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Growth and biomass performance of Gamhar (*Gmelina arborea* Roxb.) under different intercropping systems in an agroforestry system at Ranchi, Jharkhand

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Abstract

Agroforestry, the deliberate integration of woody perennials with agricultural crops, offers a means of combining timber production with continued agricultural output. *Gmelina arborea* Roxb. (Gamhar), a fast-growing multipurpose tree species widely used in Indian agroforestry, is commonly intercropped with short-duration legumes during its early growth phase. A two-year field investigation (2023-2025) was carried out at the agroforestry research farm of Birsa Agricultural University, Ranchi, Jharkhand, to evaluate the growth and biomass performance of Gamhar trees under three intercropping systems Gamhar + pigeon pea (*Cajanus cajan*), Gamhar + cowpea (*Vigna unguiculata*) and Gamhar + black gram (*Vigna mungo*) in comparison with a sole Gamhar plantation, laid out in a Randomized Block Design with three replications. Tree height, diameter at breast height (DBH), crown width, crown length, leaf area index (LAI), sub-canopy light intensity, stem volume and above-ground, below-ground and total biomass, along with their annual increments, were recorded over the study period. Intercropping with pigeon pea consistently produced the greatest tree height, DBH, crown dimensions, stem volume increment and biomass accumulation, followed closely by cowpea intercropping, while sole Gamhar recorded the lowest values for most growth attributes throughout the study. Pigeon pea intercropping enhanced pooled total biomass increment by 27.17% and pooled stem volume increment by 36.27% over the sole plantation. Sub-canopy light transmittance declined progressively with tree age and was lowest under the densest-canopy pigeon pea treatment. The results indicate that intercropping Gamhar with leguminous crops, particularly pigeon pea and cowpea, promotes superior tree growth and biomass accumulation compared with monoculture plantation, likely through improved soil nitrogen economy from symbiotic fixation and better moisture conservation, and can therefore be recommended as an economically and ecologically beneficial land-use option for the Eastern Plateau and Hill region of India.

Keywords: *Gmelina arborea*, agroforestry, intercropping, tree growth, biomass, leaf area index, stem volume

Introduction

Agroforestry the deliberate integration of woody perennials with agricultural crops and/or livestock on the same unit of land is widely recognized as a sustainable land-use strategy that combines timber and wood production with continued agricultural output while improving the ecological functioning of farmland. Globally, smallholder farmers across South and South-East Asia increasingly integrate fast-growing timber species such as *Gmelina arborea* into their farming systems alongside food and fruit crops to diversify income streams while establishing a longer-term timber asset. As output from natural forests and existing industrial plantations in the Asia-Pacific region struggles to keep pace with rising regional wood consumption, farm-grown timber from systems of this kind is taking on a larger share of the region's wood supply, which in turn raises the practical stakes of understanding and improving how well these on-farm trees actually perform (Darabant *et al.*, 2025) [10]. Among the multipurpose tree species used in tropical agroforestry, *Gmelina arborea* Roxb. (family Lamiaceae,

syn. Verbenaceae), commonly known as *Gamhar*, has emerged as one of the most preferred species across South and South-East Asia, including India, Bangladesh, Myanmar, Sri Lanka, Thailand, China and Indonesia (Warrier *et al.*, 2021) [24]. The species is valued for its fast juvenile growth attaining roughly 30 m in height and 60 cm DBH within 15 years under favourable conditions, with reported mean annual volume increments in the order of 12-50 m³ ha⁻¹ yr⁻¹ depending on site quality (Zeaser, 1999) [25] its coppicing ability, and its compatibility with a wide range of understorey crops. It performs best on well-drained, fertile soils but tolerates a broad climatic envelope, with a natural temperature range of about 20-45°C (Tewari, 1995) [21] and rainfall regimes from 760 to 4,500 mm (PROTA, 2016) [18]. Its pale, even-grained timber is widely used for furniture, plywood and packing material, with small-diameter material harvested from about 7-10 years and market-grade timber obtained from more mature stands, mature plantations reportedly yielding in the order of 250-300 t ha⁻¹ (Troup, 1921) [22]. Because of its rapid growth,

multiple end-uses and favourable economic returns, *Gamhar* is often positioned as a substitute for teak and is a preferred species among farmers and forest-based industries in eastern India. Its adaptability is not confined to its traditional range either: when planting stock sourced from Jharkhand was trialled well outside the species' usual eastern-India seed zone, at four demonstration sites across the lower Himalayan tracts of Himachal Pradesh and Jammu & Kashmir, roughly six trees in seven were still standing two years on, pointing to a species that can take hold in agroforestry settings quite different from where it is conventionally grown (Bala, 2025)^[2].

