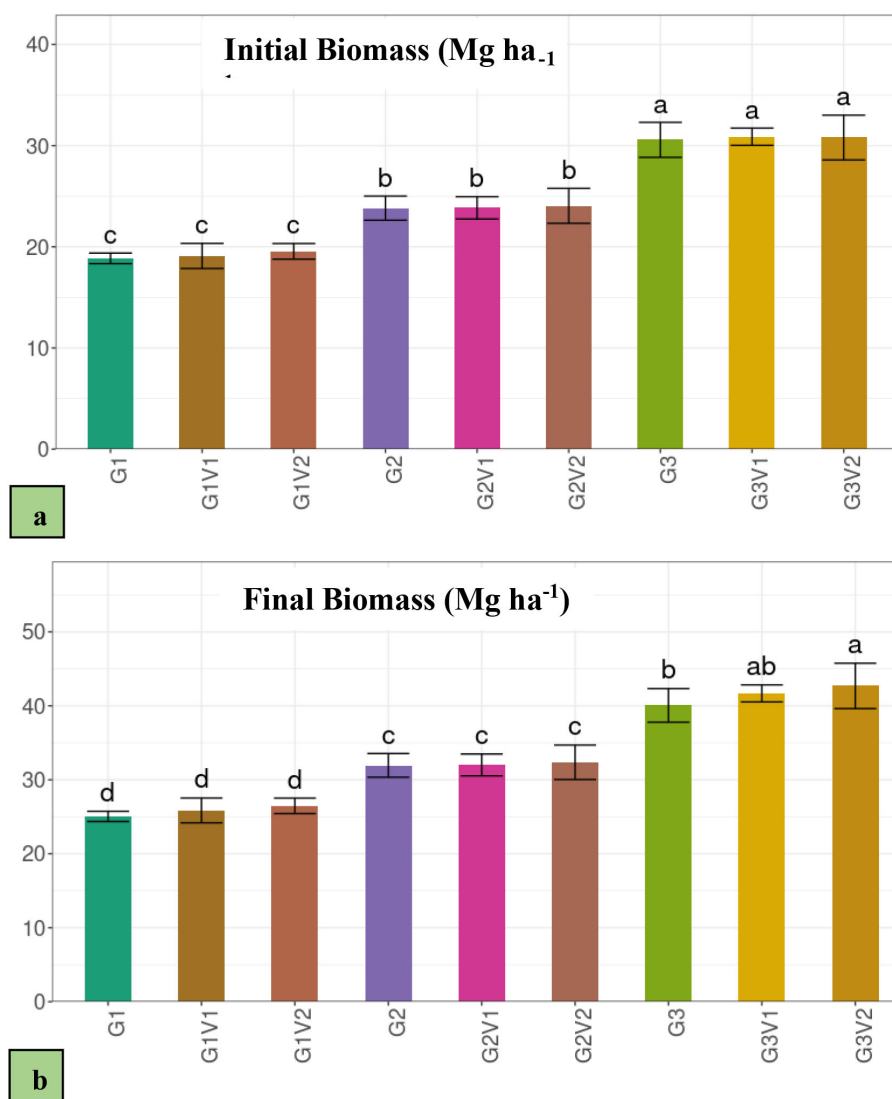


FIGURE 5

Total biomass [(a) initial biomass; (b) final biomass] of *Melia dubia* under under Lentil intercropping in agroforestry system (Treatments: G₁V₁ = *Melia dubia* at 5m × 5m + Lentil variety IPL 316, G₁V₂ = *Melia dubia* at 5m × 5m + Lentil variety L 4727, G₁ = *Melia dubia* at 5m × 5m sole tree, G₂V₁ = *Melia dubia* at 5m × 4m + Lentil variety IPL 316, G₂V₂ = *Melia dubia* at 5m × 4m + Lentil variety L 4727, G₂ = *Melia dubia* at 5m × 4m sole tree, G₃V₁ = *Melia dubia* at 5m × 3m + Lentil variety IPL 316, G₃V₂ = *Melia dubia* at 5m × 3m + Lentil variety L 4727, G₃ = *Melia dubia* at 5m × 3m sole tree). Lowercase letters on error bar denote statistical significance ($p \leq 0.05$) among treatment means. Treatment with same letter on error bar is statistically at par and vice versa.

