Climate-resilient horti–silvi–pasture systems enhance fodder productivity and nutritional quality in the semi-arid Bundelkhand region

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Abstract

Horti-silvi-pasture (HSP) systems offer a climate-resilient strategy to improve fodder productivity and sustainability in semi-arid areas. This study assessed two HSP systems, *Holoptelea integrifolia* + *Punica granatum* (H1) and *Holoptelea integrifolia* + *Annona squamosa* (H2), across two spacings (5 m × 5 m and 5 m × 4 m) to determine their impacts on the growth, yield, and nutritional quality of BN hybrid grass, as well as tree biomass and carbon dynamics during 2024 and 2025 in Bundelkhand, India. The H2 system markedly enhanced growth attributes, achieving greater plant height (130.85 cm), shoots per m^2 (149.55), and leaf area index (4.21) in pooled analysis. It also yielded superior green (27.97 t ha^{-1}) and dry forage (6.17 t ha^{-1}) compared to H1. The proximate composition improved under H2, exhibiting elevated levels of crude protein (8.45%), crude fiber (61.64%), and total ash (13.57%). Increased spacing (5 m × 5 m) enhanced the growth and yield of BN hybrid grass, while reduced spacing (5 m × 4 m) led to comparatively elevated fiber fractions and biochemical components. Among tree species, *H. integrifolia* (5 m × 4 m) demonstrated the greatest biomass (4.60 Mg ha^{-1}), carbon stock (2.90 Mg ha^{-1}), and CO_2 mitigation potential (10.64 Mg ha^{-1}). Correlation study revealed significant positive correlations between growth attributes and yield, but fibre fractions exhibited negative correlations with growth attributes. The study illustrates that ideal species combinations and spacing in HSP systems can markedly enhance fodder yield, nutritional quality, and carbon sequestration, providing a sustainable approach for climate-resilient livestock farming systems.

Introduction

The semi-arid areas of central India, especially the Bundelkhand region, are marked by unpredictable rainfall, frequent droughts, and significant soil degradation, all of which jeopardise agricultural output and livestock-dependent livelihoods[1,2]. A major challenge for farmers in these areas is the persistent lack of high-quality green fodder, which detrimentally affects both livestock productivity and agricultural income[3]. Conventional monocropping approaches often struggle to sustain production in fragile ecological settings, thereby necessitating the development of climate-resilient and resource-efficient land-use systems[4,5]. Agroforestry-based land practices have proven to be effective methods for augmenting land productivity, fostering soil health, and diversifying agricultural outputs in regions experiencing climate stress[6,7]. Horti-silvi-pasture systems represent an integrated land-use strategy that purposefully integrates fruit trees, forestry species, and pasture grasses within a single land unitto optimize resource utilization and improve system productivity[8,9,10].

In these systems, fruit crops like pomegranate (*Punica granatum*) and custard apple (*Annona squamosa*) constitute the horticultural component, yielding high-value produce and supplementary income for farmers, especially in semi-arid regions where these species demonstrate significant drought resistance and adaptability to suboptimal soils[11,12,13].Tree species like *Holoptelea integrifolia* help conserve soil, create biomass, and improve soil fertility. This happens through the buildup of litter and the recycling of nutrients[14,15,16].The pasture element, comprising high-yielding forage grasses, ensures a consistent supply of quality feed for cattle[17,18].These elements, when considered together, promote efficient use of resources along both vertical and temporal axes, including light, water, and essential nutrients, thereby diminishing production uncertainties in rainfed regions[19,20]. Furthermore, trees contribute to improved soil structure, the regulation of microclimatic factors, and enhanced ecological stability; concurrently, pasture grasses provide a consistent fodder supply for livestock[21,22].

The Napier–Bajra hybrid (*Pennisetum purpureum*×*Pennisetum americanum*) is valued as one of the most prolific perennial forage grasses in tropical and subtropical areas[23,24]. This hybrid grass demonstrates robust growth, extensive tillering, and significant leafiness, allowing for substantial green feed production from April to November in northern India[25,26]. Beyond its considerable biomass output, the feed exhibits advantageous nutritional properties, such as elevated crude protein content, improved dry matter degradation, and a high degree of palatability for livestock[27,28]. Its persistent growth pattern and robust regenerative capacity make it exceptionally suited for multi-harvest fodder production systems[29,30]. Consequently, the Napier–Bajra hybrid is commonly cultivated along field bunds, on wastelands, in watershed areas, on terraces, and within silvi-pastoral and agroforestry systems[31,32].

In integrated production systems, such as horti-silvi-pasture systems, the effective spatial organization and management of trees, fruit crops, and pasture components are essential to mitigate competition and optimize resource utilization[33]. The strategic positioning of trees as shelterbelts or windbreaks along orchard perimeters can diminish wind velocity, protect crops from adverse weather conditions, and improve the microclimate within the production system[34,35,36].Properly training and maintaining fruit trees can increase light availability in the pasture below, which helps forage grasses grow[37,38]. Furthermore, understanding how integrated systems can improve climate resilience, use resources more efficiently, and support sustainable livestock production is essential for addressing global challenges like food security and land degradation.

While the benefits of integrated agroforestry systems for improving agricultural sustainability in dryland areas are recognized, there is a lack of research on the productivity and nutritional value of Napier–Bajra hybrids grown in horti–silvi–pasture systems in semi-arid environments.The effect of fruit-tree-based agroforestry and its spacing on fodder productivity and composition in Bundelkhand have not been thoroughly studied.The objectives were to evaluate the impact of tree-based spacing on fodder yield and to examine the proximate composition of the forage, with the goal of identifying sustainable agroforestry practices that improve fodder productivity and nutritional quality while promoting resilient livestock farming systems.

Materials and Methods

Study area

The field experiment was executed from 2023 to 2025 at the forestry farm of Rani Lakshmi Bai Central Agricultural University in Jhansi (Fig. 1). The area is defined by a semi-arid climate, marked by unpredictable precipitation and recurrent droughts[39]. The region's typical annual precipitation varies between around 800 and 900 mm, predominantly occurring during the southwest monsoon season (June–September). Summers are characterized by high temperatures and dry conditions, although winters are comparatively cold. The soils at the experimental site are primarily classified as degraded "Rakhar" soils, characterized by their shallow depth, coarse texture, and low organic carbon content. These soils generally demonstrate inadequate water retention and restricted fertility, keeping crop production significantly susceptible to moisture stress.