Since *Gamhar* is predominantly grown under an agrisilvicultural arrangement, its early growth is strongly influenced by the accompanying intercrop through effects on soil moisture, nutrient competition, microclimatic modification and canopy/root management, and a growing body of recent evidence continues to reinforce this tree-crop interaction. Working with a *Gmelina arborea*-based agrisilvicultural system at Birsa Agricultural University, Ranchi the same experimental site as the present study Kumar *et al.* (2026)^[14] recently reported that intercropping *Gamhar* with pigeon pea, cowpea-mustard or greengram-mustard produced a markedly higher land equivalent ratio and superior economic viability than a sole *Gamhar* plantation, confirming the productivity advantage of legume-based intercropping under the same agro-climatic conditions examined here. In a comparable evaluation on degraded lateritic soils of north-eastern India, Biswas *et al.* (2022)^[4] found that pigeon pea intercropping raised the timber yield of *Gmelina arborea* from 4.39 to 4.64 m³ ha⁻¹ yr⁻¹ within an agri-horti-silviculture system relative to *Gamhar* grown without pigeon pea, directly corroborating a growth-promoting effect of legume intercropping on the tree component. Likewise, in a split-plot evaluation of *Gmelina arborea*- and *Alnus nepalensis*-based systems in the Eastern Himalayan region, Choudhury *et al.* (2025)^[1] reported that the tree component enriched soil nutrient status and favourably influenced the physiological performance of associated understorey crops relative to open cropping, illustrating that the tree-crop facilitation in *Gamhar*-based agroforestry operates in both directions. Bala (2025)^[2], evaluating *Gmelina arborea* for introduction into agroforestry systems of the lower Indian Himalayan region using planting stock sourced from Jharkhand, similarly highlighted the species' rapid early growth and wide site adaptability as key attributes underpinning its suitability for smallholder agrisilviculture.

Several field-level studies specifically documenting *Gamhar* growth response to legume intercrops further support these findings. Momin *et al.* (2017)^[15], working with a *Gamhar*-mango based agroforestry system in the red and lateritic soils of West Bengal, found that intercropping with pigeon pea was the most effective of five arable crops tested in improving the growth and soil-fertility performance of the tree component, while Vanlalngurzaiva *et al.* (2010)^[23] and Banerjee and Dhara (2009)^[3] recorded the greatest height and DBH of *Gamhar* under black gram intercropping in a similar red-and-lateritic agroforestry model. In an earlier long-term evaluation of an agri-horti-silvicultural system on red and lateritic soils, Dhara (BCKV, Jhargram) likewise reported that the growth characters of *Gmelina arborea*

were consistently higher where the interspaces were cropped than under a pure, uncropped stand, confirming a facilitative rather than competitive tree response to intercropping in this soil type. The enhanced growth under legume intercropping has generally been attributed to biological nitrogen fixation by root-nodulating companion crops, which improves the nitrogen economy of the shared rhizosphere, together with the additional tillage, weeding and residual soil-moisture conservation associated with intercrop management (Swamy *et al.*, 2008)^[19]. At the same time, below-ground competition between tree and crop roots can, under certain intercrop combinations or spacing regimes, depress rather than enhance tree growth (Swamy *et al.*, 2008)^[19], underscoring the importance of intercrop choice in determining the direction and magnitude of the tree-crop interaction.

Despite the wide cultivation of *Gamhar*-based agrisilvicultural systems in the Chotanagpur plateau region of Jharkhand, and despite recent economic evaluations of this same experimental system (Kumar *et al.*, 2026)^[14], quantitative, treatment-wise data on the comparative growth and biomass response of the *Gamhar* tree component itself to different leguminous intercrops under the acidic, red lateritic soils of this agro-climatic zone remain limited. A clearer understanding of these responses is necessary to identify intercrop combinations that maximise tree productivity without compromising the yield of the companion crop, and to strengthen recommendations for *Gamhar*-based agroforestry as a climate-resilient, income-diversifying land-use option. Keeping these considerations in view, the present investigation was undertaken with the following objectives: (i) to study the growth and canopy performance height, DBH, crown dimensions, leaf area index and stem volume of *Gamhar* trees under different intercropping systems; (ii) to estimate the above-ground, below-ground and total biomass accumulated by *Gamhar* trees, along with their annual increments, under the different treatments; and (iii) to compare the growth and biomass performance of intercropped *Gamhar* against a sole *Gamhar* plantation over two years of active intercropping at Ranchi, Jharkhand. The parameters selected for this investigation were chosen to give a complete and mutually reinforcing picture of tree performance, consistent with the growth-and-biomass framing of the study. Height, DBH, crown width and crown length are direct dendrometric measures of structural growth, while stem volume integrates height and DBH into a single measure of standing timber accretion, directly relevant to the productive value of *Gamhar* as a plantation species. Leaf area index and sub-canopy light intensity were included not as growth measures in themselves but as canopy-structural and microclimatic parameters that mechanistically link tree growth to the light environment beneath the stand, a relationship of direct practical relevance for selecting shade-tolerant intercrops as the canopy closes with advancing rotation age. Above-ground, below-ground and total biomass, together with their annual increments, complete the assessment by translating structural growth into a quantitative measure of carbon and biological yield accumulation, the dimension most closely tied to the economic and ecological value of the tree component in an agrisilvicultural system. Taken together, these growth, canopy and biomass parameters provide a

comprehensive basis for evaluating and comparing the tree-component performance of Gamhar under the different intercropping systems examined, consistent with the objectives of the study.

