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Silvicultural characterization and biochemical variation of *Butea monosperma* (Lam.) Taub. across different diameter classes and localities in the Bundelkhand region

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Introduction: *Butea monosperma* (Lam.) Taub. is an ecologically and economically important dry-deciduous tree species widely distributed in the semi-arid Bundelkhand region. Despite its multipurpose utility, like gum production, flowers for dye, fodder, fuelwood, and medicinal compounds, there is limited scientific information on its growth variation, biomass and carbon dynamics, and nutritional composition across diameter classes and localities. Understanding silvicultural behaviour and biochemical variation is crucial for optimizing its use in agroforestry, carbon sequestration, and livelihood enhancement in the Bundelkhand region.

Methods: A multistage stratified random sampling approach was adopted across 10 localities (Jhansi and Lalitpur districts), covering agroforestry systems (AFS) and naturally regenerated areas (NRA). The research employed a factorial randomized block design with the first factor as three diameter classes: D₁ (10–30 cm), D₂ (30–50 cm), and D₃ (>50 cm), and the second factor as locality (L₁–L₅). Trees per class per site were measured for DBH, height, stem volume, above- and below-ground biomass, carbon stock, and CO₂ mitigation potential. Reproductive traits (leaf and flower characteristics), gum yield, and biochemical properties of gum and flowers were analysed using standard laboratory procedures.

Results: Diameter class exerted a significant influence on tree growth, biomass accumulation, and carbon sequestration. The largest diameter class (D₃) consistently recorded the highest DBH (55.56 cm), stem volume (10.90 m), AGB (0.72 t tree⁻¹), BGB (0.18 t tree⁻¹), Carbon stock (0.45 t tree⁻¹), and CO₂ mitigation potential (1.67 t tree⁻¹) in Jhansi district. Lalitpur district also followed the same trend in terms of growth, biomass, and carbon parameters. Reproductive traits such as leaf fresh/dry weight and flower characteristics showed mostly non-significant differences among diameter classes and localities. Gum yield was significantly highest ($p \leq 0.05$) in Jhansi and Lalitpur districts in medium-sized trees (D₂) (207.76 g tree⁻¹, 224.6 g tree⁻¹), indicating locality-specific physiological responses. Biochemical composition of gum exhibited significant variation, with higher phenolic content (13.61 mg g⁻¹), ash (4.12%), and ascorbic acid (42.08 mg

100 g⁻¹) in larger diameter trees. Flower biochemical traits differed significantly across sites, with Lalitpur showing greater variation in phenols (16.03 mg g⁻¹), ash (6.78%), antioxidants (68.90%), and carotenoids (37.14 mg 100 g⁻¹). Overall, D₂ and D₃ trees demonstrated superior biochemical traits, reflecting higher metabolic activity.

Conclusion: *Butea monosperma* shows substantial variation in growth performance, carbon sequestration potential, gum productivity, and biochemical composition across diameter classes and localities in Bundelkhand. Larger trees serve as major contributors to biomass and carbon storage, while gum and biochemical quality are influenced by both tree size and site conditions. The findings highlight that *B. monosperma* has strong ecological resilience and economic potential, supporting its wider adoption in agroforestry and livelihood-based interventions in semi-arid regions.

KEYWORDS

Butea monosperma, agroforestry, carbon stock, biochemical variation, biomass accumulation

Introduction

Forests are crucial to the ecological balance of the planet, playing a significant role in maintaining biodiversity, regulating climate, and supporting the livelihood of many people (Deshmukh et al., 2025a). In India, forests cover and tree cover is about 25.17% of the total geographical area (Forest Survey of India, 2023), providing habitat to a wide variety of flora and fauna (Talukdar et al., 2024). Forest is the source of food, timber, fuelwood, livestock grazing, and medicines, which contribute significantly to the economy and subsistence of rural and marginal communities (Aryee et al., 2024; Tiwari et al., 2024; Tiwari and Deshmukh, 2025). The Bundelkhand, located in Central India, forms an essential part of the country's natural resources and is home to several species of trees (Lal et al., 2024). The Bundelkhand region spans seven districts in Uttar Pradesh and six districts in Madhya Pradesh, covering an area of approximately 7.85 million hectares. The climate in this region is characterized by high temperatures and erratic rainfall, with an average annual precipitation of 900 mm (Singh et al., 2024). However, the region faces numerous challenges, including deforestation, land degradation, harsh climatic conditions, inadequate infrastructure, low agricultural productivity, low in fertility, poor water retention capacity, limited crop diversification, etc. which contribute to uncertainty in livelihoods of local communities (Gupta et al., 2014; Singh Jatav, 2020; Dobhal et al., 2024; Deshmukh et al., 2025b). The livelihood of the people in this region is predominantly agriculture-based, serving as the primary source of income and employment. The farming system is dominated by small and marginal farmers, characterized by fragmented landholdings, poverty, limited institutional support, and restricted access to markets and modern technologies.

Despite the challenging conditions, this region is home to a diverse range of tree species, many of which thrive in forest areas and agroforestry systems (Yadav, 2024), with species like *Acacia* spp., *Anogeissus* spp., and *B. monosperma* being dominant (Verma and Pal, 2019). The tree species in this region play a vital role in stabilizing the environment by controlling soil erosion, maintaining soil fertility, and improving the water-holding capacity of the soil (Palsaniya and Ghosh, 2016; Jinger et al., 2022; Behera et al., 2024). Among them, *B. monosperma* is an important agroforestry tree, commonly found at

an average density of 10–15 trees per hectare in farmers' fields across Bundelkhand, within various agroforestry systems, and trees occur naturally and are widely distributed on degraded land, common grazing area, and forest (Ramanan et al., 2024).

Butea monosperma (Lam.) is one of the most common trees, and is known as Palas, Dhak, Tesu, and Chhulla in various regional languages. It belongs to the Fabaceae family and is native to tropical and subtropical climates, especially in the Indian subcontinent and Southeast Asia (Kumar et al., 2023). It is widely distributed across India, particularly in Uttar Pradesh, Madhya Pradesh, Bihar, Odisha, and Jharkhand (Chavan et al., 2015). The tree is known for its bright orange-red flowers, which bloom during the dry season, giving rise to its name, the Flame of the Forest (More et al., 2012). It is a medium-sized, deciduous, and leguminous tree, typically growing to a height of 12–15 metres (Kunjam et al., 2021). Its bark is fibrous and rough, exuding a reddish-brown juice known as Butea gum or Bengal kino (Dhakad et al., 2023). The wood of *B. monosperma* is soft and greenish-white in colour, while its leaves are large, leathery, and pinnate (Das et al., 2022). The flowers, which bloom from February to April, are vibrant and attract various pollinators, including bees and birds (Kushwaha et al., 2017). The tree naturally reproduces through seeds and vegetative propagation from root suckers (Chaudhary et al., 2024). *Butea monosperma* is a light-demanding tree that is drought-tolerant, frost-hardy, and coppicing in nature (Fayiah et al., 2018). These silvicultural characteristics make it remarkably adaptable to a wide range of climatic conditions. It thrives in diverse environments, including flooded areas, black cotton soils, saline soils, alkaline soils, swampy and poorly drained soils, as well as barren lands (Dagar et al., 2016). The tree can tolerate mean annual temperatures ranging from 10 °C to 50 °C, and its distribution is generally confined to altitudes up to 1,500 metres (Karuppusamy, 2024) its resilience to drought, ability to grow in poor soils, and its role in agroforestry systems (Rai et al., 2016; Dagar and Gupta, 2021). *Butea monosperma* plantations are commonly observed in drier plain regions, forest areas, open grasslands, and scattered within mixed forests and wastelands due to its adaptability to a wide range of climatic conditions (Raj et al., 2014; Singh et al., 2016).

Butea monosperma is a multipurpose tree with significant ecological, economic, and medicinal value (Sindhia and Bairwa, 2010; Hiremath et al., 2024). In terms of medicinal applications, *B.*

monosperma has been utilized in traditional Ayurvedic, Unani, and Homeopathic medicine (Tiwari et al., 2019). The tree exhibits a range of pharmacological properties such as anti-diabetic, antioxidant, antimicrobial, antifungal, anti-inflammatory, and anticancer activities (Kumari et al., 2022). Phytochemicals like monospermoside, butin, chalcones, flavonoids, and tannins are present in different parts of the plant, which contribute to its therapeutic effects (Joshi et al., 2024). The flowers of *B. monosperma* are used to prepare a natural orange-red dye, which is popular in the textile industry, especially during the festival of Holi (Sinha et al., 2012). Additionally, the tree produces lac, a resin harvested from the branches of the tree by lac insects (Kumar et al., 2017). The wood pulp of *B. monosperma* is suitable for manufacturing newsprint and packaging materials, while its leaves are used for making plates, cups, and wrappers (Chakrabarty and Datta, 2020).