Experimental details

The study was conducted under a horti–silvi–pasture (HSP) system, which integrates forestry species, fruit crops, and pasture grasses within the same land unit. The system consisted of the following components; *Holoptelea integrifolia*, *Punica granatum* (pomegranate) and *Annona squamosa* (custard apple), with Napier–Bajra hybrid (*Pennisetum purpureum × Pennisetum americanum*), as the fodder crop (Fig. 2).The pasture grass (BN hybrid) was established in the interspaces between the tree rows. The experiment was laid out in factorial randomized block design with two factors. The two systems, *Holoptelea integrifolia* + *Punica granatum*(pomegranate)and*Holoptelea integrifolia +Annona squamosa* (custard apple) were employed as first factor whereas, two spacings, 5m×5m, and 5m× 4m were employed as second factor and replicated four times.Stem cuttings of the BN hybrid were cultivated in the field according to established agronomic practices. The grass was cultivated in rows within the gaps of the agroforestry system to optimize the use of available area and resources. Cultural techniques including irrigation, weed management, and fertilizer application were adhered to during the growing period. The crop was harvested at consistent intervals to preserve optimal feed quality.The tree growth, biomass and carbon parameters were also measured with treatments, T1: *H. integrifolia* (5 m × 5 m), T2: *Punica granatum* (5 m × 5 m), T3: *Annona squamosa* (5 m × 5 m), T4: *H. integrifolia* (5 m × 4 m), T5: *Punica granatum* (5 m × 4 m), and T6: *Annona squamosa* (5 m × 4 m).

Fodder growth and yield measurement

The growth metrics, including plant height, number of shoots per square meter, leaf-stem ratio, and leaf area index, were assessed.The height of the plants was assessed at each cut by randomly picking five plants from each net plot. The quantity of shoots per square meter from each plot was recorded using a one-meter quadrat at both systems and spacings during each NBH cut, and the average of them was represented as the number of shoots per square meter. To calculate the leaf stem ratio, the fresh weight of stems and leaves was recorded individually for each plant, and the ratio was subsequently determined. The leaf area of sampling units was quantified using graph paper, and the Leaf Area Index (LAI) was determined as the mean of the ratios of leaf area to ground area from three replications.Fodder yield of BN hybrid was recorded during the harvesting period for the experimental years in 2024 and 2025. During each harvest, the aboveground biomass was severed at an acceptable height above ground level and weighed to determine the new feed productivity. The biomass harvested from each treatment plot was recorded and subsequently translated into tonnes per hectare (t ha^{-1}) for comparative analysis among treatments. The annual fodder productivity was determined by aggregating the yields from consecutive harvests during the cropping period.

Proximate composition of fodder

Representative samples of BN hybrid fodder were collected from each treatment for nutritional analysis. The samples were shade dried and then oven dried at an appropriate temperature to obtain constant weight. Dried samples were ground to pass through a standard sieve for laboratory analysis.The ground samples were subjected to proximate analysis todetermine crude protein (CP), ash content, crude fibre, and nitrogen free-extract according to standard procedure[40]**.** Ether extract was estimated byextraction with petroleum ether (boiling point 40-60°C) by a Soxhlet's extractor. Acid detergent fibre (ADF), neutral detergent fibre (NDF), oxalate contents were determined by the different methodsrespectively[41,42,43].

Tree growth, biomass, and carbon assessment

Tree height (m) of each tree was measured using a Ravi Altimeter in year 2024 and 2025. Diameter at breast height (DBH) was recorded at 1.37 m above the ground using a measuring tape.Above-ground biomass (AGB, Mg ha^{-1}) was estimated for each species and spacing using the pan-tropical allometric equation[44] (1).

$$\mathrm{AGB} = 0.0673 \times (\mathrm{WD} \times \mathrm{DBH}^2 \times H)^{0.975} \qquad (1)$$

where wood density (WD) of *Holoptelea integrifolia*, *Punica granatum*, and *Annona squamosa* were taken as 0.64 g cm^{-3}, 0.6 g cm^{-3}& 0.56g cm^{-3}. Below-ground biomass (BGB, Mg ha^{-1}) was calculated by multiplying AGB by a root-to-shoot ratio of 0.26[45]. Total biomass was computed as the sum of AGB and BGB.Carbon stock (Mg ha^{-1}) was estimated by assuming that 50% of total biomass is carbon[46], and CO_2sequestration potential (Mg ha^{-1}) was calculated by multiplying the carbon stock by 3.67, the molecular weight ratio of CO_2 to carbon[47].All observations were recorded separately for each species under two spacing systems (5 × 5 m and 5 × 4 m) and for two years (2024 and 2025).

Statistical analysis.

Data pertaining to growth, yield metrics, and proximate composition were subjected to analysis of variance (ANOVA) utilizing a factorial randomized block design, with the Horti-silvi-pasture system as the primary factor and spacings as the secondary factor. The analysis of tree growth, biomass, and carbon sequestration was conducted utilizing a Completely Randomized Block Design (CRBD). The significance of differences was evaluated at the 5% significance level utilizing OPSTAT statistical software.

Results and Discussion

Growth and morphological attributes of BN hybrid

The horti-silvi-pasture system significantly influenced all growth and morphological attributes of BN Hybrid grass (Table 1). In both years, **H2**(*Holoptelea integrifolia +Annona squamosa*) outperformed**H1**(*Holoptelea integrifolia +Punica granatum*) across all parameters in year 2024,2025 and pooled data viz, plant height (136.45 cm, 125.25 cm, and 130.85 cm), shoots per m^2 (158, 141.1, and 149.55), leaf stem ratio (1.12, 1.08, and 1.09), and leaf area index (4.24, 4.17, 4.21). This indicates that the H2 system provided a more favorable environment for growth, likely due to better light interception, microclimatic conditions, and resource availability.Spacing had a pronounced effect on all growth parameters. Wider spacing (**S1**) consistently produced superior results compared to closer spacing (**S2**) across 2024, 2025 and pooled data viz, plant height (139.58 cm, 126.87 cm,and 133.22 cm), shoots per m^2 (165, 146.6, and 155.8), leaf stem ratio (1.11, 1.09, and 1.11), and leaf area index (4.27, 4.21, and 4.24). This demonstrates that reduced inter-plant competition in S1 allowed better resource utilization, leaf expansion, and tillering.The interaction between the horti-silvi-pasture system and spacing was largely non-significant for traits, such as plant height, LSR, and LAI, suggesting that the impacts of spacing were uniform across systems. A significant interaction was detected for shoots per m^2, indicating that the effect of spacing on tillering varied marginally between H1 and H2. This indicates that system-specific spacing management can enhance shoot density.These findings correspond with prior research in agroforestry and pasture management, wherein shade significantly affect growth and fodder quality of BN hybrid grass[31]. The shade significantly influenced the fodder grass varieties in humid conditions of Kerala and Suparna variety was suited for shaded conditions[48].The Custard apple-based agroforestry system tends to have beneficial effect on growth of intercrops[49].Agri-horti systems with Custard apple as horticultural component improved plant growth, root development and nutrient uptake in chickpea[50].