under G₃V₁ (15.44 Mg ha⁻¹, 56.68 Mg ha⁻¹), which was at par with G₃V₂ (15.41 Mg ha⁻¹, 56.54 Mg ha⁻¹), and G₃ (15.28 Mg ha⁻¹, 56.1 Mg ha⁻¹), while the lowest was under G₁ (9.55 Mg ha⁻¹, 35.06 Mg ha⁻¹). After harvest, carbon storage and CO₂ sequestration potential increased markedly, with G₃V₂ showing the highest carbon storage and CO₂ sequestration potential (21.35 Mg ha⁻¹, 78.37 Mg ha⁻¹), which was at par with G₃V₁ (20.84 Mg ha⁻¹, 76.48 Mg ha⁻¹) and G₃ (20.03 Mg ha⁻¹, 73.52 Mg ha⁻¹). These studies have also shown that closer spacing in trees and intercropping practices can augment tree biomass production in agroforestry systems (Figure 5). Similar results were given by Ramesh et al. (2023) that Eucalyptus intercropped with pearl millet recorded higher above-ground biomass as compared to a sole stand of Eucalyptus. A three-year-old *M. dubia* plantation at a

density of 500 trees per hectare could sequester 25.64 Mg C ha⁻¹ in the Bundelkhand region of Central India (Gautam et al., 2025). Prajapati et al. (2020) also found a similar trend in an *M. dubia*-based silvopasture system. Vanlalngurzaiva et al. (2010) found the biomass of *Gmelina arborea* increases when intercropped with black gram and groundnut as compared to sole *G. arborea*. These findings further substantiate the results reported in our study by Prajapati et al. (2023) that higher biomass was obtained under spacing of 4m × 4m *M. dubia*-based silvopasture system. Chandana et al. (2020) observed that highest carbon stock was observed under closer spacing of *M. dubia*-based agroforestry. Agroforestry has substantial potential for carbon sequestration, this finding aligns with previous studies that have highlighted positive effects of intercropping (Murthy et al., 2013).

TABLE 4 Economic Analysis of the *M. dubia*-based agroforestry system.

Treatments	Cost of cultivation (US\$ ha ⁻¹)	Gross returns (US\$ ha ⁻¹)	Net returns (US\$ ha ⁻¹)	B: C Ratio
Tree spacings				
G ₀	485	798	313	1.64
G ₁	1240	3333	2093	2.68
G ₂	1352	3772	2420	2.79
G ₃	1444	4227	2783	2.92
SEm±	–	25.21	25.21	0.02
CD _{0.05}	–	87.24	87.24	0.06
Lentil varieties				
V ₁	1130	3060	1930	2.7
V ₂	1130	3004	1874	2.65
SEm±	–	14.16	14.16	0.01
CD _{0.05}	–	46.17	46.17	0.03
Interaction				
CD _{0.05}	–	NS	NS	NS

G₀, Sole lentil crop; G₁, *Melia dubia* at 5 m × 5 m; G₂, *Melia dubia* at 5 m × 4 m; G₃, *Melia dubia* at 5 m × 3 m; V₁, Lentil variety IPL 316; V₂, Lentil variety L 4727. NS, Non-significant at p ≤ 0.05.

Chauhan et al. (2012) demonstrated that carbon sequestration potential of *Populus deltoides* tree was higher under intercropping in poplar-wheat-based agroforestry.