Tree-based livelihood in the Bundelkhand region plays a critical role in sustaining local livelihoods (Jinger et al., 2023). Among these, *B. monosperma* has a dominant population, which plays a vital role in Bundelkhand by offering ecological, economic, and socio-cultural benefits, with immense potential to enhance rural income (Dagar and Tewari, 2016). It has the potential to provide alternative livelihood options to local farmers in the forms of gum, flower dye, lac, leaf plate, and donna, retention of existing trees (Lahori and Jain, 2020). Its ability to thrive under semi-arid and resource-constrained conditions enhances its suitability as a key agroforestry species. *Butea monosperma* is an important tree, commonly found in farmers' fields across Bundelkhand, though the study on its distribution and silvicultural

characterization in agroforestry systems and naturally regenerated areas is limited, particularly across different diameter classes and locations. The current study was designed with the objectives to study the growth performance, silvicultural characterization, and distribution patterns of *B. monosperma* in Jhansi and Lalitpur districts of Bundelkhand, along with the estimation of biochemical and nutritional composition in flowers and gum obtained from *B. monosperma*.

Materials and methods

Study area

The study was conducted in Jhansi and Lalitpur districts, located within the Bundelkhand region of Uttar Pradesh (Figure 1), which lies between latitudes 24.6° N and 25.5° N and longitudes 78.4° E to 78.6° E (Table 1). Both districts lie at an average elevation of 328 metres above sea level and fall within a semi-arid climatic zone, characterized by a rugged and undulating terrain. The region has poor soil cover, which is predominantly shallow, coarse-textured, and rocky. These edaphic conditions contribute to low water retention capacity, resulting in a major portion of the limited rainfall averaging between 800 to 900 mm annually being lost to surface runoff. The variability and unreliability of rainfall exacerbate the moisture stress, with the number of rainy days fluctuating between 48 and 75 per year, followed

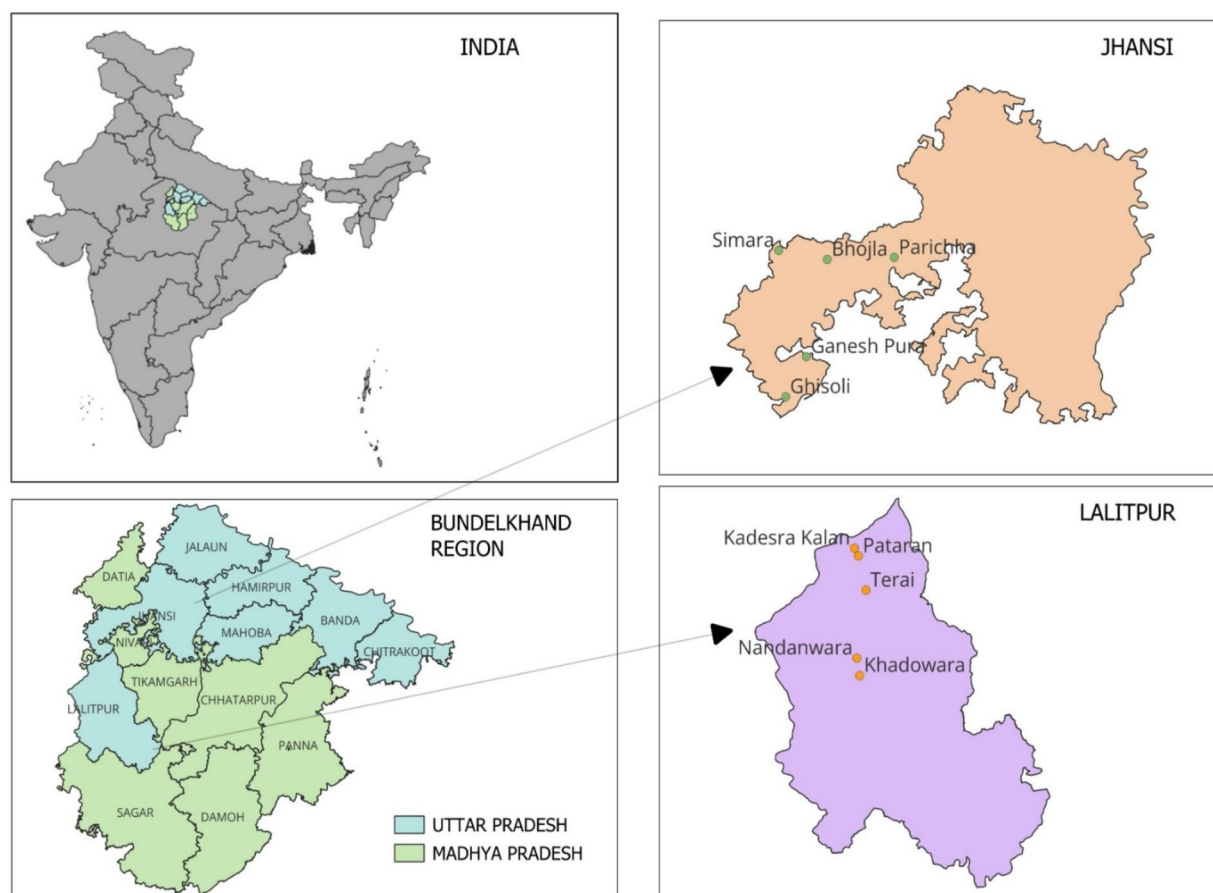


FIGURE 1
Location map of study sites in Jhansi and Lalitpur districts of the Bundelkhand region, India.

TABLE 1 Geographic coordinates of study sites in Jhansi and Lalitpur districts.

District	Study site	Latitude (°N)	Longitude (°E)
Jhansi	L ₁ : Ghisoli	25.174243	78.462601
	L ₂ : Ganesh Pura	25.274788	78.516212
	L ₃ : Parichha	25.522778	78.744731
	L ₄ : Simra	25.540276	78.444499
	L ₅ : Bhojla	25.517771	78.570641
Lalitpur	L ₁ : Khadowara	24.747495	78.461063
	L ₂ : Terai	24.977425	78.478402
	L ₃ : Nandan Wara	24.794261	78.453386
	L ₄ : Pataran	25.069553	78.457523
	L ₅ : Kadesra Kalan	25.090294	78.446326

by prolonged dry periods lasting from 3 to 7 months. Temperatures can soar up to 48 °C during the peak summer months, intensifying drought conditions and posing substantial challenges for agriculture and water availability.

Experimental details

The study was conducted using a multistage stratified random sampling method to ensure adequate representation of different localities and diameter classes. In the first stage, two districts of the Bundelkhand region in Uttar Pradesh, namely Jhansi and Lalitpur, were selected. In the second stage, five localities were randomly selected from each district. The research employed a factorial randomized block design using diameter classes with diameter between 10 and 30 cm (D₁), diameter between 30 and 50 cm (D₂), and diameter above 50 cm (D₃), as the first factor. During the study period, five locations (L₁–L₅), each from Jhansi and Lalitpur districts, were employed as the second factor, and replicated five times. A systematic distributional analysis of *B. monosperma* was carried out to understand its growth, biomass, and carbon parameters along with leaf and flower morphological traits in the study area. For the distributional analysis of *B. monosperma* in agroforestry systems and naturally regenerated areas in different localities, where the trees were selected based on each diameter class. In the present study, an agroforestry system was defined as agricultural lands where *B. monosperma* trees are integrated with seasonal crop cultivation. The trees were either grown along the field boundaries or interspersed within the farmland where intercrops were grown. These systems represent a field-level tree-crop combination, typical of farmer-managed agroforestry practices in the Bundelkhand region. Naturally occurring populations of *B. monosperma* were studied in forest patches, wastelands, grassland and fallows in farmer own land.

Measurement of growth, biomass, and carbon parameters

Growth parameters of *B. monosperma* trees were recorded following standard forestry procedures (Chaturvedi and Khanna, 1982).

