

Assessment of Biomass Production and Carbon Sequestration in Fruit Tree–Based Agroforestry Systems of the Semi-Arid of Vindhyan Region in India

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Research Article

Keywords: Agri-horticulture, Biomass, Carbon stock, Soil Organic Carbon, Climate Mitigation

Posted Date: October 20th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11113161/v1>

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Additional Declarations: No competing interests reported.

Abstract

Agroforestry systems are increasingly recognised for their dual role in supporting rural livelihoods and contributing to climate-change mitigation through carbon sequestration. A field experiment was conducted during the Kharif cropping season at the Rajiv Gandhi South Campus, Barkachha, Mirzapur (Vindhyan region, Uttar Pradesh, India) to quantify biomass accumulation and carbon sequestration under bael (*Aegle marmelos*) and guava (*Psidium guajava*) based agri-horticulture systems intercropped with two varieties each of black gram (*Vigna mungo*) and sesame (*Sesamum indicum*) relative to sole-crop open-field controls. Twelve land-use treatments were arranged in a randomised complete-block design with three replications. Tree and crop biomass were estimated using non-destructive allometric approaches and destructive sampling of intercrops such as carbon stocks were derived assuming a biomass carbon fraction of 0.50 and converted to CO₂ equivalents. Soil organic carbon (0–30 cm) was determined by the Walkley-Black method. Bael-based systems accumulated significantly higher total biomass (50.1–56.2 t ha⁻¹) and total carbon stock (27.1–30.8 t C ha⁻¹) than guava-based systems (31.3–38.0 t ha⁻¹ biomass, 17.3–21.4 t C ha⁻¹) and sole crops (1.8–3.1 t ha⁻¹ biomass, 0.9–1.6 t C ha⁻¹). The highest total carbon stock was recorded under bael + black gram (Shekar-1). Annual carbon sequestration rates ranged from 1.9 to 3.4 t C ha⁻¹ yr⁻¹ in the agri-horti systems. Soil organic carbon was modestly higher under tree-based systems (0.42–0.51%) than under open-field crops (0.34–0.37%). The results demonstrate that well-managed bael- and guava-based agri-horticulture systems can deliver meaningful carbon benefits while supporting intercrop production in the Vindhyan region, and provide a quantitative basis for their inclusion in regional climate-mitigation and payment-for-ecosystem-services schemes.

1. Introduction

Rising atmospheric concentrations of carbon dioxide (CO₂) and other greenhouse gases are the principal drivers of anthropogenic climate change (Filonchyk, M et al.2024). Land-use systems that simultaneously produce food, generate income and sequester carbon are therefore of high policy relevance (Searchinger, T. D et al.2018) Agroforestry is the intentional integration of trees with crops and/or livestock has been widely recognised as a promising land-use strategy for climate-change mitigation because of its capacity to store carbon in both aboveground and belowground biomass and in soil (Nair et al., 2009; Albrecht & Kandji, 2003). Global estimates suggest that agroforestry systems can sequester between 1.5 and 3.5 Mg C ha⁻¹ yr⁻¹ under smallholder tropical conditions, with total carbon stocks ranging from 9 to more than 60 Mg C ha⁻¹ depending on climate, species and management (Montagnini & Nair, 2004).

Beyond direct carbon storage, agroforestry can reduce pressure on natural forests by providing alternative sources of fuelwood, timber and non-timber products, thereby conserving existing carbon stocks (Khan, I. A et al.2024). In addition, improved soil conservation under tree-based systems can reduce erosion-related carbon losses.

(Sivakumar, K., et al.2025). These multiple pathways make agroforestry particularly relevant to national climate commitments under the Paris Agreement and to India's Nationally Determined Contributions, which emphasise the role of the land sector in mitigation (Dhyani, S et al.2021).

In India, agri-horticulture systems that combine fruit trees with annual intercrops are common on marginal and semi-arid lands (Mohamed, M. N et al.2026). Bael (*Aegle marmelos* Correa) and guava (*Psidium guajava* L.) are widely planted in the Vindhyan region of Uttar Pradesh because of their drought tolerance, multipurpose utility and market value (Singh, A. K., et al.2025) When intercropped with short-duration legumes (e.g., black gram) or oilseeds (e.g., sesame) these systems can provide both early returns from the understorey crop and longer-term returns from the fruit trees, while potentially enhancing carbon storage relative to sole cropping (Cangela, A et al 2026).In the Vindhyan region specifically, the combination of shallow soils, seasonal drought and smallholder land holdings makes low-input, multipurpose systems particularly attractive (Singh, R., et al.2025). Bael is valued for its medicinal fruit, drought tolerance and ability to grow on degraded lands, while guava provides regular fruit yields and is widely accepted in local markets (Ahirwar, S. K et al. 2024).

Both species are well adapted to the seasonal moisture stress characteristic of the Vindhyan plateau. Bael, is particular known for its deep rooting habit and ability to access subsoil moisture, while guava responds well to moderate management intensity and yields marketable fruit within a few years of planting (Gokul, P,et al.2025). Intercropping these trees with short-duration black gram (a nitrogen-fixing legume) or sesame (an oilseed adapted to residual moisture) (Bastia, D. K et al.2025) allows farmers to obtain an annual income stream during the juvenile phase of the orchard and to continue generating understorey income even after the trees reach bearing age.