Yield attributes of BN hybrid

The horti-silvi-pasture system significantly influenced both green and dry forage yield of BN Hybrid grass (Table 2). Across 2024, 2025, and pooled data, H2 (*Holoptelea integrifolia* + *Annona squamosa*) consistently outperformed H1 (*Holoptelea integrifolia* + *Punica granatum*) with green forage yields of 28.3 t ha^{-1}, 27.6 t ha^{-1}, and 27.97 t ha^{-1}, and dry forage yields of 6.3 t ha^{-1}, 6.05 t ha^{-1}, and 6.17 t ha^{-1}, respectively. This indicates that the H2 system provided a more favorable environment for biomass accumulation, likely due to improved light interception, nutrient availability, and microclimatic conditions.Spacing also had a significant effect on forage production. Wider spacing (S1) consistently resulted in higher green and dry forage yields compared to closer spacing (S2) across 2024, 2025, and pooled data, with green forage yields of 28.3 t ha^{-1}, 27.2 t ha^{-1}, and 27.74 t ha^{-1}, and dry forage yields of 6.0 t ha^{-1}, 5.7 t ha^{-1}, and 5.85 t ha^{-1}. This demonstrates that reduced inter-plant competition in S1 facilitated better leaf expansion, tillering, and overall biomass production. The interaction between horti-silvi-pasture system and spacing was non-significant for both green and dry forage yields, indicating that the beneficial effects of wider spacing were consistent across both H1 and H2 systems. These results align with earlier studies in silvi-pasture systems, which show that canopy composition and optimal plant spacing are key determinants of forage productivity[51]. The yield of BN hybrid grass under tree shade was reduced compared to open conditions, since grasses are light demanding and they require abundance of sunlight for their proper growth and yield[31]. Poplar based agroforestry improve the yield of fodder sorghum in poplar-based alley crop systems, spacing of 8 × 3 m was suitable for significantly higher green forage, and grain yields and nutrient uptake[52]. The similar results were observed in grain yields that closer spacing in agroforestry has less yield as compared to wider spacings[53]. The grass yield was significantly reduced under agroforestry system when grown a s a under storey crop with trees[54]. The higher yields of grasses under custard apple may be attributed to improved microclimatic conditions beneath its canopy, such as better light distribution, moderated soil temperature, and enhanced moisture retention, which collectively favor photosynthetic efficiency and biomass accumulation[55].The yield of fodders in custard apple-based horti-pastoral system showed improve performance and soil health[56].These findings corroborate earlier studies in silvi-pastoral systems, where optimizing tree–grass interactions through spacing management was shown to increase both green and dry matter yield[57].

Proximate composition of BN Hybrid grass

The horti-silvi-pasture system significantly influenced most of the proximate composition parameters of BN Hybrid grass (Table 3& 4). In both years, H2 (Holoptelea integrifolia + Annona squamosa) recorded comparatively higher values than H1 (Holoptelea integrifolia + Punica granatum) across 2024, 2025 and pooled data viz., total ash (13.54%, 13.59%, and 13.57%), crude fibre (59.59%, 63.69%, and 61.64%), crude protein (8.09%, 8.81%, and 8.45%), ether extract (4.32%, 4.57%, and 4.45%), acid detergent fibre (50.02%, 51.79%, and 50.90%), neutral detergent fibre (60.41%, 62.89%, and 61.65%), nitrogen free extract (8.83%, 8.83%, and 8.83%), and oxalate content (2.78%, 2.70%, and 2.74%). This indicates that the H2 system improved the nutritional quality of BN Hybrid grass, likely due to better nutrient cycling, favorable microclimatic conditions, and enhanced soil fertility under diversified tree components.Spacing had a variable effect on proximate composition parameters. Closer spacing (S2) recorded relatively higher values for total ash (13.49%, 13.47%, and 13.48%), ether extract (4.27%, 4.50%, and 4.41%),acid detergent fibre (50.56%, 52.32%, and 51.44%), neutral detergent fibre (60.62%, 63.29%, and 61.95%), nitrogen free extract (8.87%, 8.83%, and 8.85%), and oxalate content (2.79%, 2.75%, and 2.77%). This suggests that spacing had a limited and inconsistent influence on quality parameters, possibly due to compensatory effects of plant density and nutrient availability.The relationship between the horti-silvi-pasture system and spacing was predominantly non-significant for most proximal constituents, suggesting that the influences of tree systems and spacing functioned separately. The mineral accumulation in forage may vary under particular combinations of tree species and spacing[58]. The tree species composition significantly influences fodder quality[59].Shade significantly influenced the proximate composition of the BN hybrid, with effects intensifying as shade levels increased. The crude protein content is more influenced by shade than other quality attributes, as nitrogen buildup was elevated in all green plants cultivated in shaded conditions[60].The crude protein content in fodder grasses increases with higher shadow levels[61].Oxalate synthesis correlates with light and photosynthesis; under conditions of light stress, increased production of oxalates occurs[62]. The shade ha significant effect on nutritional composition in herbaceous species[63].The reduction of soluble carbohydrates in plants exposed to shade results in a noticeable rise in the cell wall fraction, namely the neutral detergent fiber of the dry matter[64]. The results were in close conformity with the findings of other research done on BN hybrid grass[65,66]. Guava-based agroforestry systems can function as a viable climate-smart alternative as the overall system performance excelled in forage quality, soil fertility, and carbon sequestration[67]. The NDF and ADF in AFS likely indicate an increased leaf-to-stem ratio and a younger physiological age in shaded conditions, which diminishes the synthesis of structural carbohydrates[68,69].

Correlation matrix of growth, yield and proximate composition of BN hybrid under Horti-silvi-pasture system

The univariate correlation matrix demonstrated substantial associations across growth, yield, and quality variables (Fig. 3). Growth parameters, including leaf stem ratio (LSR), plant height (PH), number of shoots per square meter (SPM), and leaf area index (LAI), demonstrated persistent positive and significant associations with one another (r = 0.92–0.99). The growth factors exhibited a positive and significant correlation with green forage yield (GFY) and dry forage yield (DFY), signifying their direct impact on biomass production.Plant height exhibited substantial positive associations with SPM (r = 0.99), LAI (r = 0.96), GFY (r = 0.80), and DFY (r = 0.71), indicating that taller plants with enhanced canopy growth improved forage yield. GFY and DFY exhibited a strong positive correlation (r = 0.94), signifying consistency in the accumulation of fresh and dry biomass.Fiber fractions, comprising acid detergent fiber (ADF) and neutral detergent fiber (NDF), had a high positive correlation with each other (r = 0.89–0.94) and demonstrated significant positive associations with nitrogen-free extract (NFE) and oxalate content (OC) (r = 0.88–0.96). ADF and NDF demonstrated substantial negative relationships with growth indices including LSR, PH, SPM, and LAI (r = –0.38 to –0.76), suggesting that increased fiber content correlated with diminished growth performance.NDF had negative relationships with GFY and DFY, while NFE and OC shown positive associations with quality indicators including total ash (TA), ether extract (EE), crude fibre (CF), and crude protein (CP). TA, EE, CF, and CP had significant positive correlations (r = 0.85–0.99), signifying a synchronized enhancement in fodder quality attributes