Tree height (m) was measured from ground level to the top of the crown using a Haga altimeter. Diameter at breast height (DBH) was measured at 1.37 m above ground using a tree calliper. Tree stem volume was estimated using the tree bio-volume formula $TBV = 0.4 \times D^2 \times H$, where D is diameter (m), and H stands for height (m) (Dave et al., 2018). Above-ground biomass (AGB) was derived by multiplying tree stem volume with wood density (0.465 t m⁻³) (Salunkhe et al., 2016), and below-ground biomass (BGB) was estimated as 26% of AGB (Ravindranath and Ostwald, 2008). Carbon storage was calculated by multiplying the sum of AGB and BGB by a carbon fraction of 0.5. The CO₂ mitigation potential was then determined by multiplying stored carbon by 3.67, representing the molecular weight ratio of CO₂ to C (Howard et al., 2014).

Leaf and flower parameters

For leaf parameters, three mature leaves were randomly collected from the canopy of each tree between September and February. Fresh and dry leaf weights were determined using an electronic balance, with drying done at 55–60 °C for 60 h to a constant weight. Leaf length and leaf width were measured using an electronic leaf area metre. During the flowering time in the months of February–March, the flowers have been collected manually from the selected trees of different localities. Three panicles per tree were selected, and panicle length was measured from the peduncle base to the terminal tip using a measuring scale. Flower fresh weight was determined by weighing three randomly collected flowers per tree, while dry weight was recorded after drying the flowers under sunlight to a constant weight.

Gum collection

Gum collected from the selected trees through the gum extraction method, i.e., the knotching method. The knotching method is a traditional technique used for gum extraction based on the principle of induced injury to the bark, which stimulates the tree's natural defence response (Chavan et al., 2016). Gum extraction in *B. monosperma* using the knotching method was carried out during the months of November and December. The process began with cleaning the bark to remove surface debris and dead bark. Sharp tools such as a bill hook, axe, or similar instruments were used to make incisions on the tree. Each incision measured approximately 1.0 cm in depth, 2.5 cm in length, and 0.5 cm in width, and was made in an upward direction from bottom to top. After the incisions were made, the trees were left undisturbed for 2–3 days to allow the gum to ooze out and harden. The ruby-coloured brittle gum exudates were then collected manually by hand. The total gum yield per tree was recorded by weighing the collected gum.

Qualitative parameters

Reliable biochemical analysis requires careful sample preparation and standardized laboratory procedures. For the biochemical estimations of *B. monosperma* flowers and gum, replications were maintained by compositing samples collected from randomly selected trees under each treatment. 0.1 g of each sample was homogenized and processed according to standard analytical protocols. Total phenolic content was determined by extracting the sample in 80% ethanol, followed by centrifugation and reaction with Folin–Ciocalteu reagent; absorbance was recorded at 650 nm to quantify phenols (Gol et al.,

2015). For ash estimation, a pre-weighed amount of dried sample was placed in a crucible and ignited in a muffle furnace at 575 °C until a constant weight was obtained, and the ash percentage was calculated gravimetrically.

Antioxidant activity was assessed using the DPPH free radical scavenging method. The methanolic extract of the sample was reacted with a DPPH solution and incubated in the dark, and the reduction in absorbance at 515 nm was used to compute antioxidant activity (Abrol et al., 2014). Total carotenoid content was estimated by extracting pigments in acetone, transferring them into petroleum ether, and measuring absorbance at 452 nm; carotenoid concentration was expressed as mg β -carotene equivalent per 100 g of sample. Ascorbic acid content was determined by extracting the sample in 3% metaphosphoric acid and titrating the filtrate against 2,6-dichlorophenol indophenol dye, with results expressed as mg 100 g⁻¹ based on the calculated dye factor (Pila et al., 2010). Crude fat was quantified through Soxhlet extraction using petroleum ether, and the percentage of fat was computed from the difference in sample weight before and after extraction (AOAC, 1975).

Statistical analysis

Data on growth, biomass, carbon parameters, along with leaf and flower morphological traits, were analysed using analysis of variance (ANOVA) for a factorial randomized block design, with diameter classes (D₁–D₃) as the first factor and locations from both Jhansi and Lalitpur district (L₁–L₅) as the second factor. The biochemical analysis

of flowers and gums was also conducted. Treatment differences were analysed using OPSTAT software at 5% level of significance.

Results and discussion

Growth, biomass, carbon attributes, and leaf–flower morphological traits of *Butea monosperma* in agroforestry system in Jhansi District

The diameter class had a significant influence on growth, biomass, and carbon attributes of *Butea monosperma* in agroforestry systems in Jhansi district (Table 2). Trees in D₃ (above 50 cm) recorded the significantly highest growth, biomass, and carbon parameters ($p \leq 0.05$) (DBH 55.56 cm, tree height 10.90 m, stem volume 1.55 m³, AGB 0.72 t tree⁻¹, BGB 0.18 t tree⁻¹, carbon stock 0.45 t tree⁻¹, and CO₂ mitigation potential 1.67 t tree⁻¹). These results indicate a strong positive relationship between diameter class and biomass accumulation, carbon storage, and CO₂ mitigation potential. Leaf and flower traits were observed as non-significant across diameter classes. However, the highest leaf fresh weight was observed in D₃ (3.28 g), leaf dry weight in D₂ (1.90 g), flower fresh weight and dry weight in D₃ (1.90 g and 0.47 g), leaf length, leaf width, and panicle length in D₂ (15.44 cm, 14.19 cm, 15.80 cm), respectively.

The growth, biomass, and carbon have a significant effect across the localities (Table 2). The significantly highest growth, biomass, and

TABLE 2 Tree growth, biomass, and carbon parameters of *Butea monosperma* trees in agroforestry systems (AFS) and naturally regenerated areas (NRA) of different localities in Jhansi district.

Treatments	DBH (cm)		Tree height (m)		Tree stem volume (m ³)		Above-ground biomass (t tree ⁻¹)		Below-ground biomass (t tree ⁻¹)		Carbon stock (t tree ⁻¹)		CO ₂ mitigation potential (t tree ⁻¹)	
	AFS	NRA	AFS	NRA	AFS	NRA	AFS	NRA	AFS	NRA	AFS	NRA	AFS	NRA
Diameter class														
D ₁	22.43	22.71	6.50	6.40	0.13	0.13	0.06	0.06	0.01	0.01	0.04	0.04	0.14	0.14
D ₂	37.45	38.50	9.21	9.07	0.56	0.58	0.26	0.27	0.06	0.07	0.16	0.17	0.60	0.62
D ₃	55.56	53.33	10.90	10.61	1.55	1.21	0.72	0.56	0.18	0.15	0.45	0.35	1.67	1.30
SE (m)	1.15	0.90	0.33	0.28	0.09	0.04	0.04	0.02	0.01	0.01	0.02	0.01	0.09	0.04
CD (0.05)	3.29	2.56	0.94	0.80	0.25	0.12	0.11	0.06	0.03	0.03	0.07	0.03	0.27	0.13
Locations														
L ₁	35.45	35.28	9.46	8.98	0.57	0.52	0.26	0.24	0.07	0.06	0.16	0.15	0.61	0.56
L ₂	38.59	38.72	7.64	7.71	0.56	0.57	0.26	0.26	0.06	0.07	0.16	0.17	0.60	0.62
L ₃	44.03	38.28	9.78	9.11	1.22	0.70	0.57	0.32	0.14	0.08	0.36	0.2	1.31	0.75
L ₄	39.49	39.49	8.90	9.00	0.73	0.73	0.34	0.33	0.08	0.09	0.21	0.21	0.78	0.78
L ₅	38.17	39.15	8.58	8.67	0.65	0.68	0.30	0.31	0.07	0.08	0.19	0.19	0.70	0.73
SE (m)	1.49	1.16	0.43	0.36	0.11	0.05	0.05	0.02	0.01	0.01	0.03	0.07	0.12	0.06
CD (0.05)	4.24	NS	1.22	NS	0.33	NS	0.15	NS	0.04	NS	0.09	NS	0.35	NS
Interaction														
CD (0.05)	7.36	NS	2.11	1.79	0.57	NS	0.26	NS	0.06	NS	0.16	NS	0.61	NS

AFS, agroforestry system; NRA, naturally regenerated areas; D₁: dbh b/w 10–30 cm, D₂: dbh b/w 30–50 cm, D₃: dbh above 50 cm, L₁: Ghisoli, L₂: Ganesh Pura, L₃: Parichha, L₄: Simra, L₅: Bhojla.