2. Materials and Methods

2.1 Study Site

The investigation was carried out at the agroforestry research farm adjoining the Ranchi Veterinary College campus of Birsa Agricultural University (BAU), Kanke, Ranchi, Jharkhand, falling within Agroclimatic Zone VII, Sub-Zone IV (Central and North-Eastern Plateau Zone) of the Eastern Plateau and Hill Region. The site lies at an elevation of about 625 m above mean sea level, on the southern margin of the Chotanagpur plateau. The region experiences a humid subtropical climate (Köppen classification) with three well-marked seasons summer (March-June), the rainy season (June-October) and winter (November-February) and receives a mean annual rainfall of 1,304-1,409 mm, more than 80% of which is contributed by the south-west monsoon between June and September. Summer maxima range from about 20 to 42°C and winter minima from 0 to 25°C. The experimental soil is a lateritic, sandy-loam derivative of granite-gneiss, free-draining but structurally weak, acidic in reaction, low in organic matter and available nitrogen, and deficient to medium in available phosphorus, characteristic of the red and lateritic Alfisols that dominate about 71% of Jharkhand's land area.

2.2 Experimental Materials

2.2.1 Tree component *Gmelina arborea* (Gamhar) trees, planted on 4 July 2018, formed the perennial component of the system. Leaf fall occurs between January and March, with flushing and flowering following from February to April, and the species regenerates readily from seed or coppice, responding strongly to weeding and irrigation in its early years.

2.2.2 Intercrop components: Three kharif-season legume intercrops were evaluated in combination with Gamhar: pigeon pea (*Cajanus cajan* (L.) Millsp. cv. UPAS-120), a deep-rooted, nitrogen-fixing legume maturing in 120-130 days; cowpea (*Vigna unguiculata* (L.) Walp. cv. Swarna Mukut), a dual-purpose grain-and-fodder legume reaching maturity in 90-125 days; and black gram (*Vigna mungo* (L.) Hepper, cv. Birsa Urd-1), a short-duration nitrogen-fixing legume maturing in 60-80 days. All three crops were compared against a sole Gamhar plantation without an intercrop.

2.3 Experimental Design and Layout

The trial was laid out in a Randomized Block Design (RBD) with three replications. Each plot carried 16 Gamhar trees at a spacing of 8 m × 2.5 m, chosen to allow adequate canopy and root development alongside space for intercrop cultivation. The present study reports the growth and biomass performance of Gamhar under the four treatments in which standing trees were present, namely Gamhar + pigeon pea, Gamhar + cowpea, Gamhar + black gram, and sole Gamhar, monitored at baseline (2023) and after the first

(2024) and second (2025) year of intercropping.

2.4 Field Preparation and Crop Management

Ahead of each monsoon (early June), the interspaces of the established Gamhar stand were worked with tractor-drawn implements one deep ploughing, followed by harrowing and planking to prepare a fine, weed-free seedbed. Sowing dates for the kharif intercrops were governed by monsoon onset and fell in June of both years, with seed hand-sown in open furrows at row spacings and seed rates of 45 cm/15 kg ha⁻¹ (pigeon pea), 45 cm/20 kg ha⁻¹ (cowpea) and 30 cm/15 kg ha⁻¹ (black gram); cowpea and black gram seed was treated with Thiram + Carbendazim and Rhizobium culture prior to sowing. Crops were harvested manually with sickles at physiological maturity and processed following standard threshing procedures.

2.5 Growth Parameters of Gamhar

Total tree height (base of trunk to tip of leading shoot) was measured on standing trees using a graduated bamboo pole, and diameter at breast height (DBH, outside-bark stem diameter at 1.37 m) was recorded with a digital calliper; both were measured at the start (March) and close (November) of the active growth period in each year (Chaturvedi and Khanna, 1982)^[6]. Crown width was taken as the mean of two perpendicular crown diameters, and crown length was measured from the apex of the tree to the midpoint between the lowest live branch and the crown base (Chaturvedi and Khanna, 1982)^[6]. Individual-tree stem volume was estimated using the quadratic volume equation of Akinnifesi and Akinsanmi (1995)^[11]:

$$V = 0.0206 + 0.00004 D^2 H \quad (r^2 = 0.975)$$

where V is stem volume (m³ tree⁻¹), D is DBH (cm) and H is tree height (m); per-tree values were scaled to a per-hectare basis using stand density. Volume increment (%) was calculated as $[(V_e - V_i) / V_i] \times 100$, where V_i and V_e are the initial (March) and final (November) stem volumes, respectively.

2.6 Leaf Area Index and Sub-Canopy Light Intensity

Leaf area index (LAI) was estimated non-destructively for three representative trees per plot using the specific-leaf-area (SLA) method: a sub-sample of approximately 50 leaves was collected from the upper, middle and lower canopy strata of each tree, leaf area was measured with a leaf-area meter, and the sample was oven-dried at 70°C to constant weight to derive SLA (cm² g⁻¹); total canopy leaf dry weight, obtained from destructive sampling of one border-row tree per treatment at the close of each growing season, was then multiplied by the corresponding SLA and divided by the ground area occupied by the tree canopy to obtain LAI, following standard SLA-based non-destructive procedures (Jonckheere *et al.*, 2004)^[13]. Sub-canopy light intensity was recorded with a digital lux meter (Lutron LX-107HA) at 1:00 pm under full-sun, cloud-free conditions at four fixed points per plot beneath the tree canopy and at an adjacent open-area reference point, and is expressed both in k Lux and as a percentage of open-area light intensity.