Economic analysis

The cost of cultivating one hectare of land using various combinations of the *M. dubia*-based agroforestry system showed different trends (Table 4). As compared to lentil sole cropping, the expenses increased by 2–3 percent when planting *M. dubia* alongside lentil. The total cost of cultivation was calculated for the entire three-year establishment period of the *M. dubia* plantation, including the lentil intercrop season of 2023. On the other hand, when lentil was intercropped with *M. dubia* under 5m × 3m (G₃) and 5m × 4m (G₂) spacing, the net returns were \$2782 ha⁻¹ and \$2420 ha⁻¹, respectively. These returns were higher than sole cropping (G₀). Profitability increased progressively from G₀ to G₃, indicating that closer tree spacing positively impacts returns. The significantly higher Benefit-Cost Ratio (B:C) of 2.92 under 5m × 3m (G₃). Both varieties had similar costs of cultivation but differed slightly in gross returns, making IPL 316 (V₁) the preferred choice. Among the lentil varieties, the highest net returns of \$1930 ha⁻¹ with a Benefit-Cost Ratio of 2.7 were achieved by IPL 316 (V₁). The lesser return in sole cropping can be linked to the sole presence of a single crop, which produces comparatively lesser amounts and so generates diminished income. The findings align with the study conducted by Dev et al. (2020), which assessed the performance of sesame-chickpea in a bamboo-based agroforestry system and revealed that sesame-chickpea cultivation growing with bamboo yielded greater gross

returns and profits compared to growing it as a sole crop. Similar results were given by Pratap et al. (2020) under *M. composita*-based agroforestry. Thakur et al. (2022) and Jilariya et al. (2019) also observed higher net returns and greater benefit-cost ratio for *M. dubia*-based agroforestry in comparison to sole cropping.

Conclusion

The study emphasizes the diverse advantages of incorporating *M. dubia* into agroforestry systems alongside *L. culinaris* farming in the semi-arid Bundelkhand region. The spacing of trees markedly affected the nutrient composition of lentil seeds, the quantity and quality of litterfall, tree development patterns, biomass accumulation, carbon sequestration, and overall economic feasibility. The 5m × 3m (G₃) tree spacing exhibited optimal performance regarding total biomass (42.7 Mg ha⁻¹), carbon storage (21.35 Mg ha⁻¹), and CO₂ sequestration potential (78.37 Mg ha⁻¹), in addition to the highest litterfall (1.19 Mg ha⁻¹) and nutrient return to the soil, thereby improving ecosystem sustainability. The lentil variety IPL 316 (V₁) consistently outperformed L 4727 (V₂) in terms of nutrient quality attributes and profitability with net returns (\$ 1930 ha⁻¹). The economic analysis indicated that the G₃ spacing yielded the highest net returns (\$ 2783 ha⁻¹) and Benefit-Cost Ratio (2.92), suggesting that denser spacings can enhance profitability while preserving the ecological balance. Despite diminished photosynthetically active radiation (PAR) under denser tree cover impacting crop light availability, the compensatory benefit of improved soil nutrient recycling and elevated crop nutritional quality highlights the benefits of optimized agroforestry systems. This study confirms that a properly managed *M. dubia*-based agroforestry system can enhance crop

production, ecological resilience, and farmers' income, establishing it as a sustainable land use model for climate-vulnerable areas.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

PD: Conceptualization, Formal Analysis, Investigation, Methodology, Project administration, Software, Visualization, Writing – original draft, Writing – review & editing. PT: Conceptualization, Formal Analysis, Investigation, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing. MD: Conceptualization, Resources, Supervision, Writing – original draft, Writing – review & editing. RY: Conceptualization, Data curation, Formal Analysis, Methodology, Resources, Validation, Writing – original draft, Writing – review & editing. AH: Conceptualization, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing. NK: Conceptualization, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. DR: Conceptualization, Formal Analysis, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. ID: Data curation, Formal Analysis, Visualization, Writing – original draft, Writing – review & editing. DY: Conceptualization, Data curation, Validation, Visualization, Writing – original draft, Writing – review & editing. HA: Conceptualization, Data curation, Formal Analysis, Validation, Writing – original draft, Writing – review & editing. AS: Investigation, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. VS: Formal Analysis, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. AK: Data curation, Formal Analysis, Software, Writing – original

draft, Writing – review & editing. SB: Formal Analysis, Supervision, Visualization, Writing – original draft, Writing – review & editing.

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