Growth, Biomass and carbon attributes in Horti-silvi-pasture system

The growth traits, biomass production, and carbon indices of various tree species were markedly affected by species and spacing throughout both years (Table 5). Among all treatments, T4, *H. integrifolia* (5 m × 4 m) exhibited the highest values in 2024 and 2025 for most parameters, including DBH (7.47 cm and 8.30 cm), tree height (3.16 m and 3.52 m), above-ground biomass (3.38Mg ha^{-1} and 4.60 Mg ha^{-1}), below-ground biomass (0.88Mg ha^{-1} and 1.19 Mg ha^{-1}), total biomass (4.26 Mg ha^{-1} and 5.79 Mg ha^{-1}) (Fig. 4), carbon stock (2.13Mg ha^{-1} and 2.90 Mg ha^{-1}), and CO_2 mitigation potential (7.82Mg ha^{-1} and 10.64 Mg ha^{-1}). T1,*H. integrifolia* (5 m × 5 m) demonstrated greater growth performance and carbon sequestration ability, particularly with denser spacing (5 m × 4 m).Among the fruit tree species, T6, *Annona squamosa* (5 m × 4 m) demonstrated superior performance relative to T3,*Annona squamosa* (5 m × 5 m). It documented elevated measurements for DBH (3.32 cm and 4.13 cm), tree height (1.52 m and 1.93 m), above-ground biomass (0.29Mg ha^{-1} and 0.58 Mg ha^{-1}), carbon stock (0.19Mg ha^{-1} and 0.37 Mg ha^{-1}), and CO_2 mitigation potential (0.69Mg ha^{-1} and 1.34 Mg ha^{-1}). In general, denser spacing (5 m × 4 m) consistently yielded greater biomass production, carbon stock, and CO_2 mitigation potential across all species compared to broader spacing (5 m × 5 m). The increase in growth indices of trees inside the horti-silvi-pasture system exhibited distinct variation among treatments (Fig. 5). The box plot analysis demonstrated that the height increment of *Holoptelea integrifolia* (Fig. 5a) was typically superior and more consistent than that of *Annona squamosa* and *Punica granatum*, as evidenced by elevated median values and comparatively wider interquartile ranges. Likewise, the diameter at breast height (DBH) increase (Fig. 5b) displayed a similar pattern, with *H. integrifolia* demonstrating higher median increments and variability, indicating enhanced growth performance within the system.The data distribution, illustrated by whiskers, demonstrated slight variability among treatments, although the existence of few outliers implied sporadic aberrations in growth, potentially attributable to micro-site variations or individual tree responses.The increased tree density with reduced spacing led to enhanced cumulative biomass per unit area, albeit slight variations in individual tree development[70].The accumulation of biomass and carbon in agroforestry systems is predominantly determined by plant species and structural composition[71].Enhanced biomass accumulation was observed in an agri-horti system integrating bael with soybean[72].The Pomegranate–lemongrass-based agroforestry system in central India significantly influenced tree growth parameters, likely due to improved microclimatic conditions, and better resource utilization[73].Agroforestry systems significantly enhance carbon stocks in biomass and soil, depending on species and system design[74]. The improved biomass accumulation and carbon sequestration noted with closer spacing in this study align with evidence that *Gmelina arborea*-based agroforestry systems substantially improve carbon stock and CO_2 mitigation potential through enhanced biomass production and stand density[75].Biomass and levels of carbon differ substantially among species, with increased biomass correlating to enhanced carbon storage[76].

Conclusion

This study illustrates that climate-resilient horti-silvi-pasture systems markedly improve fodder yield, nutritional quality, and carbon sequestration capacity in the semi-arid conditions of the Bundelkhand region. Among the analyzed systems, the combination of *Holoptelea integrifolia* and *Annona squamosa* (H2) demonstrated superiority in enhancing growth, yield, and proximate composition of BN hybrid grass, signifying its appropriateness for integrated forage-based production systems. Wider spacing (5 m × 5 m) promoted growth characteristics and forage output of the grass component by minimizing competition, whereas denser spacing (5 m × 4 m) augmented tree biomass accumulation and carbon sequestration per unit area.The study additionally demonstrated significant positive correlations between growth parameters and forage yield, whereas fibre fractions exhibited negative associations with growth, underscoring the trade-off between biomass output and structural composition. Tree component analysis revealed that *H. integrifolia* demonstrated the greatest biomass accumulation and carbon sequestration potential, especially at denser spacing, highlighting its ecological and functional significance in agroforestry systems.The incorporation of appropriate tree species with optimized spacing in horti-silvi-pasture systems presents an effective climate-smart approach to mitigate fodder shortages, augment livestock production and increase carbon sequestration in degraded semi-arid regions.

Declarations

Data Availability Statement

The data related to research are contained in the manuscript.

Plant guidelines: The collection and use of plant materials complied with the relevant local and national guidelines. No endangered or protected plant species were involved in this study.

Ethical approval: Not Applicable

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Authors contribution

(1) PT: Conceptualization, Methodology, Supervision, Data curation, (2) PPD: Formal Analysis, Writing – Original Draft; (3) MJD: Supervision, Writing – Review & Editing; (4) PKS: Investigation, Data curation, Resources; (5) SB: Formal Analysis, Validation, Writing – Review & Editing; (6) GSA: Methodology, Validation 7) MS: Review & Editing.