2.7 Biomass Estimation

Above-ground biomass (AGB) was estimated using the pan-tropical allometric model of Chave *et al.* (2014)^[7]:

$$AGBest = 0.0673 \times (\rho D^2 H)^{0.976}$$

where D is DBH (cm), H is tree height (m) and ρ is wood specific gravity ($g\ cm^{-3}$), with values scaled to $t\ ha^{-1}$ using stand density. Below-ground biomass (BGB) was estimated by applying the IPCC (2006) default root-to-shoot ratio of 0.26 the mean value reported by Cairns *et al.* (1997)^[5] from a review of 160 tropical and temperate forest studies to the corresponding AGB (BGB = AGB $\times$ 0.26), and total biomass was obtained as the sum of AGB and BGB.

2.8 Statistical Analysis

Data recorded during the study were subjected to analysis of variance (ANOVA) appropriate to a Randomized Block Design, carried out in SPSS. Sources of variation were tested for significance using the F-ratio at the 5% probability level, and the Standard Error of Mean (S.Em $\pm$) was computed as the population standard deviation divided by $\sqrt{n}$. Treatment means were separated using the Critical Difference (C.D.) at the 5% level, with pairwise comparisons made using Duncan’s Multiple Range Test (DMRT), and treatment variability was summarised through the coefficient of variation (C.V., %), following standard procedures (Cochran and Cox, 1957; Panse and Sukhatme, 1967; Gomez and Gomez, 1984)^[9, 11, 17].

3. Results and Discussion

3.1 Tree Height and Diameter at Breast Height (DBH)

Data on tree height, height increment, DBH and DBH increment of Gamhar trees, recorded at baseline (2023) and after the first (2024) and second (2025) year of intercropping, are presented in Table 1. Both parameters, along with their annual increments, differed significantly ($p = 0.05$) among treatments in each year of observation as well as in the pooled analysis of increments. Tree height was recorded highest under Gamhar + pigeon pea (4.97, 5.73 and 7.13 m during 2023, 2024 and 2025, respectively), remaining statistically at par with Gamhar + cowpea (4.81, 5.64 and 6.77 m) throughout, and additionally at par with

Gamhar + black gram (4.77 m) in 2023 and with all three intercropped treatments in 2025, while it was significantly superior to sole Gamhar (4.46, 5.43 and 6.47 m) in every year. Pigeon pea intercropping thus enhanced tree height by 11.43, 5.52 and 10.20 per cent over the sole plantation in 2023, 2024 and 2025, respectively, with cowpea and black gram intercropping producing intermediate gains of 7.85-4.64 and 6.95-3.55 per cent, respectively. In the pooled analysis of increments, all three intercropped treatments (0.95-1.09 m) were statistically at par with one another and significantly higher than sole Gamhar (0.94 m). DBH followed a broadly similar pattern, being maximum under Gamhar + pigeon pea (9.57, 10.73 and 12.72 cm in 2023, 2024 and 2025) and statistically at par with Gamhar + cowpea (9.26, 10.98 and 12.69 cm), but significantly higher than sole Gamhar (8.88, 10.13 and 11.79 cm), translating into 7.77, 5.92 and 7.89 per cent higher DBH under pigeon pea intercropping. Cowpea intercropping recorded the single highest DBH of all treatments in 2024 (10.98 cm, 8.39% over sole), underlining that the two legume intercrops performed comparably in promoting girth increment; sole Gamhar recorded the lowest DBH increment in every year (Table 1). The consistently superior height and girth growth of Gamhar under leguminous intercropping agrees with Momin *et al.* (2017)^[15], who found pigeon pea to be the most effective of five arable intercrops in improving the growth performance of Gamhar in a Gamhar-mango agroforestry system, and with Vanlalngurzaiva *et al.* (2010)^[23] and Banerjee and Dhara (2009)^[3], who recorded the greatest height and DBH of Gamhar under black gram intercropping. Similarly, Singh *et al.* (2024) reported a regular increase in both height and girth of *Gmelina arborea* under agroforestry over successive years, and Kumar *et al.* (2026)^[14], working at the same experimental site, recorded the highest land-use efficiency and profitability under Gamhar + pigeon pea among all agrisilvicultural treatments evaluated, consistent with the superior height and DBH gains recorded here under the same intercrop. The enhanced growth may be ascribed to biological nitrogen fixation by the root-nodulating intercrops, together with the additional tillage, weeding and residual soil-moisture conservation associated with intercrop management (Swamy *et al.*, 2008)^[19].

Table 1: Height (m) and diameter at breast height (cm) of Gamhar trees with their respective annual increment under different intercropping systems

Treatment	Ht 2023 (m)	Ht 2024 (m)	Ht 2025 (m)	Ht Incr. 23-24	Ht Incr. 24-25	Ht Incr. Pooled
Gamhar + Pigeon pea	4.97a	5.73a	7.13a	0.76a	1.40a	1.09a
Gamhar + Cowpea	4.81a	5.64a	6.77a	0.83ab	1.13a	0.98a
Gamhar + Black gram	4.77ab	5.60b	6.70a	0.83b	1.10ab	0.95a
Sole Gamhar	4.46b	5.43b	6.47b	0.97c	1.04b	0.94b
S.Em $\pm$	0.04	0.06	0.09	0.02	0.03	0.02
CD ($p=0.05$)	0.12	0.17	0.26	0.05	0.09	0.07
CV (%)	4.81	5.11	5.72	6.55	7.43	7.07

Means followed by the same letter(s) within a column do not differ significantly at $p = 0.05$ as per DMRT.