Previous work in India has documented carbon stocks of 20–60 t C ha⁻¹ in various fruit-tree and multipurpose-tree agroforestry systems under semi-arid and sub-humid conditions (Newaj & Rai, 2005; NRCAF, 2007). However, quantitative estimates of biomass accumulation and carbon sequestration for bael- and guava-based agri-horticulture systems intercropped with black gram and sesame in the Vindhyan region remain scarce. Most existing studies focus on timber or multipurpose tree species, or report only qualitative observations. Accurate, location-specific data on carbon stocks and sequestration rates are essential for calibrating national and regional greenhouse-gas inventories and also for designing payment-for-ecosystem-services (PES) or carbon-credit schemes that reward farmers for climate-smart land use and guiding the selection of tree-crop combinations that optimise both productivity and carbon benefits (Hao, Y et al. 2025).

Without such data, it is difficult to design credible carbon-credit projects to set realistic baselines for additionality assessments or to advise farmers on the long-term climate benefits of adopting agri-horticulture. Previous Indian studies have largely focused on timber species such as teak, eucalyptus or multipurpose trees (e.g., *Dalbergia sissoo*, *Leucaena leucocephala*), leaving a gap for fruit-tree systems that are more relevant to smallholder livelihoods in the Vindhyan region.

The present study was therefore undertaken to quantify aboveground and belowground biomass, carbon stocks and soil organic carbon under bael- and guava-based agri-horticulture systems intercropped with two varieties each of black gram and sesame and to compare these systems with sole-crop open-field controls in the Vindhyan region of India. Specific objectives were: (1) to estimate aboveground, belowground and total biomass accumulation under the different land-use systems (2) to quantify carbon stocks in tree and crop biomass and in soil (3) to calculate annual rates of carbon sequestration and CO₂-equivalent storage (4) to assess the contribution of soil organic carbon and (5) to identify the most carbon-efficient agri-horticulture combinations for the region.

2. Materials and Methods

2.1 Experimental site

The field experiment was conducted during the Kharif and Rabi seasons at the Agroforestry Block of the Rajiv Gandhi South Campus (RGSC), Barkachha, Mirzapur, Banaras Hindu University, located in the Vindhyan region of south-eastern Uttar Pradesh, India (25°10' N, 82°37' E; 147 m above sea level). The region experiences a

subtropical climate with mean annual rainfall of approximately 900–1100 mm, the majority of which falls during the south-west monsoon (June–September). Soils of the experimental site are sandy loam to loamy sand with low to medium organic carbon, typical of the Vindhyan uplands. Baseline soil properties (0–15 cm) were bulk density 1.43 Mg m⁻³, organic carbon 0.35%, and pH in the slightly acidic to neutral range.

Figure I. Geographic location of the experimental site (Rajiv Gandhi South Campus, Barkachha, Mirzapur) within India, highlighting the Vindhyan region of Uttar Pradesh.

2.2 Experimental design and treatments

Twelve land-use treatments were arranged in a randomised complete-block design (RCBD) with three replications. The treatments comprised: (T1) sole black gram (Shekar-1), (T2) sole black gram (Shekar-2), (T3) sole sesame (T4), (T4) sole sesame (T78), (T5) bael + black gram (Shekar-1), (T6) bael + black gram (Shekar-2), (T7) bael

+ sesame (T4), (T8) bael + sesame (T78), (T9) guava + black gram (Shekar-1), (T10) guava + black gram (Shekar-2), (T11) guava + sesame (T4), and (T12) guava + sesame (T78). Bael and guava trees were of moderate age (approximately 8–12 years) and planted at standard orchard spacings. Intercrops were sown in the alleys following recommended packages of practice for the region. Plot size was 50 × 10 m for biomass sampling. The experimental design deliberately included two varieties of each intercrop so that any variety specific differences in biomass or competitive ability could be detected. while still allowing a clear comparison between sole cropping and the two tree-based systems.

Figure II. Experimental layout of the 12 land-use treatments in a randomised complete block design (RCBD) with three replications. Plot size = 50 m × 10 m. Grey = Sole crops, Green = Bael-based systems, Blue = Guava-based systems.

2.3 Biomass estimation

Aboveground tree biomass was estimated non-destructively. Diameter at breast height (DBH) and total height were measured for all trees within each plot using a Ravi's multi-meter caliper and clinometer. Volume was calculated using species-appropriate form factors (Pressler's formula) where local volume equations were unavailable. Biomass was obtained by multiplying volume by wood basic density. Belowground (root) biomass was estimated as 25% of aboveground tree biomass, a widely adopted default ratio for tropical fruit trees in the absence of species-specific root:shoot ratios (Cairns et al., 1997; IPCC, 2006). Intercrop (black gram and sesame) biomass was determined by destructive harvest of 1 × 1 m quadrats at physiological maturity, oven-dried at 70°C to constant weight, and scaled to a per-hectare basis. Total biomass was the sum of tree aboveground, tree belowground and intercrop biomass.

2.4 Carbon stock and sequestration rate

Carbon content of biomass was assumed to be 50% of oven-dry biomass (Pearson et al., 2005, 2007), a standard conversion widely applied to woody and herbaceous biomass in tropical systems. Carbon stock (t C ha^{-1}) was therefore calculated as total biomass $\times$ 0.50. CO_2 equivalents were obtained by multiplying carbon stock by the molecular-weight factor 44/12 (≈ 3.67). Annual carbon sequestration rate ($\text{t C ha}^{-1} \text{ yr}^{-1}$) was derived by dividing total carbon stock by the estimated stand age of the trees (taken as 10 years for the purpose of rate calculation) and adding the seasonal contribution of the intercrop. Soil organic carbon (SOC) concentration was determined by the Walkley–Black rapid titration method (Walkley & Black, 1934). Soil bulk density was measured with core samplers. SOC stock (t C ha^{-1}) to 30 cm depth was calculated as:

$\text{SOC stock} = \text{bulk density (g cm}^{-3}\text{)} \times \text{depth (cm)} \times \text{organic carbon (\%)} \times 100.$

2.5 Statistical analysis

Data were subjected to analysis of variance (ANOVA) appropriate to the RCBD (Gomez & Gomez, 1984). Treatment means were compared using the critical difference (CD) at the 5% level of significance when the F-test was significant. Standard error of the mean ($\text{SEm} \pm$) and coefficient of variation (CV) were also calculated.