NS, Non-significant at $p \leq 0.05$.

carbon parameters ($p \leq 0.05$) were observed in L_3 (DBH 44.03 cm, stem volume 1.22 m³, carbon stock 0.36 t tree⁻¹, and CO₂ mitigation potential 1.31 t tree⁻¹). The tree height was found significantly highest ($p \leq 0.05$) in L_3 (9.78 m), which was at par with L_1 (9.46 m), L_4 (8.9 m), and L_5 (8.58 m), respectively. These trends of *B. monosperma* reflect the influence of favourable site conditions on growth and carbon accumulation. Leaf and flower parameters were mostly found to be non-significant, except that leaf width was observed to be significant across the localities. The highest leaf width was noted in L_5 (15.02 cm), which was at par with L_2 (14.5 cm). Leaf fresh weight was observed to be highest in L_4 (3.53 g), leaf dry weight in L_2 (2.01 g), flower fresh weight in L_4 (1.91 g), flower dry weight in L_3 and L_5 (0.45–0.47 g), and panicle length in L_5 (16.20 cm) (Figure 2). The interaction between diameter class and locations had significant effects on growth, biomass, and carbon parameters, reflecting site-specific growth responses across diameter classes.

Leaf and flower traits did not show significant interaction effects but exhibited slight variations. The present study observed a positive association between increasing diameter class and biomass/carbon accumulation, indicating that larger trees of diameter more than 50 cm (D_3) contributed disproportionately to ecosystem carbon storage compared to smaller trees (D_1). This trend is consistent with earlier findings that large-diameter trees play a dominant role in biomass accumulation and carbon sequestration across forest ecosystems (Stephenson et al., 2014). Similarly, a larger diameter tree is a stronger determinant of carbon storage than stand density or species richness (Ali et al., 2019). Location-specific differences in tree performance further emphasized the role of site conditions in modulating growth. Trees in L_3 exhibited the highest DBH, stem volume, and biomass, while those in L_1 showed the lowest values. These variations may be attributed to differences in edaphic and microclimatic conditions,

which strongly influence carbon accumulation and biomass allocation (Kumar et al., 2024; Kaushal and Baishya, 2021). Similar patterns have been reported in other Indian dry deciduous forest, where site quality significantly regulate biomass distribution (Raha et al., 2020; Raj and Jhariya, 2021). These findings align with the conclusions of Sist et al. (2014), Dube and Mutanga (2015), Kaushal et al. (2024), and Gautam et al. (2025), who emphasized that spatial heterogeneity in growth potential must be incorporated into biomass and carbon stock assessments.

The physiological and reproductive behaviour in *B. monosperma* remains relatively stable across varying sizes and sites. However, little differences such as higher flower biomass in larger trees may reflect size-dependent reproductive allocation, consistent with the theory that larger individuals invest more in reproduction while maintaining functional leaf traits for carbon assimilation (Thomas, 2011). The findings highlight that *B. monosperma* has strong potential for biomass accumulation and carbon sequestration in agroforestry systems, aligning with evidence that such land-use practices enhance carbon sinks, soil health, and climate resilience in India (Kant et al., 2020; Birla et al., 2024).

Growth, biomass, carbon attributes, and leaf–flower morphological traits of *Butea monosperma* in naturally regenerated areas in Jhansi district

Diameter class significantly influenced to tree linear growth parameters in naturally regenerated areas (Table 2). The trees in D_3 (diameter above 50 cm) recorded maximum tree growth parameters, viz., DBH (53.33 cm), tree height (10.61 m), stem volume (1.21 m³), AGB (0.56 t tree⁻¹), BGB (0.15 t tree⁻¹), carbon stock (0.35 t tree⁻¹), and

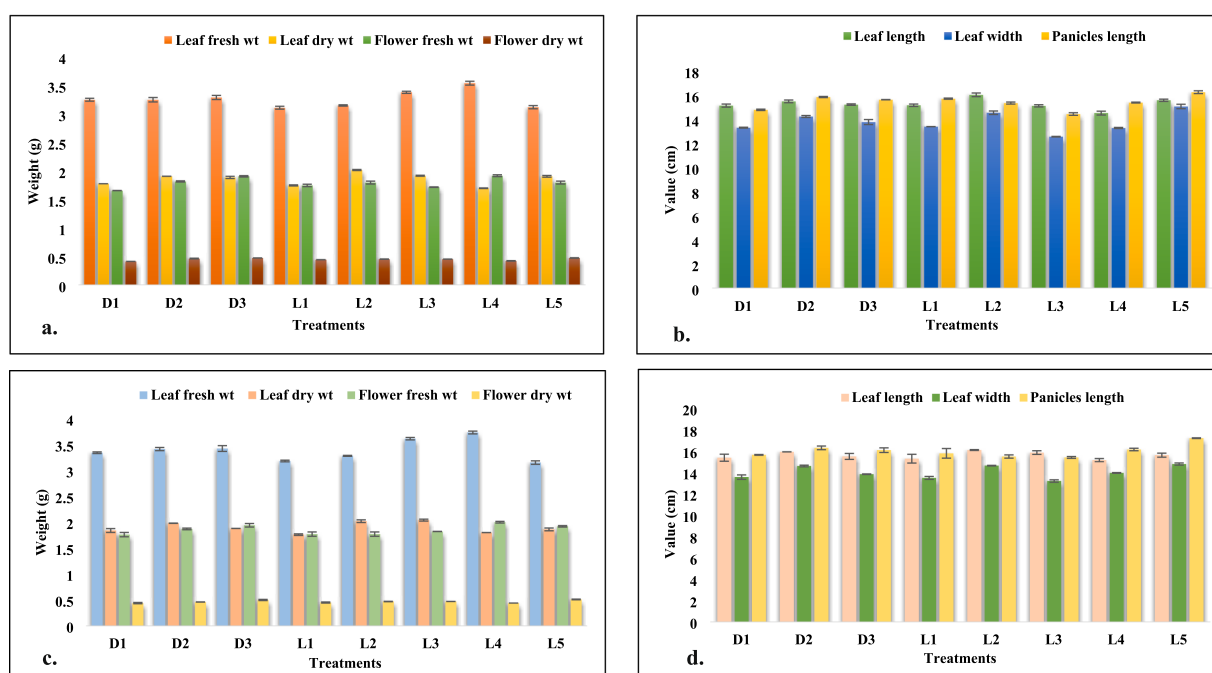


FIGURE 2

Variation in flower and leaf traits of *B. monosperma* in Jhansi district: (a) leaf and flower fresh/dry weight in AFS; (b) leaf and panicle dimensions in AFS; (c) leaf and flower fresh/dry weight in NRA; (d) leaf and panicle dimensions in NRA (treatments, D_1 : DBH b/w 10–30 cm, D_2 : DBH b/w 30–50 cm, D_3 : DBH above 50 cm, L_1 : Ghisoli, L_2 : Ganesh Pura, L_3 : Parichha, L_4 : Simra, L_5 : Bhojla). Error bars indicate the standard error of the mean. Most parameters did not differ significantly among treatments.

CO₂ mitigation potential (1.30 t tree⁻¹). The leaf and flower traits were found statistically non-significant across the diameter class. Non-significant differences were observed in tree growth and biomass parameters across localities (Table 2). However, L₄ exhibited the highest DBH (39.49 cm), tree height (9.00 m), stem volume (0.73 m³), carbon stock (0.21 t tree⁻¹), and CO₂ mitigation potential (0.78 t tree⁻¹).

These findings correlated with earlier studies, which have consistently shown that tree size is the primary determinant of biomass accumulation and carbon storage, with large-diameter individuals contributing disproportionately to ecosystem-level carbon dynamics (Lutz et al., 2018; Paponiot et al., 2022). Larger trees were found to store more carbon, emphasizing the conservation of mature individuals for sustaining carbon stocks and ecosystem stability (Hauck et al., 2023; Kozák et al., 2023). Previous studies on *B. monosperma* also suggest genetic and environmental influences on vegetative and flowering traits (Singh et al., 2015; Singh et al., 2017), which could explain the slight variation observed across localities. Mikosch et al. (2012) found that *B. monosperma* maintained stable photosynthetic performance across contrasting habitats in Rajasthan, despite site-specific variations in irradiance and isotope signatures.

Growth, biomass, carbon attributes, and leaf–flower morphological traits of *Butea monosperma* in agroforestry system in Lalitpur district

The growth, biomass, and carbon parameters of *B. monosperma* in agroforestry systems were significantly influenced by diameter class

(Table 3). Trees in the smallest diameter class (D₁) recorded the lowest growth. In contrast, the trees in D₃ (diameter above 50 cm) exhibited the highest DBH (52.56 cm), tree height (12.78 m), stem volume (1.42 m³), AGB (0.66 t tree⁻¹), BGB (0.17 t tree⁻¹), carbon stock (0.41 t tree⁻¹), and CO₂ mitigation potential (1.52 t tree⁻¹), indicating a strong positive relationship between tree size and biomass potential. Leaf dry weight and leaf length were significantly highest ($p \leq 0.05$) in D₂ (2.29 g and 15.77 cm), which was at par with D₃ (2.02 g and 15.5 cm), respectively. Panicle length was significantly highest ($p \leq 0.05$) in D₃ (15.7 cm), which was at par with D₂ (15.02 cm) (Figure 3). The other leaf and flower traits generally showed non-significant variation across diameter classes.