Table 2: DBH (cm) of Gamhar trees with their respective annual increment under different intercropping systems

Treatment	DBH 2023 (cm)	DBH 2024 (cm)	DBH 2025 (cm)	DBH Incr. 23-24	DBH Incr. 24-25	DBH Incr. Pooled
Gamhar + Pigeon pea	9.57a	10.73a	12.72a	1.16a	1.99a	1.58a
Gamhar + Cowpea	9.26ab	10.98a	12.69ab	1.72a	1.71ab	1.70ab
Gamhar + Black gram	9.13ab	10.65ab	12.41bc	1.52a	1.76bc	1.66bc
Sole Gamhar	8.88b	10.13b	11.79c	1.25b	1.66c	1.42c
S.Em±	0.07	0.10	0.16	0.04	0.07	0.05
CD (p=0.05)	0.20	0.31	0.49	0.12	0.21	0.17
CV (%)	5.09	5.18	5.43	6.27	6.94	6.67

Means followed by the same letter(s) within a column do not differ significantly at $p = 0.05$ as per DMRT.

3.2 Crown width and crown length

Data on crown width and crown length of Gamhar trees, along with their annual increments, are furnished in Table 3, which revealed significant ($p = 0.05$) variation among treatments during all years of observation and in the pooled analysis of increments. Crown width was recorded maximum under Gamhar + pigeon pea (3.42, 4.93 and 6.64 cm during 2023, 2024 and 2025), exceeding sole Gamhar (2.95, 4.13 and 5.88 cm) by 15.93, 19.37 and 12.93 per cent, respectively, followed by Gamhar + cowpea (3.19, 4.61 and 6.17 cm) and Gamhar + black gram (3.18, 4.54 and 5.96 cm). Crown length showed an analogous pattern, being

greatest under Gamhar + pigeon pea (3.92, 5.25 and 6.72 cm), 10.73-12.18 per cent higher than sole Gamhar (3.54, 4.68 and 6.06 cm) across the three years. The consistently larger crown dimensions recorded under intercropping, particularly with pigeon pea and cowpea, indicate that lateral and vertical canopy expansion of Gamhar was facilitated rather than suppressed by the associated legumes, likely on account of the wider effective growing space, reduced weed competition and improved nutrient availability in these plots a trend also noted by Momin *et al.* (2017) ^[15] for tree crown development in gamhar-based intercropping systems.

Table 3: Crown width (cm) and crown length (cm) of Gamhar trees under different intercropping systems

Treatment	Crown W 2023	Crown W 2024	Crown W 2025	Crown L 2023	Crown L 2024	Crown L 2025
Gamhar + Pigeon pea	3.42a	4.93a	6.64a	3.92a	5.25a	6.72a
Gamhar + Cowpea	3.19ab	4.61ab	6.17b	3.68ab	5.00b	6.48ab
Gamhar + Black gram	3.18bc	4.54bc	5.96bc	3.57b	4.84bc	6.27bc
Sole Gamhar	2.95c	4.13c	5.88c	3.54b	4.68c	6.06c
S.Em±	0.02	0.04	0.08	0.03	0.04	0.07
CD (p=0.05)	0.06	0.12	0.25	0.08	0.13	0.21
CV (%)	6.19	7.32	8.21	6.63	7.07	7.83

Means followed by the same letter(s) within a column do not differ significantly at $p = 0.05$ as per DMRT. Cm = cm; W = width; L = length.

3.3 Leaf Area Index and Light Intensity under Tree Canopy

Table 4 presents the leaf area index (LAI) of Gamhar trees together with the light intensity (k Lux) transmitted below the tree canopy and its equivalent as a percentage of open-area light intensity, both of which varied significantly ($p = 0.05$) among treatments in all years of observation. LAI was consistently maximum under Gamhar + pigeon pea (2.17, 2.61 and 3.37 during 2023, 2024 and 2025), exceeding sole Gamhar (1.89, 2.37 and 2.86) by 14.81, 10.13 and 17.83 per cent, respectively, and remaining at par with the cowpea treatment (2.03, 2.56 and 3.25) throughout the study.

As a direct consequence of the progressively denser canopy associated with higher LAI, light transmittance beneath the canopy declined most sharply in the pigeon pea

intercropping treatment, where sub-canopy light intensity fell to 29.85, 24.52 and 16.67 k Lux (33.79, 27.12 and 18.54 per cent of open-area intensity) during 2023, 2024 and 2025, respectively a reduction of 13.07, 11.29 and 22.52 per cent relative to sole Gamhar, which recorded the least shading (34.34, 27.64 and 21.52 k Lux). Open-area (unshaded) light intensity itself measured 88.34, 90.43 and 89.92 k Lux during 2023, 2024 and 2025, respectively. The progressive decline in transmitted light with tree age reflects the expected canopy closure typical of a maturing Gamhar stand and carries direct implications for intercrop and shade-tolerant species selection in the later phase of the rotation, a consideration also highlighted by Kumar *et al.* (2026) ^[14] for gamhar-based agrisilvicultural systems of the Eastern Plateau region.