3. Results

3.1 Aboveground, belowground and total biomass

Total biomass accumulation differed significantly among land-use systems (Table I). Sole black gram and sesame crops produced only 1.8–3.1 t ha^{-1} of total biomass. In contrast, bael-based agri-horti

systems accumulated 50.1–56.2 t ha⁻¹, while guava-based systems accumulated 31.3–38.0 t ha⁻¹. The highest total biomass was recorded under bael + black gram (Shekar-1) (56.2 t ha⁻¹), followed by bael + sesame (T78) (54.6 t ha⁻¹). Aboveground tree biomass constituted the dominant fraction (approximately 70–75%) of total biomass in the agri-horti systems; intercrop contribution was modest (1.9–2.8 t ha⁻¹) but still higher than the corresponding sole-crop yields in several combinations, indicating limited competitive suppression under the prevailing tree spacing and management. Statistical analysis confirmed highly significant differences among land-use systems for all biomass components ($P < 0.05$). The coefficient of variation remained within acceptable limits ($< 15\%$), indicating that the experimental precision was adequate for the comparisons drawn.

Figure III. Total biomass accumulation (t ha⁻¹) under sole crops, bael-based and guava-based agri-horticulture systems.

Table I. Aboveground, belowground and total biomass (t ha⁻¹) under different land-use systems

Land-use system	AGB	BGB	Intercrop	Total
Sole black gram (Shekar-1)	–	–	2.4	2.4
Sole black gram (Shekar-2)	–	–	1.8	1.8
Sole sesame (T4)	–	–	3.1	3.1
Sole sesame (T78)	–	–	2.9	2.9
Bael + black gram (Shekar-1)	42.8	10.7	2.7	56.2
Bael + black gram (Shekar-2)	38.5	9.6	2.0	50.1
Bael + sesame (T4)	40.2	10.1	2.8	53.1
Bael + sesame (T78)	41.6	10.4	2.6	54.6
Guava + black gram (Shekar-1)	28.4	7.1	2.5	38.0
Guava + black gram (Shekar-2)	25.9	6.5	1.9	34.3
Guava + sesame (T4)	24.7	6.2	2.7	33.6
Guava + sesame (T78)	23.1	5.8	2.4	31.3
SEm±	1.85	0.46	0.12	2.21
CD (P = 0.05)	5.42	1.35	0.35	6.48

AGB = aboveground tree biomass; BGB = belowground (root) tree biomass. Intercrop biomass includes both grain and stover. Values are means of three replications.

3.2 Carbon stocks in biomass

Carbon stocks followed the same ranking as total biomass (Table II). Bael-based systems stored 27.1–30.8 t C ha⁻¹ in biomass, guava-based systems stored 17.3–21.4 t C ha⁻¹, and sole crops stored only 0.9–1.6 t C ha⁻¹. The highest biomass carbon stock (30.8 t C ha⁻¹) occurred under bael + black gram (Shekar-1). Of this total, approximately 78% resided in aboveground tree biomass, 17% in roots and 5% in the intercrop.

Figure IV. Partitioning of total system carbon (t C ha⁻¹) into aboveground tree, belowground tree, intercrop and soil organic carbon pools.

Table II. Carbon stocks in aboveground and belowground biomass (t C ha⁻¹)

Land-use system	AG C	BG C	Intercrop C	Total biomass C
Sole black gram (Shekar-1)	–	–	1.2	1.2
Sole black gram (Shekar-2)	–	–	0.9	0.9
Sole sesame (T4)	–	–	1.6	1.6
Sole sesame (T78)	–	–	1.5	1.5
Bael + black gram (Shekar-1)	21.4	5.4	1.4	28.2
Bael + black gram (Shekar-2)	19.3	4.8	1.0	25.1
Bael + sesame (T4)	20.1	5.1	1.4	26.6
Bael + sesame (T78)	20.8	5.2	1.3	27.3
Guava + black gram (Shekar-1)	14.2	3.6	1.3	19.1
Guava + black gram (Shekar-2)	13.0	3.3	1.0	17.3
Guava + sesame (T4)	12.4	3.1	1.4	16.9
Guava + sesame (T78)	11.6	2.9	1.2	15.7
SEm±	0.85	0.23	0.06	1.05
CD (P = 0.05)	2.49	0.67	0.18	3.08

3.3 Soil organic carbon and total system carbon

Soil organic carbon concentration (0–30 cm) was significantly higher under the agri-horti systems (0.42–0.51%) than under sole-crop open-field plots (0.34–0.37%) (Table III). Corresponding SOC stocks ranged from 18.1 to 22.4 t C ha⁻¹ under tree-based systems and 14.6–15.9 t C ha⁻¹ under sole crops. When biomass carbon and soil carbon were summed, total system carbon reached 45.1–51.2 t C ha⁻¹ under bael systems and 33.0–40.5 t C ha⁻¹ under guava systems (Table IV).

Figure V. Soil organic carbon concentration (%) in the 0–30 cm soil layer under different land-use systems.