Across localities (L₁–L₅), all growth, leaf, and flower parameters were found statistically non-significant. However, DBH was highest in L₄ (38.91 cm), tree height in L₂ (10.98 m), and stem volume in L₂ (0.82 m³). The maximum AGB (0.38 t tree⁻¹), BGB (0.099 t tree⁻¹), carbon stock (0.24 t tree⁻¹), and CO₂ mitigation potential (0.88 t tree⁻¹) were also observed in L₂, reflecting the influence of favourable site conditions.

The results clearly demonstrate that the growth, biomass, and carbon dynamics of *B. monosperma* in agroforestry systems of Lalitpur district are strongly governed by tree diameter, while locality and interaction effects play a relatively minor role. The significant increase in DBH, tree height, stem volume, and biomass across diameter classes, with D₃ trees showing the highest accumulation, reflects the well-established principle that larger trees disproportionately contribute to biomass & carbon stocks (Lutz et al., 2018; Mildrexler et al., 2020). Similar findings have been reported from other tropical and

TABLE 3 Tree growth, biomass and carbon parameters of *Butea monosperma* trees in agroforestry system (AFS) and naturally regenerated areas (NRA) of different localities in Lalitpur district.

Treatments	DBH (cm)		Tree height (m)		Tree stem volume (m ³)		Above-ground biomass (t tree ⁻¹)		Below-ground biomass (t tree ⁻¹)		Carbon stock (t tree ⁻¹)		CO ₂ mitigation potential (t tree ⁻¹)	
	AFS	NRA	AFS	NRA	AFS	NRA	AFS	NRA	AFS	NRA	AFS	NRA	AFS	NRA
Diameter class														
D ₁	24.17	23.27	8.14	7.68	0.20	0.17	0.09	0.08	0.02	0.02	0.06	0.05	0.21	0.19
D ₂	37.55	36.05	11.58	10.61	0.66	0.55	0.30	0.26	0.08	0.06	0.19	0.16	0.71	0.60
D ₃	52.56	50.80	12.78	11.90	1.42	1.23	0.66	0.57	0.17	0.02	0.41	0.36	1.52	1.33
SE (m)	0.92	0.85	0.31	0.28	0.03	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.04	0.03
CD (0.05)	2.56	2.43	0.90	0.81	0.1	0.09	0.05	0.04	0.02	0.01	0.03	0.02	0.11	0.10
Locations														
L ₁	38.08	36.92	10.76	10.06	0.76	0.67	0.35	0.31	0.09	0.08	0.22	0.19	0.82	0.72
L ₂	38.25	37.02	10.98	10.27	0.82	0.72	0.38	0.33	0.01	0.09	0.24	0.21	0.88	0.77
L ₃	37.77	36.58	10.36	10.54	0.78	0.69	0.36	0.32	0.01	0.08	0.23	0.20	0.84	0.74
L ₄	38.91	37.38	10.56	9.57	0.73	0.60	0.34	0.28	0.09	0.07	0.21	0.17	0.78	0.65
L ₅	37.45	35.62	10.66	9.88	0.69	0.59	0.32	0.27	0.08	0.07	0.20	0.17	0.75	0.63
SE (m)	1.16	1.10	0.41	0.36	0.04	0.04	0.02	0.02	0.01	0.01	0.04	0.01	0.05	0.04
CD (0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Interaction														
CD (0.05)	NS	NS	NS	1.81	NS	0.21	NS	0.09	NS	0.03	NS	0.06	NS	0.22

AFS, agroforestry system, NRA, naturally regenerated areas, D₁: dbh b/w 10–30 cm, D₂: dbh b/w 30–50 cm, D₃: dbh above 50 cm, L₁: Khadowara, L₂: Terai, L₃: Nandan Wara, L₄: Patarn, L₅: Kadesra Kalan.

NS, non-significant at $p \leq 0.05$.

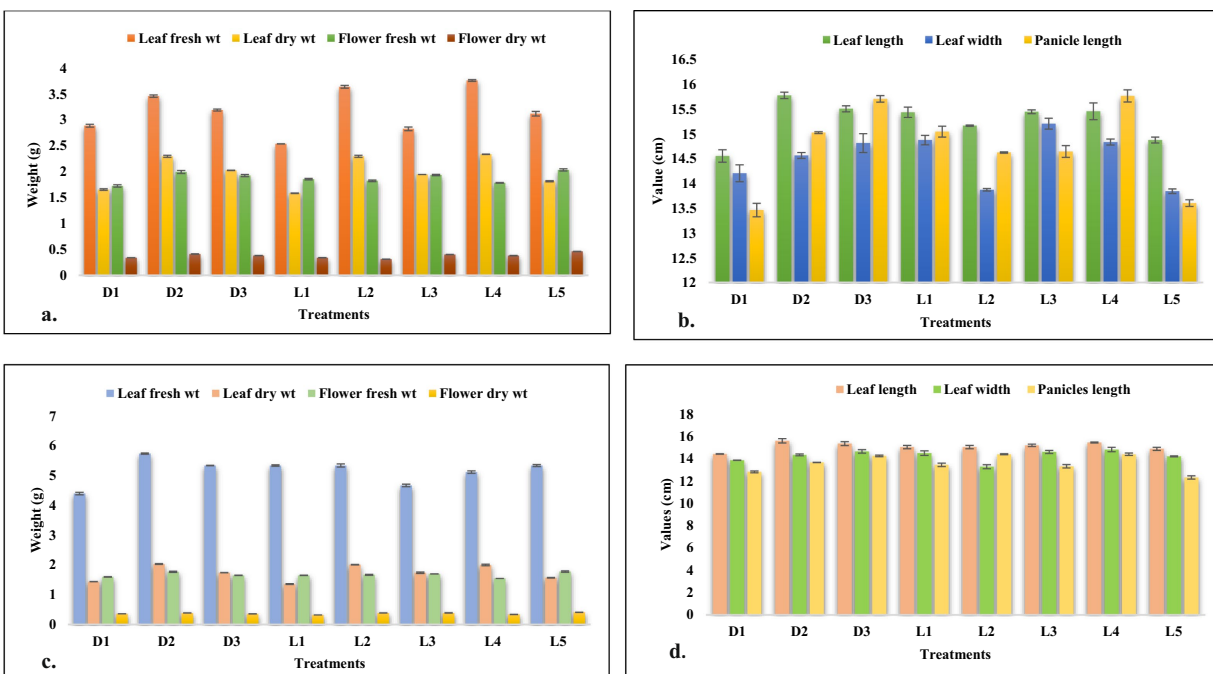


FIGURE 3

Variation in flower and leaf traits of *B. monosperma* in Lalitpur district: (a) leaf and flower fresh/dry weight in AFS; (b) leaf and panicle dimensions in AFS; (c) leaf and flower fresh/dry weight in NRA; (d) leaf and panicle dimensions in NRA (treatments, D₁: dbh b/w 10–30 cm, D₂: dbh b/w 30–50 cm, D₃ = dbh above 50 cm, L₁: Khadowara, L₂: Terai, L₃: Nandan Wara, L₄: Pataran, L₅: Kadesra Kalan). Error bars indicate the standard error of the mean. Most parameters did not differ significantly among treatments.

subtropical areas, where tree size and age strongly determine carbon sequestration capacity (Köhl et al., 2017; Piconiot et al., 2022). Leaf and flower traits, which were mostly non-significant across diameter classes and sites, suggest that reproductive allocation in *B. monosperma* may not scale strictly with tree size but could be regulated by physiological trade-offs between growth and reproduction (Obeso, 2002). The effect of locality was non-significant for most growth parameters, likely due to high environmental homogeneity across naturally regenerated sites and potential genetic uniformity within wild populations, which may have reduced site-specific variability. Diameter class is the principal determinant of growth and carbon sequestration in *B. monosperma*, with larger trees serving as keystone contributors to ecosystem carbon dynamics. These findings align with global evidence emphasizing the ecological and climatic significance of conserving and managing large-diameter trees in agroforestry systems (Poorter et al., 2015).