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Tables

Table 1. Growth and morphological attributes of BN Hybrid grass under different Horti-silvi-pasture systems and spacings												
Treatments	**Plant height (cm)**			**Shoots per metre square**			**Leaf Stem Ratio**			**Leaf Area Index**		
	2024	**2025**	**Pooled**	**2024**	**2025**	**Pooled**	**2024**	**2025**	**Pooled**	**2024**	**2025**	**Pooled**
Horti-silvi-pasture system												
H1	125.89	114.65	120.27	143.5	127.65	135.57	1.07	1.05	1.06	4.14	4.12	4.13
H2	136.45	125.25	130.85	158	141.1	149.55	1.12	1.08	1.09	4.24	4.17	4.21
SE(m)	1.34	0.77	0.79	1.11	0.46	0.47	0.01	0.03	0.004	0.08	0.02	0.02
CD (0.05)	4.33	2.49	2.57	3.58	1.49	1.52	0.03	0.1	0.01	0.03	NS	0.06
Spacings												
S1	139.58	126.87	133.22	165	146.6	155.8	1.11	1.09	1.11	4.27	4.21	4.24
S2	122.75	113.03	117.89	136.5	122.15	129.32	1.07	1.04	1.05	4.11	4.08	4.09
SE(m)	1.34	0.77	0.79	1.11	0.46	0.47	0.01	0.03	0.04	0.08	0.02	0.02
CD (0.05)	4.33	2.49	2.57	3.58	1.49	1.52	0.03	0.1	0.01	0.03	0.08	0.06
Interaction												
CD (0.05)	NS	NS	NS	NS	2.12	2.15	NS	0.03	0.02	NS	NS	NS

H1: *Holoptelea integrifolia* + *Punica granatum*; H2: *Holoptelea integrifolia* + *Annona squamosa*; S1: 5 m × 5 m; S2: 5 m × 4 m

NS, Non-significant at p ≤ 0.05.

Table 2. Green and dry forage yield of BN Hybrid grass under different Horti-silvi-pasture systems and spacings						
Treatments	**Green forage Yield (t ha^{-1})**			**Dry forage Yield (t ha^{-1})**		
	2024	**2025**	**Pooled**	**2024**	**2025**	**Pooled**
Horti-silvi-pasture system						
H1	26.1	25.0	25.56	5.35	5.05	5.2
H2	28.3	27.6	27.97	6.3	6.05	6.17
SE(m)	0.24	0.21	0.14	0.05	0.04	0.03
CD (0.05)	0.79	0.65	0.45	0.15	0.14	0.11
Spacings						
S1	28.3	27.2	27.74	6.0	5.7	5.85
S2	26.1	25.5	25.78	5.65	5.4	5.52
SE(m)	0.24	0.21	0.14	0.05	0.04	0.03
CD (0.05)	0.79	0.65	0.45	0.15	0.14	0.11
Interaction						
CD (0.05)	NS	NS	NS	NS	NS	NS

H1: *Holoptelea integrifolia* + *Punica granatum*; H2: *Holoptelea integrifolia* + *Annona squamosa*; S1: 5 m × 5 m; S2: 5 m × 4 m

NS, Non-significant at p ≤ 0.05.

Table 3. Proximate composition of BN Hybrid grass under different Horti-silvi-pasture systems and spacings												
Treatments	**Total Ash (%)**			**Crude fibre (%)**			**Crude Protein (%)**			**Ether extract (%)**		
	2024	**2025**	**Pooled**	**2024**	**2025**	**Pooled**	**2024**	**2025**	**Pooled**	**2024**	**2025**	**Pooled**
Horti-silvi-pasture system												
H1	13.16	13.22	13.19	57.77	60.9	59.34	7.91	8.66	8.29	4.15	4.29	4.22
H2	13.54	13.59	13.57	59.59	63.69	61.64	8.09	8.81	8.45	4.32	4.57	4.45
SE(m)	0.07	0.05	0.04	0.36	0.35	0.21	0.04	0.07	0.03	0.03	0.02	0.01
CD (0.05)	0.23	0.18	0.13	1.18	1.12	0.63	0.13	NS	0.09	0.09	0.07	0.04
Spacings												
S1	13.21	13.35	13.28	58.0	62.95	60.48	8.02	8.69	8.35	4.15	4.37	4.26
S2	13.49	13.47	13.48	59.36	61.64	60.53	7.98	8.78	8.38	4.27	4.5	4.41
SE(m)	0.07	0.05	0.04	0.36	0.35	0.21	0.04	0.07	0.03	0.03	0.02	0.01
CD (0.05)	0.23	NS	0.13	1.18	1.12	NS	NS	NS	NS	0.09	0.07	0.04
Interaction												
CD (0.05)	NS	0.25	0.19	NS	NS	NS	NS	NS	NS	NS	NS	NS

H1: *Holoptelea integrifolia* + *Punica granatum*; H2: *Holoptelea integrifolia* + *Annona squamosa*; S1: 5 m × 5 m; S2: 5 m × 4 m

NS, Non-significant at p ≤ 0.05.

Table 4. Fiber fractions, nitrogen-free extract, and oxalate content of BN Hybrid grass under different Horti-silvi-pasture systems and spacings												
Treatments	**Acid detergent fibre (%)**			**Neutral detergent fibre(%)**			**Nitrogen free extract (%)**			**Oxalate content (%)**		
	2024	**2025**	**Pooled**	**2024**	**2025**	**Pooled**	**2024**	**2025**	**Pooled**	**2024**	**2025**	**Pooled**
Horti-silvi-pasture system												
H1	49.94	51.21	50.57	58.8	61.47	60.50	8.62	8.62	8.62	2.62	2.50	2.56
H2	50.02	51.79	50.90	60.41	62.89	61.65	8.83	8.83	8.83	2.78	2.70	2.74
SE(m)	0.4	0.18	0.26	0.48	0.43	0.28	0.06	0.05	0.05	0.01	0.02	0.01
CD (0.05)	NS	NS	NS	1.58	1.39	0.93	0.19	0.17	0.18	0.04	0.06	0.03
Spacings												
S1	49.39	50.68	50.04	58.59	61.07	60.2	8.58	8.63	8.6	2.61	2.46	2.54
S2	50.56	52.32	51.44	60.62	63.29	61.95	8.87	8.83	8.85	2.79	2.75	2.77
SE(m)	0.4	0.18	0.26	0.48	0.43	0.28	0.06	0.05	0.05	0.01	0.02	0.01
CD (0.05)	NS	0.6	0.85	1.58	1.39	0.93	0.19	0.17	0.18	0.04	0.06	0.03
Interaction												
CD (0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

H1: *Holoptelea integrifolia* + *Punica granatum*; H2: *Holoptelea integrifolia* + *Annona squamosa*; S1: 5 m × 5 m; S2: 5 m × 4 m

NS, Non-significant at p ≤ 0.05.