Table III. Soil organic carbon concentration and stock (0–30 cm) under different land-use systems

Land-use system	SOC (%)	Bulk density (Mg m⁻³)	SOC stock (t C ha⁻¹)
Sole black gram (Shekar-1)	0.36	1.43	15.4
Sole black gram (Shekar-2)	0.34	1.44	14.7
Sole sesame (T4)	0.37	1.42	15.8
Sole sesame (T78)	0.35	1.43	15.0
Bael + black gram (Shekar-1)	0.51	1.40	21.4
Bael + black gram (Shekar-2)	0.48	1.41	20.3
Bael + sesame (T4)	0.49	1.40	20.6
Bael + sesame (T78)	0.50	1.40	21.0
Guava + black gram (Shekar-1)	0.46	1.41	19.4
Guava + black gram (Shekar-2)	0.44	1.42	18.7
Guava + sesame (T4)	0.43	1.42	18.3
Guava + sesame (T78)	0.42	1.43	18.0
SEm±	0.015	0.008	0.62
CD (P = 0.05)	0.044	NS	1.82

Table IV. Total system carbon stock (biomass + soil) and CO₂ equivalents

Land-use system	Biomass C	Soil C	Total system C	CO ₂ -eq
Sole black gram (Shekar-1)	1.2	15.4	16.6	60.9
Sole black gram (Shekar-2)	0.9	14.7	15.6	57.3
Sole sesame (T4)	1.6	15.8	17.4	63.9
Sole sesame (T78)	1.5	15.0	16.5	60.6
Bael + black gram (Shekar-1)	28.2	21.4	49.6	182.0
Bael + black gram (Shekar-2)	25.1	20.3	45.4	166.6
Bael + sesame (T4)	26.6	20.6	47.2	173.2
Bael + sesame (T78)	27.3	21.0	48.3	177.3
Guava + black gram (Shekar-1)	19.1	19.4	38.5	141.3
Guava + black gram (Shekar-2)	17.3	18.7	36.0	132.1
Guava + sesame (T4)	16.9	18.3	35.2	129.2
Guava + sesame (T78)	15.7	18.0	33.7	123.7
SEm±	1.05	0.62	1.35	4.95
CD (P = 0.05)	3.08	1.82	3.96	14.5

CO₂-eq (t ha⁻¹) = Total system C × 3.67. Values are means of three replications.

3.4 Annual carbon sequestration rates

Annual carbon sequestration rates, calculated over an assumed 10-year stand age plus the seasonal intercrop contribution, ranged from 2.8 to 3.4 t C ha⁻¹ yr⁻¹ for bael systems and 1.9 to 2.3 t C ha⁻¹ yr⁻¹ for guava systems—well above the < 0.4 t C ha⁻¹ yr⁻¹ recorded for sole crops (Table V). When expressed as CO₂ equivalents, the highest-performing bael system sequestered approximately 110–125 t CO₂-eq ha⁻¹ over the 10-year period.

Figure VI. Advanced statistical relationships: (a) Pearson correlation matrix of key variables (b) Total biomass vs total system carbon (c) SOC concentration vs biomass carbon (d) Annual sequestration rates by land-use system.

Table V. Annual carbon sequestration rate and 10-year cumulative CO₂-equivalent storage

Land-use system	Rate (t C ha ⁻¹ yr ⁻¹)	10-yr CO ₂ -eq (t ha ⁻¹)
Sole black gram (Shekar-1)	0.3	11.0
Sole black gram (Shekar-2)	0.2	7.3
Sole sesame (T4)	0.4	14.7
Sole sesame (T78)	0.3	11.0
Bael + black gram (Shekar-1)	3.4	124.8
Bael + black gram (Shekar-2)	2.9	106.4
Bael + sesame (T4)	3.1	113.8
Bael + sesame (T78)	3.2	117.4
Guava + black gram (Shekar-1)	2.3	84.4
Guava + black gram (Shekar-2)	2.0	73.4

Guava + sesame (T4)	2.0	73.4
Guava + sesame (T78)	1.9	69.7
SEm±	0.12	4.4
CD (P = 0.05)	0.35	12.9

3.5 Relative contribution of system components

Partitioning of total system carbon among components (Table VI) revealed that, under bael-based systems, aboveground tree biomass contributed 42–44%, soil organic carbon 42–45%, roots 10–11% and intercrops 2–3%. Under guava systems the proportional contribution of soil carbon was relatively higher (48–53%) because of lower tree biomass. These proportions highlight the dual importance of maintaining both tree cover and soil organic matter for maximising carbon benefits.

Figure VII. Pairwise linear relationships among key biomass and carbon variables with Pearson correlation coefficients (r).

Table VI. Percentage contribution of system components to total system carbon stock

Land-use system	Tree AG (%)	Tree BG (%)	Intercrop (%)	Soil C (%)
Bael + black gram (Shekar-1)	43.1	10.9	2.8	43.2
Bael + black gram (Shekar-2)	42.5	10.6	2.2	44.7
Bael + sesame (T4)	42.6	10.8	3.0	43.6
Bael + sesame (T78)	43.1	10.8	2.7	43.5
Guava + black gram (Shekar-1)	36.9	9.4	3.4	50.4
Guava + black gram (Shekar-2)	36.1	9.2	2.8	51.9
Guava + sesame (T4)	35.2	8.8	4.0	52.0
Guava + sesame (T78)	34.4	8.6	3.6	53.4

4. Discussion

The present results demonstrate that bael- and guava-based agri-horticulture systems accumulate substantially more biomass and carbon than sole black gram or sesame crops under the edaphic and climatic conditions of the Vindhyan region. Total system carbon stocks of 45–50 t C ha⁻¹ under bael systems and 34–39 t C ha⁻¹ under guava systems fall within the range reported for fruit-tree agroforestry in semi-arid and sub-humid India (Newaj & Rai, 2005; NRCAF, 2007) and are consistent with global averages for smallholder agroforestry (Nair et al., 2009). The dominance of aboveground tree biomass and soil organic carbon as the principal carbon pools is typical of woody perennial systems and underscores the importance of maintaining tree cover for long-term carbon storage (Albert-Black, C et al.2025).