Growth, biomass, carbon attributes, and leaf–flower morphological traits of *Butea monosperma* in naturally regenerated areas in Lalitpur district

The growth and biomass parameters of *B. monosperma* in naturally regenerated areas of Lalitpur district were significantly influenced by diameter classes (Table 3). Trees in D₁ exhibited the lowest growth and biomass parameter, while largest diameter class (D₃) recorded significantly highest ($p \leq 0.05$) DBH (50.8 cm), tree height (11.9 m), stem volume (1.23 m³), AGB (0.57 t tree⁻¹), BGB (0.02 t tree⁻¹), carbon stock (0.36 t tree⁻¹), and CO₂ mitigation potential (1.33 t tree⁻¹), indicating that diameter class is a key determinant of biomass accumulation and carbon sequestration in naturally regenerated stands. Leaf fresh weight and leaf dry weight was significantly highest ($p \leq 0.05$) in D₂ (5.74 g, 2.03 g), while leaf length was significantly highest ($p \leq 0.05$) in D₂ (15.6 cm) which was at par with D₃ (15.35 cm). Flower fresh weight (1.77 g) and flower dry weight (0.39 g) were slightly higher in D₂ compared to D₃, and panicle length increased with tree size, with D₃ recording 14.25 cm (Figure 3).

Across localities, growth and biomass parameters were largely non-significant, although a specific locality showed maximum growth L₂. Leaf fresh weight was significantly highest ($p \leq 0.05$) in L₂, L₄, and L₅ (5.34 g), which was at par with L₄ (5.12 g), while leaf dry weight was also significantly highest ($p \leq 0.05$) in L₂ (2.01 g) which was at par with L₄ (2.0 g) and L₃ (1.74 g), respectively. Leaf length and width were relatively uniform across sites, with slight maxima in L₄ (154.5 mm length) and L₄ (148.2 mm width); whereas panicle length was significantly highest ($p \leq 0.05$) in L₂ and L₄ (14.40 cm), which was at par with L₁ (13.45 cm) and L₃ (13.32 cm). The interaction between diameter class and locality (D × L) was mostly significant for all parameters except diameter at breast height (Table 3), suggesting that tree size is the primary driver of growth and biomass accumulation.

The trend observed here aligns with global findings that large-diameter trees disproportionately contribute to stand-level carbon dynamics due to their accelerated growth and higher accumulation rates over time (Forrester, 2021). Similar trait-specific variations have been reported in other tropical species, where reproductive and vegetative allocations fluctuate depending on developmental stage and tree size (Thomas, 2011). The observed maximum flower weight in intermediate classes suggests that *B. monosperma* may allocate relatively more resources to reproduction before attaining maximum

vegetative size, a trade-off pattern also noted in other forest species (Gower and Richards, 1990). Maintaining large numbers of *B. monosperma* could substantially enhance carbon sequestration in semi-arid landscapes, echoing global evidence on the ecological and carbon storage importance of conserving large and old trees (Kozák et al., 2023). The reproductive allocation observed in intermediate classes underscores the dual ecological role of *B. monosperma* as a carbon sink and as a keystone species supporting ecosystem regeneration. These findings reinforce the need for conservation and sustainable management practices that promote the survival and growth of larger-diameter *B. monosperma* individuals. Such strategies could significantly augment biomass carbon stocks in dry deciduous ecosystems, contributing both to climate mitigation targets and to ecosystem resilience in agroforestry landscapes (Murthy et al., 2013; Birla et al., 2024; Singh and Tiwari, 2024).

Quantity of *Butea monosperma* gum in Jhansi and Lalitpur districts

Diameter class and locality had significant effects on gum yield, while their interaction effect was also significant in Jhansi and Lalitpur (Figure 4). With respect to diameter class in Jhansi district, the significantly highest gum yield ($p \leq 0.05$) was observed in D₂ (207.76 g tree⁻¹). With respect to localities, the significantly highest gum yield was recorded in L₄ (163.66 g tree⁻¹), which was at par with L₃ (155.93 g tree⁻¹) and L₅ (144.93 g tree⁻¹). There was a significant effect of diameter class and localities on the quantity of gum collected per tree in Lalitpur. Among the diameter classes, the significantly highest gum yield was recorded in D₁ (224.60 g tree⁻¹). Among localities, the significantly maximum gum yield was recorded in L₄ (194.33 g tree⁻¹), and the interaction effect was also found to be significant.

These results indicate that gum yield in *B. monosperma* is significantly influenced by tree diameter and site-specific environmental conditions. Medium-diameter trees (D₂) consistently produced more gum than smaller (D₁) or larger (D₃) trees, likely due to their optimal physiological vigour and the presence of actively functioning resin canals, which enhance gum exudation. The observed differences between localities may be linked to variations in microclimate, soil fertility, and moisture availability, which affect resin secretion. Similar findings were reported by Gyedu-Akoto et al. (2007), that both location and tree maturity significantly influenced gum production in cashew trees in Ghana. Eltahir and Ismaeil (2020) also identified growth attributes such as stem diameter and canopy spread as key determinants of high gum yield in *Acacia senegal*, while Eltahir and Holi (2021) observed that peak gum picking coincided with specific growth parameters. Likewise, Singh et al. (2025) reported that tree density and girth class significantly impacted non-timber product yields in *Senegaliasenegal*. Ballal et al. (2005) highlighted that gum arabic yield was affected by environmental factors, tapping dates, and tapping intensity in *Acacia senegal* plantations. Verma et al. (2023) demonstrated the effect of diameter class and environmental variables on gum production from *Acacia tortilis* in the arid zone of western Rajasthan, indicating that similar ecological factors influence gum yield across species and regions. Prasad et al. (2021) and Prasad et al. (2024) studied the influence of planting geometry and seasonal variability on gum yield in *B. monosperma* plantations in semi-arid central India. Environmental variables substantially affect both the quantity and quality of *Acacia senegal* gum production in different tropical environments (Hamouda, 2017; Raj and Jhariya, 2022).

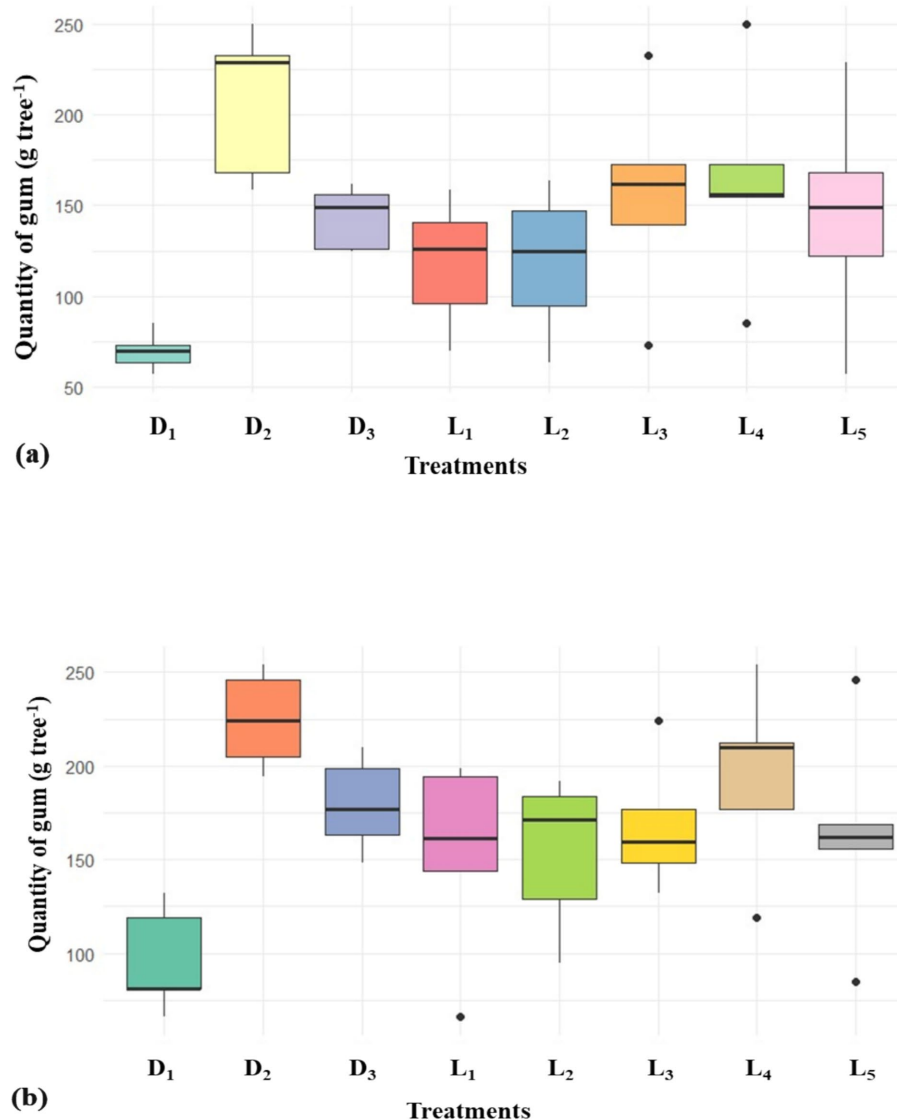


FIGURE 4

Variation in gum yield of *Butea monosperma* across different diameter classes (D_1 , D_2 , D_3) and localities (L_1 – L_5) presented through box plots for (a) Jhansi and (b) Lalitpur districts. Boxes represent the interquartile range, horizontal lines indicate medians, whiskers show data spread, and dots denote outliers.