Table 5. Growth attributes, biomass, carbon parameters of different tree species under two spacings during 2024 and 2025												
Treatments	**DBH (cm)**		**Tree Height (m)**		**Above-ground biomass ($Mg\ ha^{-1}$)**		**Below-ground biomass ($Mg\ ha^{-1}$)**		**Carbon stock ($Mg\ ha^{-1}$)**		**CO_2 mitigation potential ($Mg\ ha^{-1}$)**	
	2024	**2025**	**2024**	**2025**	**2024**	**2025**	**2024**	**2025**	**2024**	**2025**	**2024**	**2025**
T1: *H. integrifolia* (5m × 5m)	7.98	9.06	3.01	3.34	2.93	4.15	0.76	1.08	1.85	2.62	6.78	9.59
T2: *Punica granatum* (5m × 5m)	2.97	3.57	1.83	2.19	0.24	0.42	0.06	0.11	0.15	0.26	0.57	0.97
T3: *Annona squamosa*(5m×5m)	3.58	4.42	1.36	1.84	0.25	0.5	0.07	0.13	0.16	0.32	0.57	1.16
T4: *H. integrifolia* (5m × 4m)	7.47	8.3	3.16	3.52	3.38	4.6	0.88	1.19	2.13	2.9	7.82	10.64
T5: *Punica granatum* (5m × 4m)	2.63	3.49	1.94	2.27	0.26	0.52	0.07	0.13	0.16	0.33	0.59	1.20
T6: *Annona squamosa*(5m× 4m)	3.32	4.13	1.52	1.93	0.29	0.58	0.08	0.15	0.19	0.37	0.69	1.34
SE(m)	0.05	0.06	0.02	0.03	0.05	0.02	0.01	0.01	0.03	0.01	0.12	0.05
CD (0.05)	0.17	0.18	0.07	0.08	0.17	0.07	0.04	0.02	0.11	0.04	0.38	0.17
CV (%)	2.37	2.16	2.24	2.14	8.88	2.64	8.88	2.64	8.88	2.64	8.88	2.64

T1: *H. integrifolia* (5 m × 5 m), T2: *Punica granatum* (5 m × 5 m), T3: *Annona squamosa* (5 m × 5 m), T4: *H. integrifolia* (5 m × 4 m), T5: *Punica granatum* (5 m × 4 m), and T6: *Annona squamosa* (5 m × 4 m).