Table 4: Leaf area index and sub-canopy light intensity (k Lux, and % of open-area intensity) under different intercropping systems

Treatment	LAI 2023	LAI 2024	LAI 2025	Light 2023 (kLux)	Light 2024 (kLux)	Light 2025 (kLux)
Gamhar + Pigeon pea	2.17a	2.61a	3.37a	29.85b	24.52c	16.67c
Gamhar + Cowpea	2.03ab	2.56ab	3.25b	32.01ab	25.14bc	17.71b
Gamhar + Black gram	1.91bc	2.48b	3.00b	33.99ab	26.17b	20.06b
Sole Gamhar	1.89c	2.37c	2.86c	34.34a	27.64a	21.52a
S.Em±	0.02	0.02	0.04	1.19	1.10	0.98
CD (p=0.05)	0.05	0.07	0.11	3.65	3.38	3.01
CV (%)	5.87	6.37	7.08	5.09	5.81	7.13

Means followed by the same letter(s) within a column do not differ significantly at $p = 0.05$ as per DMRT. Open-area light intensity: 88.34, 90.43 and 89.92 k Lux during 2023, 2024 and 2025, respectively.

3.4 Stem volume and volume increment

Stem volume, its annual increment and the corresponding volume increment percentage of standing Gamhar trees are presented in Table 5. Variation in stem volume among treatments was non-significant in the baseline year (2023) but became significant ($p = 0.05$) in 2024 and 2025, while increment and increment percentage varied significantly among treatments in both years and in the pooled analysis. Stem volume was numerically greatest under Gamhar + pigeon pea in 2023 ($19.40 \text{ m}^3 \text{ ha}^{-1}$, 11.94% over sole) and 2025 ($33.37 \text{ m}^3 \text{ ha}^{-1}$, 17.96% over sole), at par with cowpea intercropping and significantly higher than sole Gamhar (17.33 and $28.29 \text{ m}^3 \text{ ha}^{-1}$, respectively); in 2024, cowpea intercropping recorded the single highest value ($23.90 \text{ m}^3 \text{ ha}^{-1}$, 11.47% over sole).

The pooled stem volume increment was highest under pigeon pea intercropping ($7.89 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$, 36.27% over sole), against $5.79 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ for sole Gamhar, and the percentage volume increment mirrored this trend, being highest under pigeon pea intercropping in the pooled analysis (31.89%, 14.75 percentage points over sole). This pattern of accelerating stand volume increment with advancing age, and its enhancement under legume intercropping, is consistent with growth trends reported for *Gmelina arborea* under agrisilviculture by Swamy *et al.* (2008) [19], while the comparatively lower absolute stem volumes recorded here, relative to older stands such as those studied by Onyekwelu *et al.* (2006) [16], reflect the early/mid-rotation stage of the present plantation.

Table 5: Stem volume ($\text{m}^3 \text{ ha}^{-1}$), stem volume increment ($\text{m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) and volume increment (%) of Gamhar trees under different intercropping systems

Treatment	Vol. 2023	Vol. 2024	Vol. 2025	Incr. 23-24	Incr. 24-25	Incr. Pooled	Incr.% Pooled
Gamhar + Pigeon pea	19.40	23.50a	33.37a	4.09a	9.87a	7.89a	31.89a
Gamhar + Cowpea	18.55	23.90ab	32.10ab	5.35ab	8.20ab	7.52ab	31.52ab
Gamhar + Black gram	18.25	23.00ab	30.94b	4.75b	7.93b	7.29b	30.29b
Sole Gamhar	17.33	21.44b	28.29c	4.11c	6.84c	5.79c	27.79c
S.Em±	0.17 (NS)	0.20	0.33	0.06	0.23	0.15	0.63
CD ($p=0.05$)	—	0.61	1.02	0.19	0.70	0.47	1.94
CV (%)	4.58	4.78	5.70	11.31	13.45	12.28	6.55

NS = non-significant at $p = 0.05$. Means followed by the same letter(s) within a column do not differ significantly at $p = 0.05$ as per DMRT.

3.5 Above-Ground, Below-Ground and Total Biomass

The above-ground biomass (AGB), below-ground biomass (BGB) and total biomass accumulated by standing Gamhar trees, as influenced by the different intercropping treatments, are presented in Table 6. Inter-treatment variation in tree biomass was significant ($p = 0.05$) in all three years of observation, and the differential biomass response to intercropping became progressively more pronounced with advancing stand age. AGB was recorded maximum under Gamhar + pigeon pea (6.06 and 15.03 t ha^{-1} during 2023 and 2025; 28.66 and 27.48% over sole), while in 2024 cowpea intercropping recorded the single highest AGB (8.97 t ha^{-1} , 21.38% over sole). BGB followed an identical ranking, being greatest under pigeon pea intercropping in 2023 and 2025 (1.57 and 3.90 t ha^{-1}) and under cowpea intercropping in 2024 (2.33 t ha^{-1}), against 1.22 , 1.92 and 3.06 t ha^{-1} for sole Gamhar. Consequently, total tree biomass was also highest under Gamhar + pigeon