Biochemical composition of *Butea monosperma* gum in Jhansi and Lalitpur district

The significant effect of the individual factors was observed on total phenol content in the gum of *B. monosperma* in Jhansi district (Table 4). Among the diameter classes, the significantly highest total phenol content, ash content, and ascorbic acid in gum ($p \leq 0.05$) were recorded in D_3 (11.27 mg g^{-1} , 4.12%, 38.07 mg 100 g^{-1}). The antioxidant activity, total carotenoid content, and crude fat of gum from *B. monosperma* trees showed no significant effect of diameter class. Similarly, with respect to localities, the highest total phenol content in gum was noted in L_4 (10.82 mg g^{-1}), which was at par with L_3 (10.34 mg g^{-1}), and L_4 (10.02 mg g^{-1}). The significantly highest ash content ($p \leq 0.05$) was reported in L_3 (4.10%), which was at par with L_2 (3.63%) and L_4 (3.36%). The crude fat was observed significantly highest ($p \leq 0.05$) in L_1 (1.12%) which was at par with L_3 (1.04%), L_4

(1.0%), and L_5 (0.89%), respectively. There was no significant effect of localities on antioxidant activity, total carotenoid content, and ascorbic acid.

In Lalitpur, there is a significant effect ($p \leq 0.05$) of both diameter class and locality on the total phenol content and crude fat in the gum of *B. monosperma* trees (Table 5). Among the diameter classes, the significantly highest total phenol content was recorded in D_3 (13.61 mg g^{-1}). The ash content and antioxidant activity in the gum of *B. monosperma* were not significantly affected by diameter class. The total carotenoid content was observed significantly highest in D_2 (16.61 mg 100 g^{-1}), which was at par with D_3 (15.5 mg 100 g^{-1}). The ascorbic acid was highest in D_3 (42.08 mg 100 g^{-1}), which was at par with D_2 (39.41 mg 100 g^{-1}). The highest crude fat content was recorded in gum from D_1 trees (0.67%). Among the different localities, the significantly highest total phenol content was recorded in L_5 (12.80 mg g^{-1}), which was at par with L_4 (12.42 mg g^{-1}), and L_1 (12.23 mg g^{-1}). The highest crude fat content was recorded in gum from L_1 (0.82%). Localities showed a

TABLE 4 Variation in biochemical parameters of *Butea monosperma* with respect to diameter classes and locations in Jhansi district.

Treatments	Total phenol content (mg g ⁻¹)		Ash content (%)		Antioxidant activity (%)		Total carotenoid content (mg 100 g ⁻¹)		Ascorbic acid (mg 100 g ⁻¹)		Crude fat (%)	
	Flower	Gum	Flower	Gum	Flower	Gum	Flower	Gum	Flower	Gum	Flower	Gum
Diameter class												
D ₁	14.65	7.05	5.32	2.54	72.92	80.38	34.04	14.84	4.27	26.05	2.81	0.79
D ₂	14.28	10.05	5.68	3.56	63.80	75.59	35.65	16.54	5.74	30.72	2.92	0.95
D ₃	16.03	11.27	4.96	4.12	69.27	73.79	27.58	16.36	5.61	38.07	3.02	0.90
SE (m)	0.86	0.28	0.29	0.20	1.55	0.97	1.61	0.59	0.31	2.21	0.17	0.06
CD (0.05)	NS	0.82	NS	0.57	4.41	NS	4.59	NS	0.88	6.30	NS	NS
Locations												
L ₁	15.35	7.47	4.73	2.83	66.39	80.40	30.32	15.54	4.89	28.94	2.14	1.12
L ₂	14.86	8.63	5.13	3.63	68.51	77.43	32.05	15.55	5.34	28.94	2.79	0.35
L ₃	14.26	10.34	6.66	4.10	66.45	77.49	33.51	16.07	5.12	31.17	3.21	1.04
L ₄	13.61	10.82	4.60	3.36	69.47	76.99	29.63	16.06	5.12	32.28	3.07	1.00
L ₅	16.84	10.02	5.46	3.10	72.49	76.59	56.60	16.35	5.56	36.74	3.39	0.89
SE (m)	1.11	0.37	0.38	0.26	2.00	1.26	2.08	0.77	0.40	2.86	0.21	0.08
CD (0.05)	NS	1.06	1.07	0.74	NS	NS	NS	NS	NS	NS	0.62	0.24
Interaction												
CD (0.05)	NS	NS	NS	NS	9.87	NS	NS	NS	NS	NS	NS	0.43

D₁: dbh b/w 10–30 cm, D₂: dbh b/w 30–50 cm, D₃ = dbh above 50 cm, L₁: Ghisoli, L₂: Ganesh Pura, L₃: Parichha, L₄: Simra, L₅: Bhojla.

NS, non-significant at $p \leq 0.05$.

TABLE 5 Variation in biochemical parameters of *Butea monosperma* with respect to diameter classes and locations in Lalitpur district.

Treatments	Total phenol content (mg g ⁻¹)		Ash content (%)		Antioxidant activity (%)		Total carotenoid content (mg 100 g ⁻¹)		Ascorbic acid (mg 100 g ⁻¹)		Crude fat (%)	
	Flower	Gum	Flower	Gum	Flower	Gum	Flower	Gum	Flower	Gum	Flower	Gum
Diameter class												
D ₁	12.97	8.67	4.60	2.96	68.49	77.68	37.14	14.56	4.40	26.05	2.82	0.67
D ₂	16.03	12.56	6.08	3.62	60.58	77.88	36.97	16.61	5.74	39.41	2.71	0.42
D ₃	14.72	13.61	4.76	3.24	68.90	77.75	28.25	15.50	5.34	42.08	2.80	0.29
SE (m)	0.61	0.36	0.30	0.24	1.84	0.87	1.39	0.51	0.34	1.91	0.22	0.06
CD (0.05)	1.72	1.03	0.86	NS	5.24	NS	3.95	1.45	0.96	5.43	NS	0.17
Locations												
L ₁	14.91	12.23	4.66	3.30	69.05	76.32	32.21	16.12	5.34	32.28	3.32	0.82
L ₂	14.87	10.88	5.20	2.73	64.41	76.52	34.50	16.40	5.34	35.62	1.22	0.21
L ₃	14.50	9.73	5.13	3.13	68.88	78.86	34.58	14.76	4.67	35.62	3.35	0.55
L ₄	14.11	12.42	5.26	3.36	57.98	76.98	36.35	15.29	5.12	36.74	3.06	0.42
L ₅	14.48	12.80	5.46	3.38	69.64	80.15	32.96	15.22	5.34	38.96	2.94	0.30
SE (m)	0.78	0.47	0.39	0.31	2.38	1.12	1.79	0.66	0.43	2.46	0.29	0.07
CD (0.05)	NS	1.33	NS	NS	6.76	NS	NS	NS	NS	NS	0.83	0.22
Interaction												
CD (0.05)	NS	NS	NS	NS	11.71	NS	NS	NS	NS	NS	NS	NS

D₁: dbh b/w 10–30 cm, D₂: dbh b/w 30–50 cm, D₃ = dbh above 50 cm, L₁: Khadowara, L₂: Terai, L₃: Nandan Wara, L₄: Pataran, L₅: Kadesra Kalan.

NS, non-significant at $p \leq 0.05$.

non-significant effect on the ash content, antioxidant activity, total carotenoid content, and ascorbic acid.