Figures

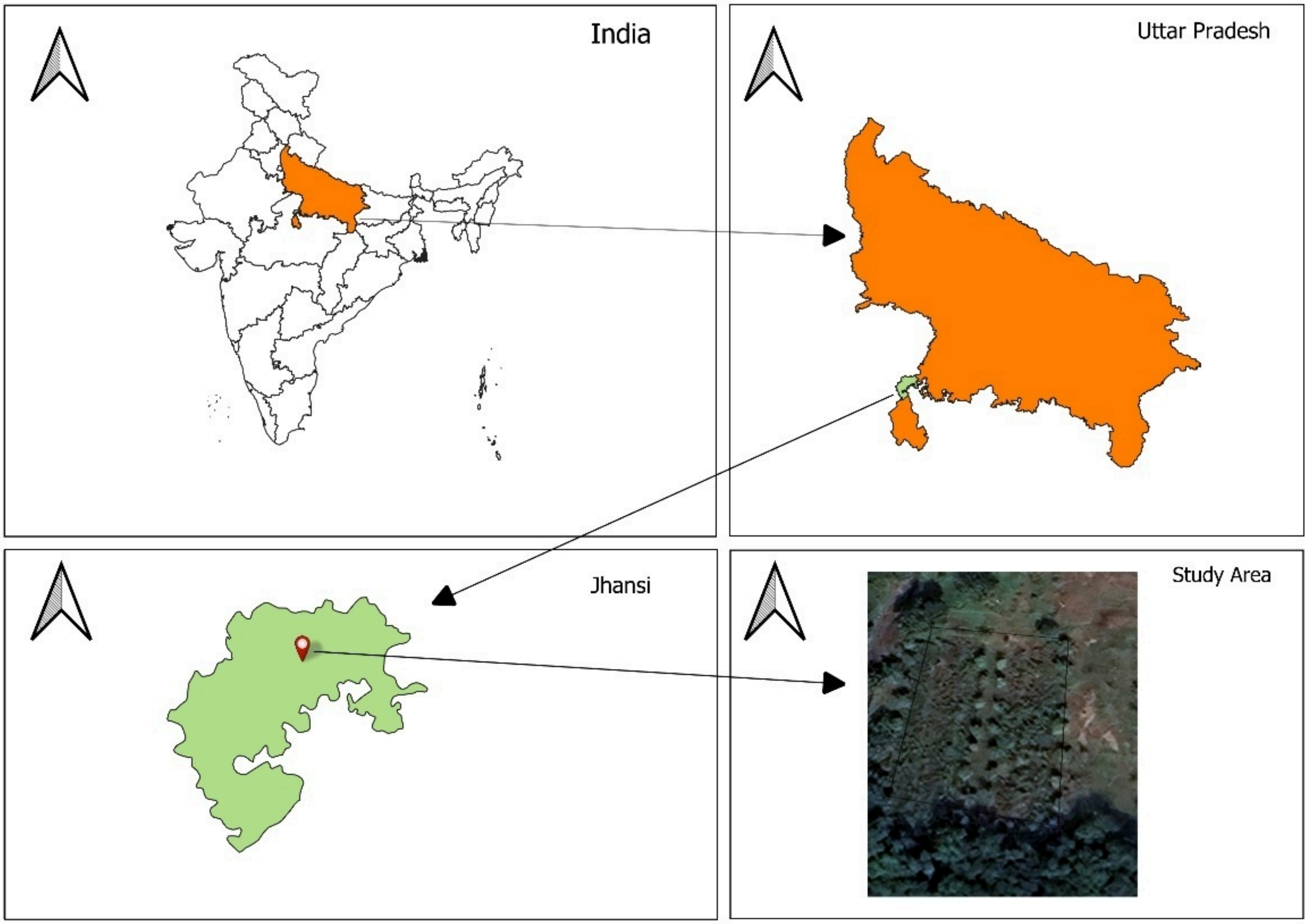

Figure 1

Location Map of experimental site at RLBCAU, Jhansi

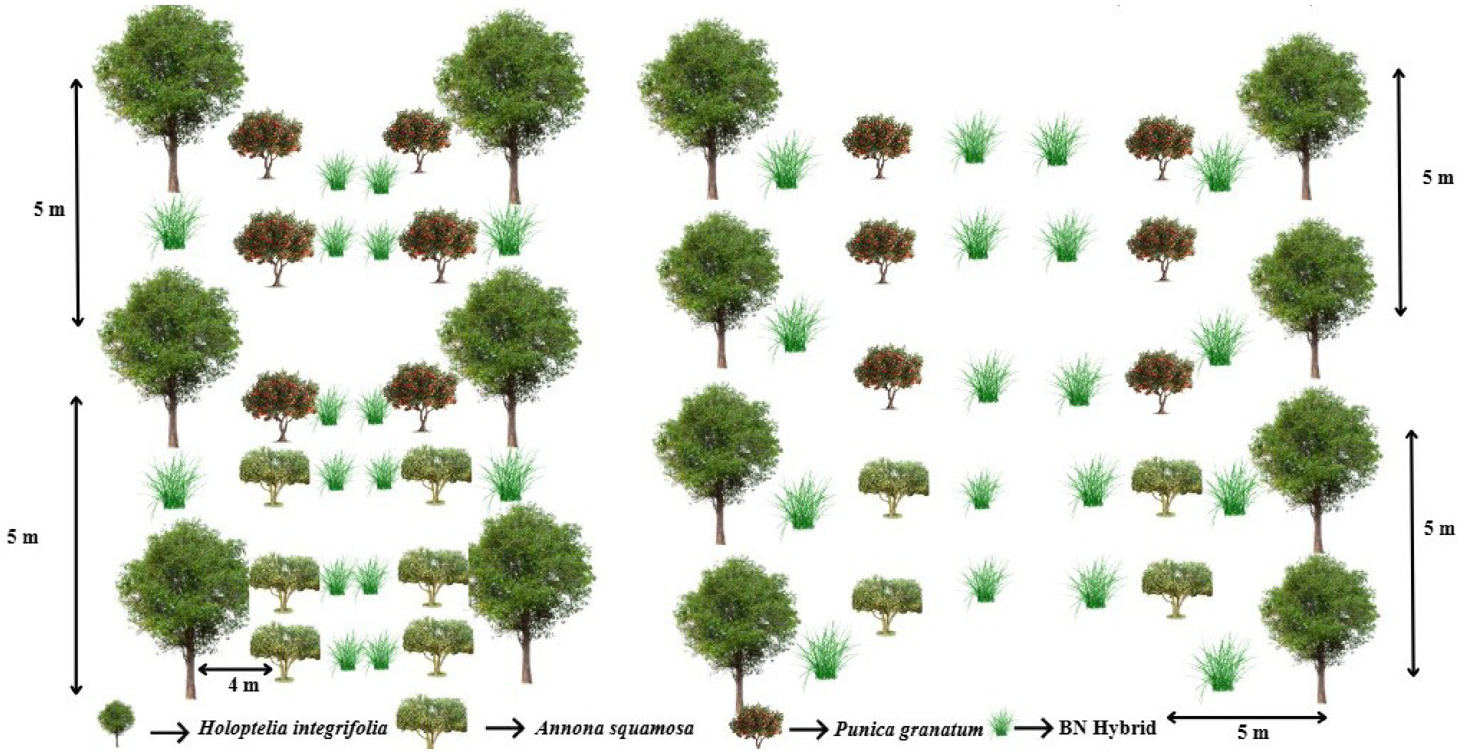

Figure 2

Representation of experimental layout showing Horti-silvi-pasture system with two spacings (5m × 5m & 5m × 4m)

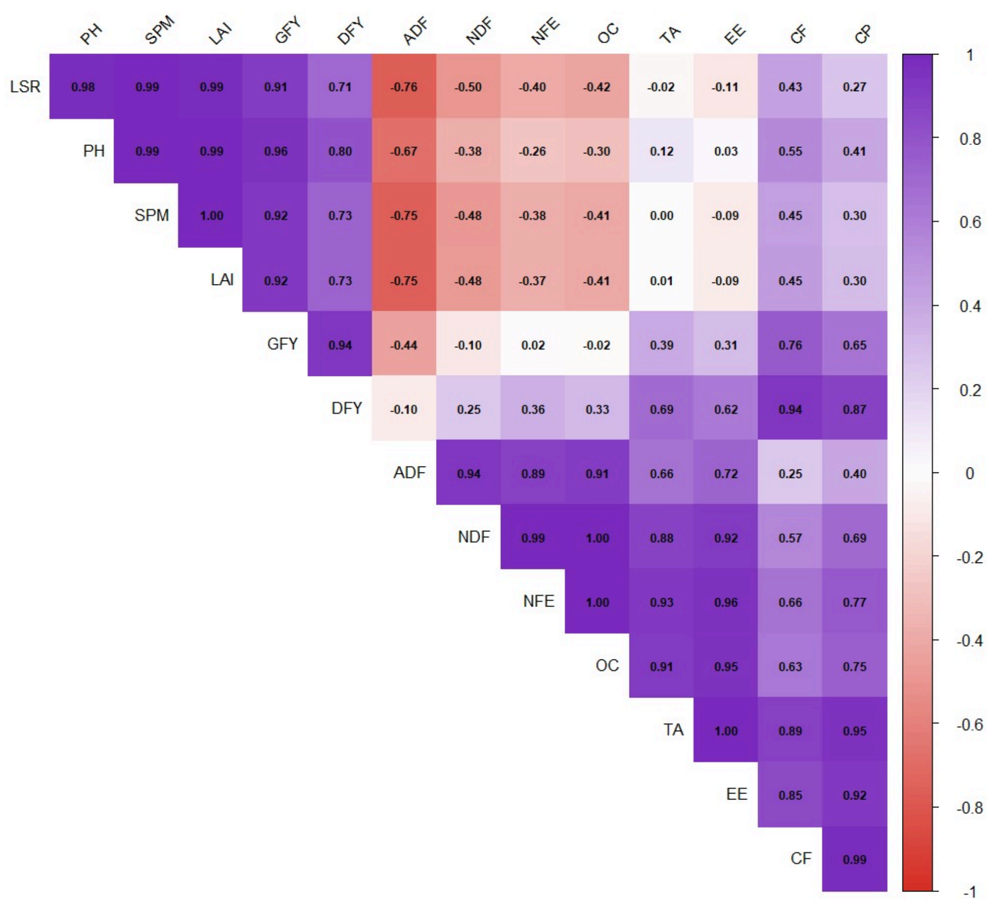

Figure 3

Correlogram representing correlation between growth, yield and proximate compositionof BN hybrid grass under Horti-silvi-pasture system