The magnitude of the difference roughly an order of magnitude between the best bael system and the best sole crop underscores the transformative potential of even moderately aged fruit-tree systems for landscape-level carbon accounting (Lemma, S.,et al.2025). Similar differentials have been reported from other semi-arid and sub-

humid agroforestry systems in India and elsewhere, confirming that the conversion of annual cropland to tree-based systems is one of the more effective land-use transitions available for carbon sequestration in the tropics (Mahato, U., & Kadaverugu, R. 2025).

Annual sequestration rates of 1.9–3.4 t C ha⁻¹ yr⁻¹ are comparable to the 1.5–3.5 Mg C ha⁻¹ yr⁻¹ range cited for tropical smallholder agroforestry (Montagnini & Nair, 2004) and exceed rates commonly reported for conventional annual cropping systems. Bael outperformed guava, reflecting its greater biomass accumulation under the prevailing conditions; this ranking may shift with stand age, density or management intensity (Ahirwar, S. K et al. 2024). The intercrops contributed only a small fraction of total carbon but provided an important early return to the farmer, an essential consideration for the adoption of agroforestry on resource-constrained holdings (Keerthika, A.,et al.2024). The relatively high intercrop

biomass under bael compared with guava may reflect differences in canopy architecture and light interception bael tends to have a more open canopy at the ages studied, allowing greater understorey productivity (Maurya, A. K. 2026).

These rates are also comparable to, or slightly higher than, those reported for some silvopastoral and alley-cropping systems under similar climatic conditions (Maitra, S et al.2025). The higher rates under bael relative to guava are consistent with the greater aboveground biomass accumulation observed for bael in this study and may reflect differences in growth rate, wood density and canopy architecture (Bhardwaj, A et al.2024). It is important to note that sequestration rates decline as stands approach equilibrium biomass, the rates reported here are therefore most applicable to the establishment and early productive phases of the orchard (Jirakajohnkool, S.et al. 2025).

The modest increase in soil organic carbon under tree-based systems is consistent with the slower turnover of woody litter and the protective effect of tree canopies against erosion and high soil temperatures (Singh, A., & Sahoo, U. K. 2026). Over longer time frames, continued litter inputs and root turnover can be expected to further enhance the soil carbon pool, reinforcing the climate-mitigation value of these systems (Ghimirey, V et al.2025). From a policy perspective, the quantified carbon stocks and sequestration rates provide a transparent basis for including bael- and guava-based agri-horticulture in regional carbon-accounting frameworks and PES schemes (Emmanouil, T et al.2026). Farmers who maintain these systems could potentially access carbon payments in addition to income from fruit and intercrops, thereby improving the economic attractiveness of climate-smart land use (Sahoo, U et al.2024).

Soil carbon dynamics under agroforestry are influenced by the quantity and quality of litter inputs, root turnover, soil temperature and moisture regimes, and the degree of soil disturbance (Fahad, S.,et al.2022). The higher SOC concentrations recorded under bael and guava (0.42–0.51% versus 0.34–0.37% under sole crops) translate into an additional 3–6 t C ha⁻¹ in the top 30 cm of soil (Ali, A et al.2024). Although this increment is smaller than the biomass carbon difference, soil carbon is more permanent on multi-decadal timescales and contributes to improved soil structure, water-holding capacity and nutrient cycling co-benefits that are highly valued by farmers even in the absence of carbon payments (Giuliani, L. M et al.2026).

Limitations of the study include the reliance on a default root:shoot ratio and a single-season assessment of intercrop biomass (Abera, W et al. 2025). Species-specific allometric equations and multi-year monitoring of both biomass and soil carbon would further strengthen future estimates (Giraldo-Salazar, J. M.,et al.2025). Despite these limitations, the clear separation of means among the major system types (bael > guava > sole crop) and the consistency of the ranking across biomass and carbon metrics give confidence that the principal conclusions are robust. Future work should prioritise the development of local allometric equations for bael and guava, multi-year monitoring of soil carbon, and socio-economic analysis of the trade-offs between carbon benefits and intercrop returns.

Species-specific allometric equations developed from destructive sampling of bael and guava in the Vindhyan region would improve the precision of future biomass estimates. Multi-year monitoring of both biomass increment and soil carbon would allow more robust calculation of net sequestration rates and would capture inter-annual variability driven by rainfall, temperature and management (Chandrakar, S et al.2026). Socio-economic analysis of the trade-offs between carbon benefits, intercrop yields and labour requirements would further strengthen the case for scaling these systems (Barman, A., et al.2024). Finally, integration of these biophysical results with remote-sensing approaches could enable landscape-scale mapping of carbon stocks under agri-horticulture across the broader Vindhyan region.

5. Conclusion

Bael- and guava-based agri-horticulture systems intercropped with black gram or sesame accumulated substantially higher biomass and sequestered significantly more carbon than sole-crop open-field systems in the Vindhyan region of India. Total biomass under bael-based systems ranged from 50.1 to 56.2 t ha⁻¹, far exceeding the 31.3–38.0 t ha⁻¹ recorded under guava systems and the 1.8–3.1 t ha⁻¹ under sole crops. Corresponding total system carbon stocks reached 45–50 t C ha⁻¹ under bael systems and 34–39 t C ha⁻¹ under guava systems. Annual carbon sequestration rates of 1.9–3.4 t C ha⁻¹ yr⁻¹ in the agri-horti systems were markedly higher than those of sole crops. The combination of bael + black gram (Shekar-1) emerged as the most carbon-efficient treatment under the conditions of this study. Soil organic carbon concentration was also modestly higher under tree-based systems (0.42–0.51%) than under open-field crops (0.34–0.37%). These results confirm that well-managed fruit-tree agri-horticulture systems can simultaneously support intercrop production and deliver meaningful climate-mitigation benefits on marginal lands. The quantified carbon stocks and sequestration rates provide a solid scientific basis for including such systems in regional greenhouse-gas inventories and payment-for-ecosystem-services schemes. Adoption of bael- and guava-based intercropping therefore offers a practical pathway for enhancing both livelihood security and carbon sequestration in the semi-arid Vindhyan region.