pea in 2023 and 2025 (7.64 and 18.94 t ha^{-1} ; 28.62 and 27.54% over sole) and under Gamhar + cowpea in 2024 (11.31 t ha^{-1} , 21.48% over sole), significantly exceeding sole Gamhar (5.94 , 9.31 and 14.85 t ha^{-1} in 2023, 2024 and 2025) throughout the study period. The magnitude of biomass gain under intercropping recorded here is broadly consistent with the land-use and productivity advantage reported for the same Gamhar + pigeon pea treatment by Kumar *et al.* (2026) [14] at this experimental site, and with the tree-growth advantage under intercropping reported by Biswas *et al.* (2022) [4] for Gamhar grown with pigeon pea on comparable lateritic soils, while the somewhat lower gains recorded under black gram intercropping reflect the closer below-ground competition noted for certain intercrop-spacing combinations by Swamy *et al.* (2008) [19], underscoring the importance of intercrop choice in determining the direction of the tree-crop interaction (Fig. 1).

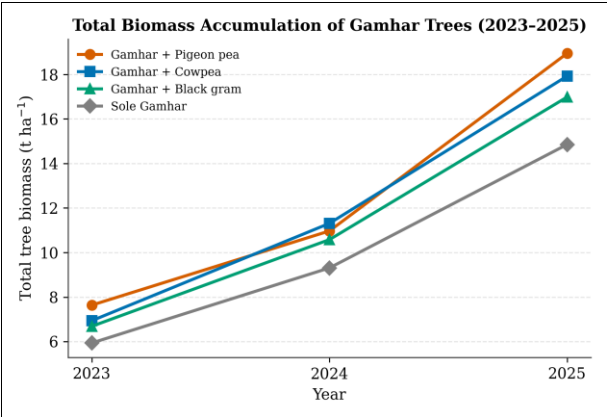


Fig 1: Total tree biomass accumulation of Gamhar (t ha^{-1}) across the three years of observation, illustrating the progressively widening gap between intercropped and sole plantations (data from Table 6).

Table 6: Above-ground biomass, below-ground biomass and total biomass (t ha^{-1}) of Gamhar trees under different intercropping systems

Treatment	AGB 2023	AGB 2024	AGB 2025	BGB 2023	BGB 2024	BGB 2025	Total 2023	Total 2024	Total 2025
Gamhar + Pigeon pea	6.06a	8.71a	15.03a	1.57a	2.26a	3.90a	7.64a	10.97a	18.94a
Gamhar + Cowpea	5.51ab	8.97ab	14.23ab	1.43ab	2.33ab	3.69ab	6.94ab	11.31ab	17.92ab
Gamhar + Black gram	5.32ab	8.39ab	13.48bc	1.38	2.18ab	3.50bc	6.69ab	10.58ab	16.98bc
Sole Gamhar	4.71b	7.39b	11.79c	1.22	1.92b	3.06c	5.94b	9.31b	14.85c
S.Em $\pm$	0.13	0.20	0.35	0.03	0.05	0.09	0.17	0.25	0.45
CD ($p=0.05$)	NS	0.61	1.09	NS	0.16	0.28	NS	0.76	1.37
CV (%)	5.77	6.27	7.24	5.77	6.27	7.24	5.77	6.27	7.24

NS = non-significant at $p = 0.05$. Means followed by the same letter(s) within a column do not differ significantly at $p = 0.05$ as per DMRT. AGB = above-ground biomass; BGB = below-ground biomass.

3.6 Annual Increments in Biomass

Annual increments in AGB, BGB and total biomass of standing Gamhar trees are presented in Table 7, which varied significantly ($p = 0.05$) among treatments in both years of observation and in the pooled analysis. Increment in AGB was greatest under Gamhar + cowpea during 2023-24 ($3.46 \text{ t ha}^{-1} \text{ yr}^{-1}$, 49.14% over sole) but shifted to Gamhar + pigeon pea during 2024-25 ($6.32 \text{ t ha}^{-1} \text{ yr}^{-1}$, 43.64% over sole) and in the pooled analysis ($4.54 \text{ t ha}^{-1} \text{ yr}^{-1}$, 30.46% over sole), against 2.32, 4.40 and $3.48 \text{ t ha}^{-1} \text{ yr}^{-1}$ for sole Gamhar in the respective periods.

As a resultant, total biomass increment was maximum under cowpea intercropping in 2023-24 ($4.36 \text{ t ha}^{-1} \text{ yr}^{-1}$, 29.76%

over sole) and under pigeon pea intercropping in 2024-25 and pooled data (7.96 and $5.57 \text{ t ha}^{-1} \text{ yr}^{-1}$; 43.68 and 27.17% over sole), compared with 3.36, 5.54 and $4.38 \text{ t ha}^{-1} \text{ yr}^{-1}$ for sole Gamhar. The progressively widening gap between intercropped and sole treatments across the study period suggests a cumulative facilitative effect of legume intercropping on Gamhar biomass accretion, likely mediated through improved soil nitrogen status arising from symbiotic fixation by the companion legumes together with better moisture conservation under the intercropped canopy a mechanism also invoked by Swamy *et al.* (2003) [19] to explain enhanced *Gmelina arborea* growth under legume-intercropped agrisilviculture systems (Fig. 2).