Based on the results obtained, it is evident that larger diameter classes accumulated higher total phenols and ascorbic acid in gum, attributed to greater metabolic activity and enhanced storage capacity in older trees. These findings are consistent with Gyedu-Akoto et al. (2008), who reported that the physico-chemical properties of cashew tree gum varied with location and tree characteristics. Environmental factors such as soil type, temperature, and water availability significantly impacted the secondary metabolism of medicinal plants (Mohiuddin, 2019). The observed increase in ash content with larger diameter classes could be attributed to the higher accumulation of mineral constituents in older trees. Variation among different localities may be due to differences in soil mineral composition and environmental factors influencing mineral uptake and deposition in gum. Tahir et al. (2007) noted that tree age and site conditions significantly affected the physiochemical properties of natural gums. Tree age and site may slightly enhance or reduce the antioxidant properties of gum, attributed to variations in plant stress factors or secondary metabolite synthesis. The significant increase in ascorbic acid content observed in medium and larger diameter trees aligns with the role of ascorbic acid as a crucial antioxidant metabolite in woody plants. Bilska et al. (2019) highlighted the multifunctional role of ascorbic acid in woody plants, particularly its involvement in stress mitigation and cellular protection. The younger trees (smaller diameter) accumulated higher crude fat levels in their gum, attributed to differences in metabolic allocation of lipophilic compounds during early growth stages. The observed differences across sites indicate that environmental factors, including soil properties, moisture availability, and microclimatic conditions, play a substantial role in influencing lipid synthesis and deposition in the gum. Quainoo and Dugbately (2016) reported that the age of Shea trees (*Vitellaria paradoxa*) significantly influenced latex flow, suggesting that physiological age-related changes impact the biosynthesis and exudation of lipophilic compounds.

Biochemical composition in *Butea monosperma* flowers in Jhansi and Lalitpur districts

In Jhansi, there is a non-significant effect of diameter class, locality on total phenol content in flowers of *B. monosperma* (Table 4). There was a significant effect ($p \leq 0.05$) of diameter classes on total carotenoid content, antioxidant activity, and ascorbic acid. The total carotenoid content was recorded in D₂ (35.65 mg 100 g⁻¹), which was at par with D₁ (34.04 mg 100 g⁻¹). The antioxidant activity was observed significantly highest in D₁ (72.92%) and at par with D₃ (69.27%). The interaction between diameter class and localities (D × L) was found to be significant in terms of antioxidant activity. Among diameter classes, the significantly highest ascorbic acid content was recorded in D₂ (5.74 mg 100 g⁻¹), which was at par with D₃ (5.61 mg 100 g⁻¹). The locality has significantly recorded the highest ash content was reported in L₃ (6.66%). With respect to locality, a significant effect on crude fat content was observed. The significantly highest crude fat content was observed in L₅ (3.39%), which was at par with L₃ (3.21%), L₄ (3.07%), and L₂ (2.79%), respectively. With respect to localities, there is a non-significant effect on total carotenoid content, antioxidant activity, and ascorbic acid.

In Lalitpur, the data revealed that the effect of diameter class on total phenol content, ash content, antioxidant activity, total carotenoid content, and ascorbic acid was statistically significant (Table 5). The

highest phenol content was recorded in D₂ (16.03 mg g⁻¹), which was at par with D₃ (14.72 mg g⁻¹). This suggests that trees in the intermediate diameter class may have optimized secondary metabolite production. The significantly highest ash content was observed in D₂ (6.08%). The highest carotenoid content (37.14 mg 100 g⁻¹) was recorded in D₁, which was at par with D₂ (36.97 mg 100 g⁻¹). D₃ showed the highest antioxidant activity (68.90%) and was at par with D₁ (68.49%). The significantly highest ascorbic acid was found in D₂ (5.74 mg 100 g⁻¹), which was at par with D₃ (5.34 mg 100 g⁻¹). In Lalitpur, the diameter class exhibited a non-significant effect on crude fat content. While among localities, the data was found to be statistically significant. Among localities, the highest antioxidant activity was observed in L₅ (69.64%), while the lowest (57.98%) was in L₄, which was at par with L₁ (69.05%), L₃ (68.88%), and L₂ (64.41%). Interaction analysis of diameter class and locality on antioxidant activity was found to be significant. The maximum crude fat was observed in L₃ (3.35%) which was at par with L₁ (3.32%), L₄ (3.06%), and L₅ (2.94%). With regard to localities, there is no significant effect of locality on phenol content, ash content, total carotenoid content, and ascorbic acid in the flowers of *B. monosperma*.

Phenolic biosynthesis may peak at an optimal balance between tree maturity and metabolic activity, which is often higher at intermediate growth stages due to optimal physiological conditions (Dong et al., 2011; Verma and Shukla, 2015; Li et al., 2020). The role of elicitors and physiological maturation in secondary metabolite accumulation has also been highlighted by Bharti et al. (2023) and Mazumder et al. (2011) in *B. monosperma*. Oguntunde et al. (2011) and Meena and Asrey (2018) demonstrated that tree age significantly affects mineral levels and nutrient allocation in fruit crops. Carotenoid pigment synthesis is closely linked to the developmental stage rather than the spatial variation. Yan et al. (2023) found similar results in *Torreya grandis*, where younger and intermediate-aged trees had higher carotenoid and flavonoid concentrations compared to older ones. Aregay et al. (2021) also recorded such age-related trends in *Citrus* spp., emphasising physiological vigour in earlier stages. Carotenoid biosynthesis is influenced by both light intensity and metabolic activity, which may explain the decline in older trees (Padghan, 2018). Antioxidant levels in plants are largely governed by phenolic and carotenoid concentrations (Lobo et al., 2010; Salar and Seasotiya, 2011). The wide variability between localities in Lalitpur could be attributed to site-specific stressors, microclimatic variations, and soil nutrient status, all of which have been shown to modulate antioxidant capacity. The association between phenolic content and antioxidant capacity was reported by Sehrawat and Kumar (2012) in *B. monosperma*. The result suggests that Ascorbic acid biosynthesis peaks at intermediate maturity before declining in older trees. This is consistent with reports that metabolic activity and antioxidant vitamin accumulation are linked to active growth phases (Pandey et al., 2015). Kumar et al. (2017) observed that climate change stress influenced antioxidant vitamin levels in medicinal plants, suggesting that under strong environmental pressures, locality could play a larger role. Crude fat content showed non-significant differences across diameter classes in both districts but significant locality-wise differences, with higher values in specific fertile sites. This aligns with research showing that lipid biosynthesis in flowers and seeds is influenced by nutrient and moisture availability (Pachkore et al., 2010). The lack of a strong age effect suggests that lipid accumulation in *B. monosperma* flowers is more sensitive to current environmental conditions, especially soil fertility and water status, than to developmental stage. Gupta et al. (2016) noted that

floral lipids in *Butea* are important for pollinator attraction, and their variation may be ecologically significant.

Conclusion

The study on distribution and silvicultural characterization of *B. monosperma* in agroforestry systems and naturally regenerated areas of Jhansi and Lalitpur districts revealed that large-diameter trees (D_3) consistently recorded the highest DBH, stem volume, biomass, carbon stock, and CO_2 mitigation potential, confirming their keystone role in carbon sequestration. Location-specific differences were less pronounced but still reflected the influence of soil and microclimate, with certain sites (Jhansi L_3 , Lalitpur L_2) performing better. Leaf and flower traits remained largely unaffected, suggesting stability of reproductive and physiological functions across environments. Biochemical analysis highlighted the complementary roles of maturity and site in shaping flower and gum quality. Intermediate-aged trees often showed higher phenols, carotenoids, and ascorbic acid in flowers, while gum yield peaked in medium-sized trees, and quality improved with larger trees through higher phenolic and antioxidant content. Site effects, especially on ash and crude fat, emphasized the role of edaphic and microclimatic conditions. Overall, *B. monosperma* demonstrates strong potential for biomass production, carbon sequestration, and livelihood support, making it a highly suitable species for agroforestry expansion and ecological restoration in the Bundelkhand region. Future research should focus on long-term monitoring across agroforestry and naturally regenerated stands to quantify growth dynamics, carbon sequestration, and productivity under climate variability. Integrating silvicultural interventions with livelihood-oriented value-chain studies will further strengthen the role of *B. monosperma* in climate-resilient land-use planning in semi-arid regions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

PT: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. DM: Investigation, Validation,

Writing – original draft. PD: Formal analysis, Writing – review & editing. MD: Project administration, Supervision, Writing – review & editing. RY: Investigation, Resources, Writing – review & editing. GA: Formal analysis, Methodology, Visualization, Writing – original draft. DB: Formal analysis, Software, Writing – review & editing. RP: Data curation, Writing – review & editing. AV: Formal analysis, Investigation, Writing – review & editing. MS: Project administration, Supervision, Validation, Writing – review & editing. SB: Formal analysis, Resources, Writing – review & editing.

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