Declarations

Conflict of Interest

The authors declare no conflict of interest.

Funding

Declaration

The authors declare that no funds, grants or other support were received during the conduct of this research.

Author Contribution

Conceptualization: NMK, UPS, DRB Methodology: NMK, UPS, SD, PS, Formal Analysis: NMK, UPS, AKS, KH, Software: NMK, KH, Visualization: NMK, PS, DRB KH, Investigation: NMK, SD, AKS Writing – Original Draft: NMK, UPS, SD, Writing – Review & Editing: NMK, UPS, DRB, SD, KH, AKS, PS Supervision: UPS

Acknowledgement

The authors thank the Institute of Agricultural Sciences, Banaras Hindu University, and the Rajiv Gandhi South Campus, Barkachha, for providing experimental facilities. The guidance of the advisory committee is gratefully acknowledged.

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Figures



Figure 1

Geographic location of the experimental site (Rajiv Gandhi South Campus, Barkachha, Mirzapur) within India, highlighting the Vindhyan region of Uttar Pradesh.

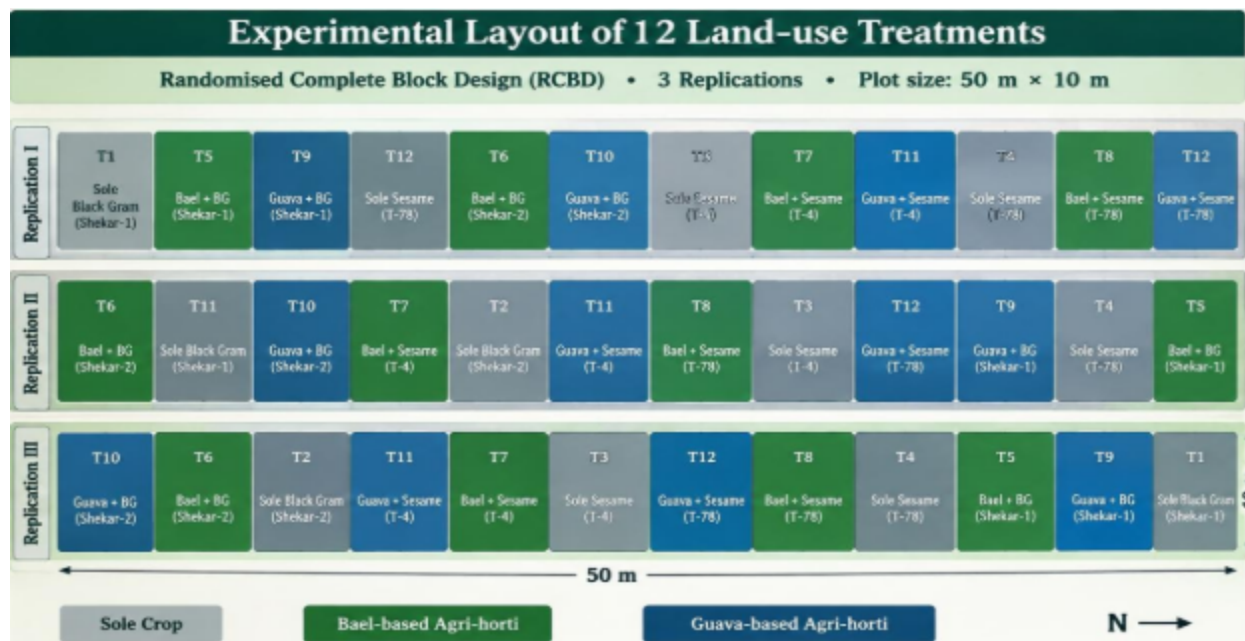


Figure 2

Experimental layout of the 12 land-use treatments in a randomised complete block design (RCBD) with three replications. Plot size = 50 m × 10 m. Grey = Sole crops, Green = Bael-based systems, Blue = Guava-based systems.