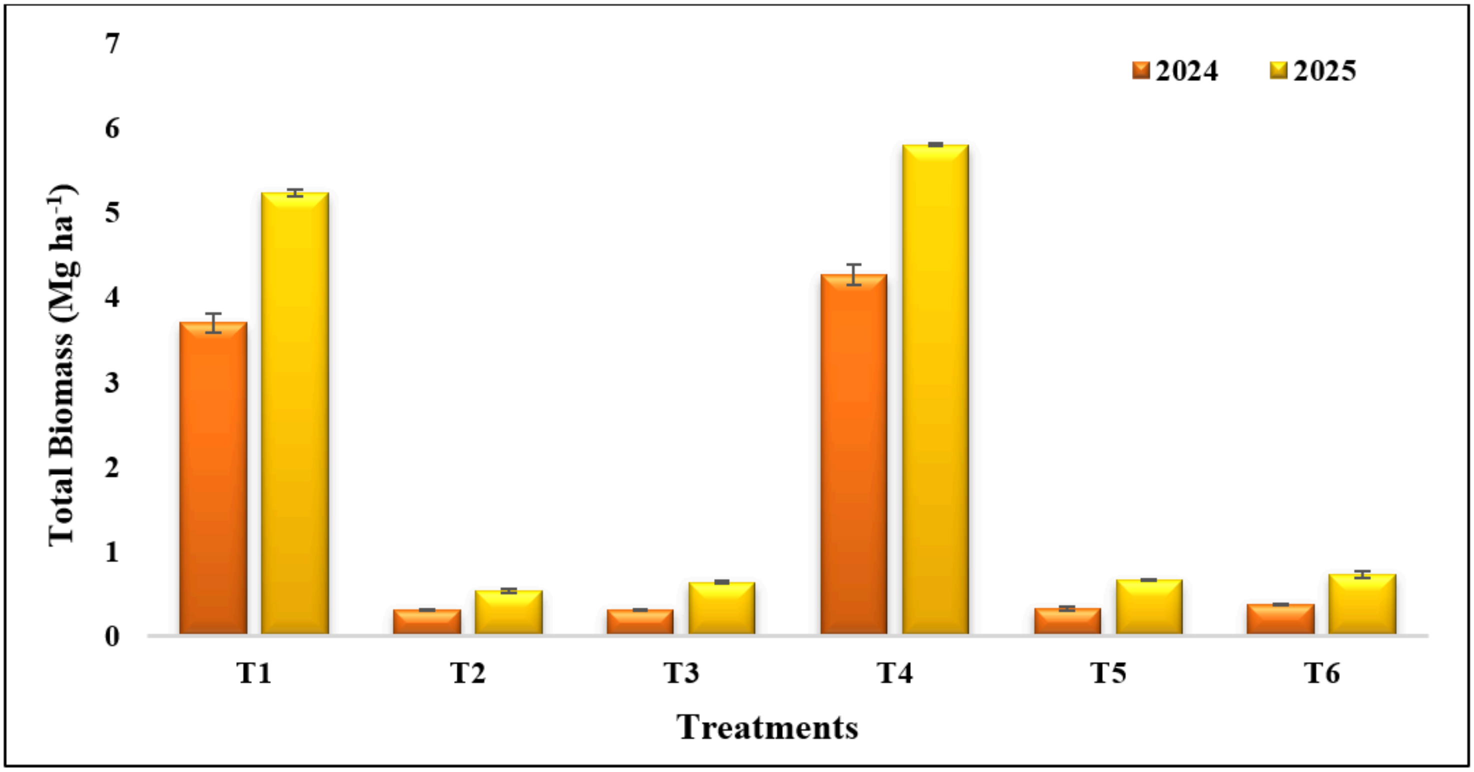

Figure 4

Total Biomass of different tree species under two spacings during 2024 and 2025

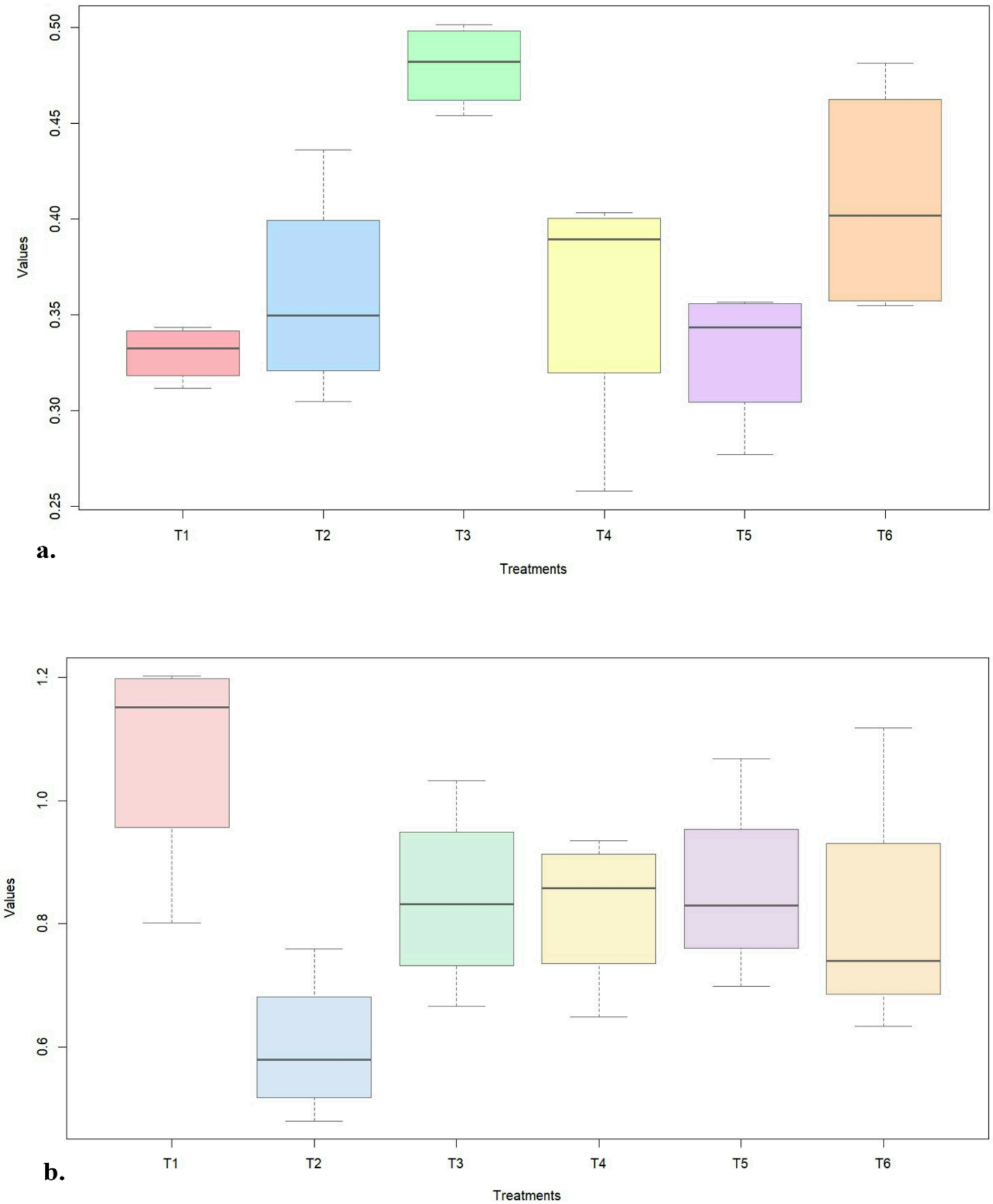

Figure 5

Increment in growth parameters of trees in Horti-silvi-pasture system (a) Height and (b) Diameter at breast height. Boxes represent the interquartile range, horizontal lines indicate medians, whiskers show data spread, and dots denote outliers