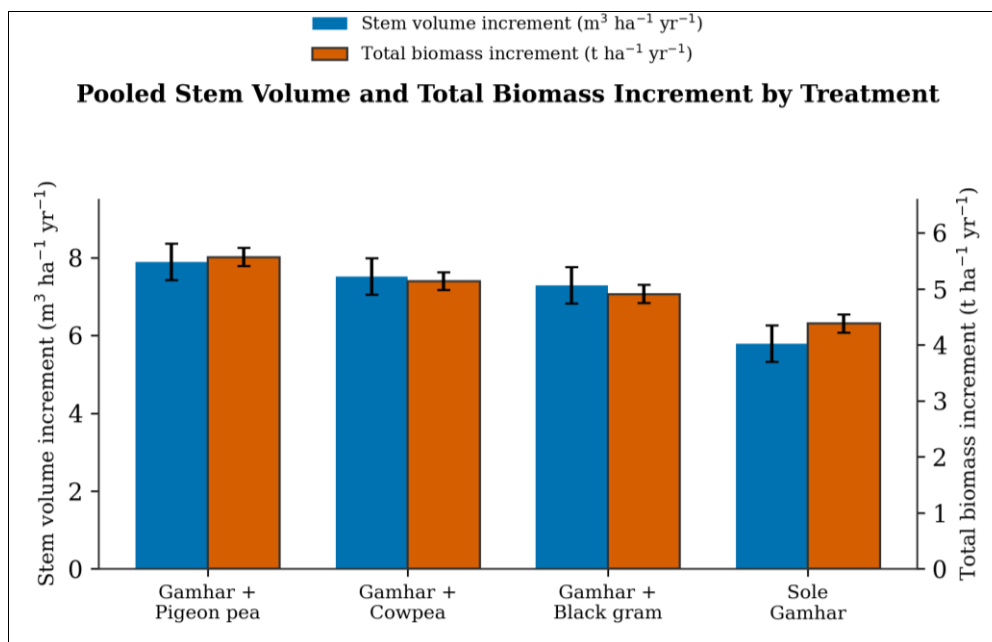


Fig 2: Pooled stem volume increment and pooled total biomass increment of Gamhar under different intercropping systems, showing the concordant ranking of the two growth measures (error bars = CD at $p = 0.05$; data from Tables 5 and 7).

Table 7: Annual increments in above-ground biomass, below-ground biomass and total biomass ($\text{t ha}^{-1} \text{ yr}^{-1}$) of Gamhar trees under different intercropping systems

Treatment	AGB Incr. 23-24	AGB Incr. 24-25	AGB Incr. Pooled	BGB Incr. Pooled	Total Incr. 23-24	Total Incr. 24-25	Total Incr. Pooled
Gamhar + Pigeon pea	2.65a	6.32a	4.54a	1.15a	3.33a	7.96a	5.57a
Gamhar + Cowpea	3.46ab	5.25ab	4.08ab	1.06ab	4.36ab	6.61ab	5.14ab
Gamhar + Black gram	2.53bc	5.08b	3.90b	1.01b	3.88bc	6.40b	4.91b
Sole Gamhar	2.32c	4.40c	3.48c	0.90c	3.36c	5.54c	4.38c
S.Em $\pm$	0.07	0.18	0.12	0.03	0.09	0.22	0.16
CD ($p=0.05$)	0.22	0.55	0.39	0.10	0.28	0.69	0.49
CV (%)	8.67	10.19	9.70	9.70	8.67	10.19	9.70

Means followed by the same letter(s) within a column do not differ significantly at $p = 0.05$ as per DMRT. AGB = above-ground biomass; BGB = below-ground biomass.

4. Conclusion

Two years of field evaluation at Ranchi, Jharkhand demonstrate that intercropping Gamhar (*Gmelina arborea* Roxb.) with short-duration legumes measurably improves the growth and biomass performance of the tree component relative to a sole plantation, with the effect strengthening as the stand matured. Pigeon pea intercropping delivered the strongest response, raising pooled stem volume increment by 36.27% and pooled total biomass increment by 27.17% over sole Gamhar, with cowpea intercropping producing a closely comparable gain and black gram an intermediate one; sole Gamhar consistently ranked lowest across nearly all growth and biomass parameters. This pattern is consistent with a facilitative rather than competitive tree-crop interaction, most plausibly driven by biological nitrogen fixation from the companion legumes together with the improved soil-moisture and weed-management conditions that accompany intercrop cultivation, and it is reinforced by the parallel decline in sub-canopy light transmittance under the densest-canopy treatments, indicating that canopy and productivity responses moved together rather than independently. Taken as a whole, these results position pigeon pea- and cowpea-based Gamhar agrisilviculture as an ecologically sound and economically promising land-use option for the acidic, red lateritic soils of the Eastern Plateau and Hill Region, capable of delivering enhanced tree productivity alongside continued legume income during the early years of the rotation. As the growth advantage of the intercropped treatments widened progressively rather than plateauing over the two years studied, these findings should be read as evidence of an early-stage trend from a single site rather than a final verdict on system performance; extending observation through canopy closure and subsequent crop rotations to full harvest age remains necessary to confirm whether the trend persists and to convert the present growth and biomass gains into verified timber-yield and system-level economic outcomes on which a broader recommendation can be built.

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