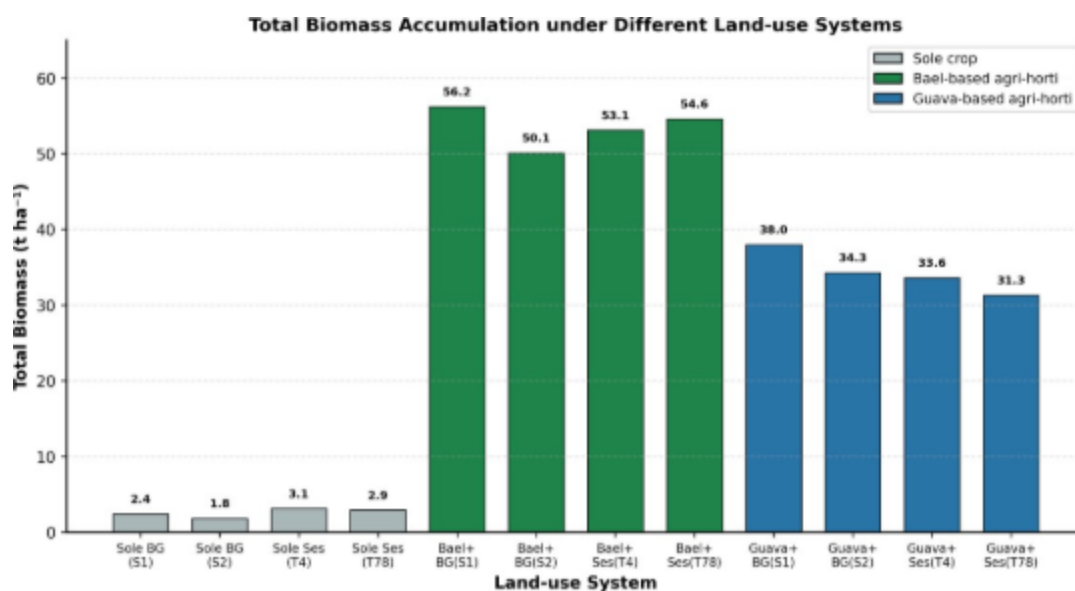


Figure 3

Total biomass accumulation (t ha⁻¹) under sole crops, bael-based and guava-based agri-horticulture systems.

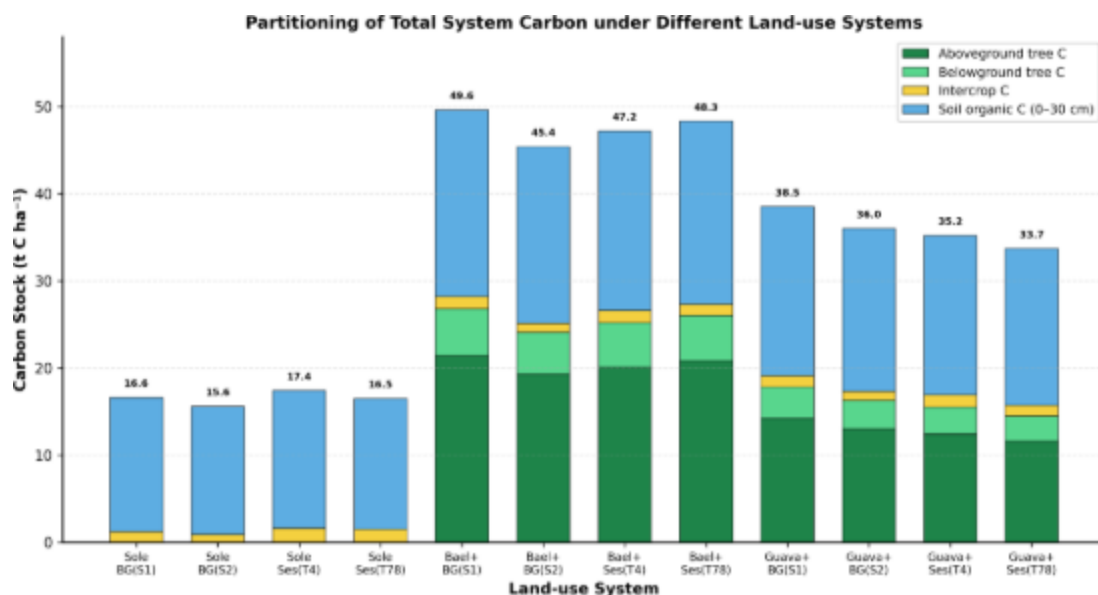


Figure 4

Partitioning of total system carbon (t C ha^{-1}) into aboveground tree, belowground tree, intercrop and soil organic carbon pools.

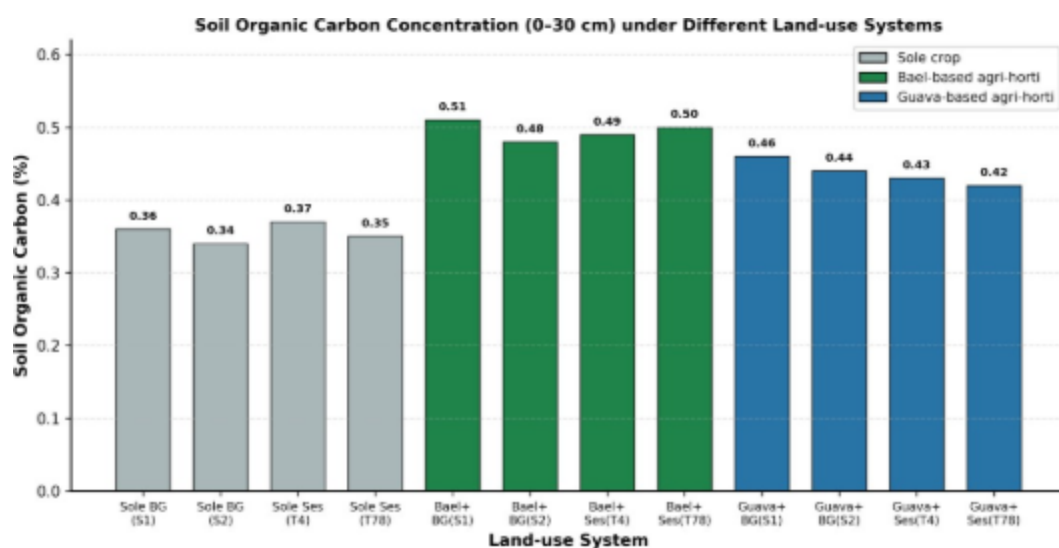


Figure 5

Soil organic carbon concentration (%) in the 0–30 cm soil layer under different land-use systems.

Advanced Statistical Relationships among Biomass, Carbon Stocks and Sequestration Metrics

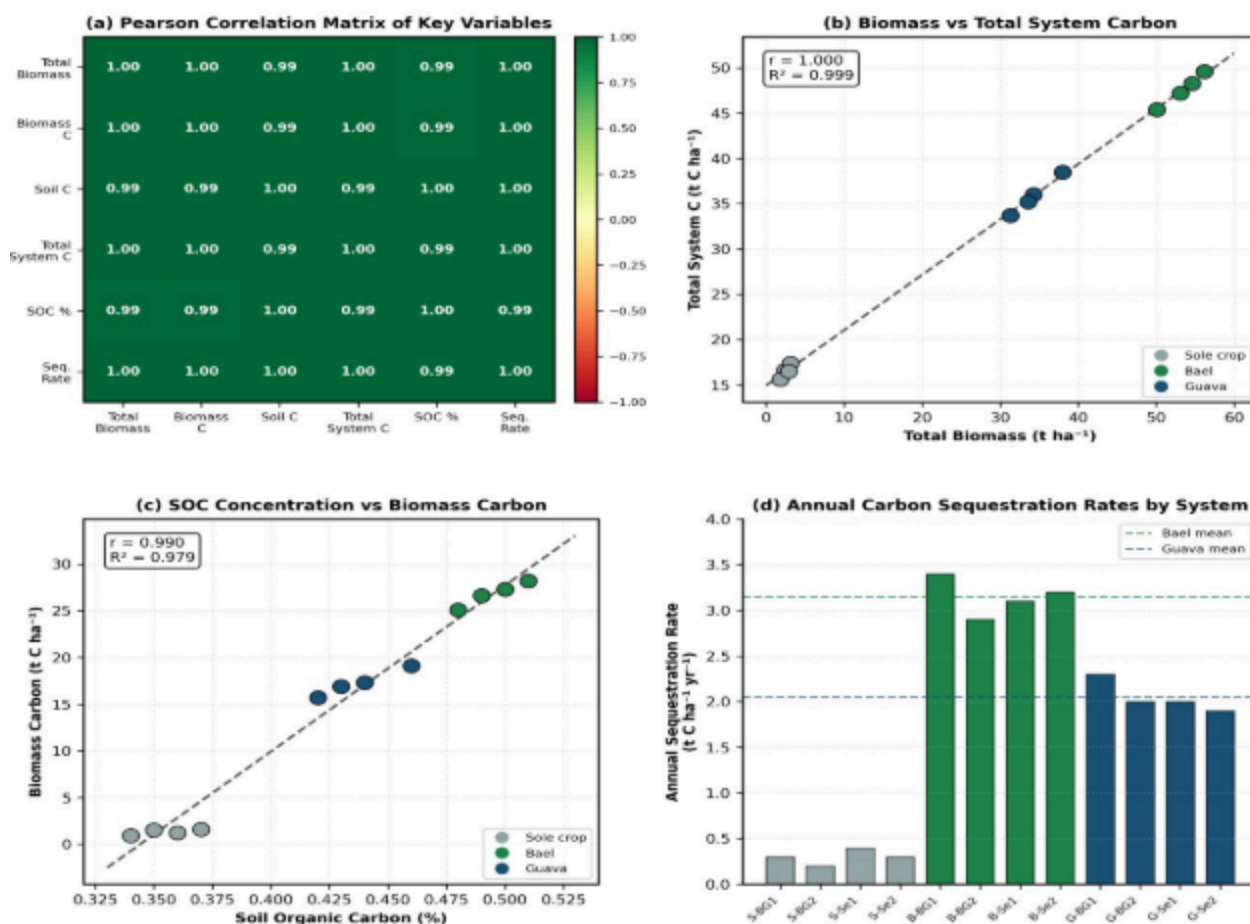


Figure 6

Advanced statistical relationships: (a) Pearson correlation matrix of key variables (b) Total biomass vs total system carbon (c) SOC concentration vs biomass carbon (d) Annual sequestration rates by land-use system.

Pairwise Linear Relationships among Key Carbon and Biomass Variables

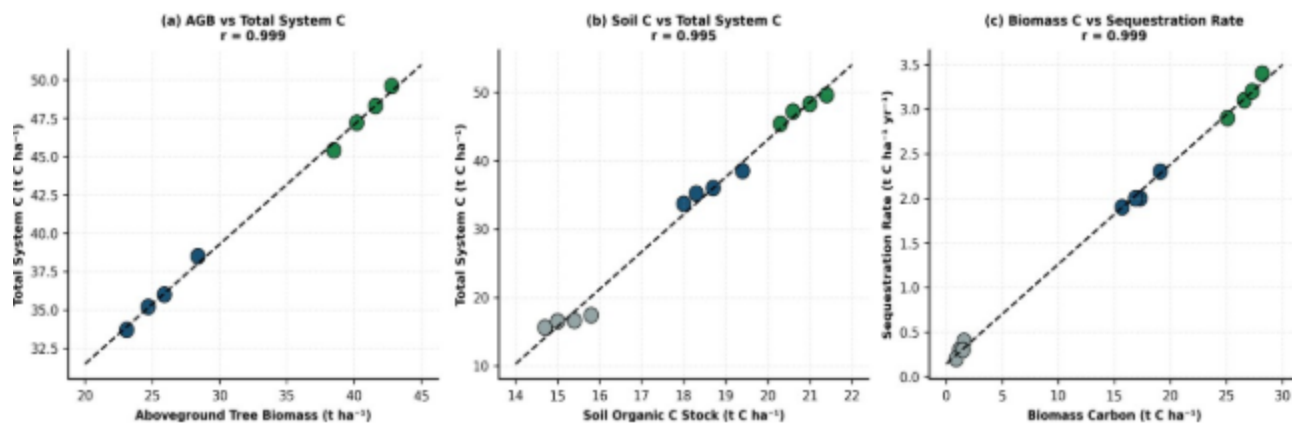


Figure 7

Pairwise linear relationships among key biomass and carbon variables with Pearson correlation coefficients (r).