



RESEARCH ARTICLE

Assessment of carbon sequestration potential in existing agroforestry systems of Ayodhya district, Uttar Pradesh

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Abstract

Agroforestry systems, which integrate trees into agricultural landscapes, offer significant potential for carbon sequestration. This study evaluates carbon sequestration under prevalent agroforestry systems in Sohawal and Rudauli blocks of Ayodhya district, Uttar Pradesh. Carbon storage was assessed in tree biomass, soil and deadwood using standardised protocols across various agroforestry practices. Results indicated that Agri-Horticulture (AH) (Mango + Mustard) had the highest 107 cm average tree girth at breast height (GBH) in Sohawal, while AH (Mango + Wheat) had the highest (103.4 cm) in Rudauli. Agri-Silviculture (AS) (Eucalyptus + Wheat) recorded the tallest average tree height (12.58 m) in Sohawal and AS (Eucalyptus + Mustard) was the tallest in Rudauli (16.10 m). The highest basal area was found in AH (Mango + Mustard) (0.091 m²) in Sohawal and AH (Mango + Wheat) (0.085 m²) in the Rudauli block. Volume peaked in AH (Mango + Wheat) (0.67 m³) in Sohawal and AS (Eucalyptus + Mustard) (0.68 m³) in Rudauli. Above-ground biomass (AGB) was highest in AS (Eucalyptus + Wheat) (17.48 Mg h⁻¹) in Sohawal and AS (Eucalyptus + Mustard) (31.87 Mg h⁻¹) in Rudauli. Below-ground biomass (BGB) followed similar trends, with 4.37 Mg h⁻¹ and 7.97 Mg h⁻¹ respectively. The highest total carbon storage was observed in AS (Eucalyptus + Wheat) (10.92 Mg h⁻¹) in Sohawal and AS (Eucalyptus + Mustard) (19.92 Mg h⁻¹) in Rudauli. Soil organic carbon (SOC) ranged from 0.21 % to 0.32 %, with the Teak + Wheat AS system recording the highest SOC (0.31–0.32 %) in both blocks. Overall, the findings underscore the carbon sequestration potential of agroforestry systems, supporting their role in sustainable land use, increasing species diversity and climate change mitigation as well as providing economic returns.

Keywords: agroforestry systems; Ayodhya; biomass, carbon stock; soil organic carbon

Introduction

Agroforestry, a sustainable land-use strategy based on the incorporation of trees into agricultural settings, has attracted increasing attention in terms of adaptation to climate change through carbon sequestration (1–5). Population growth has emerged as an important global problem, creating numerous global challenges such as land degradation, food insecurity, water scarcity, climate change, loss of biodiversity, ecosystem services, recurrent heat waves, prolonged droughts, socio-economic challenges and increased competition for natural resources (6–17). A United Nations report predicts that the world population of 7.6 billion is projected to grow to 8.6 billion by 2030, 9.8 billion by 2050 and 11.2 billion by 2100 (18). According to the Panel on Climate Change (IPCC), the surface temperature is increasing much faster than it was before the industrial revolution, about 1.1 °C and it is projected to keep rising to over 1.5 °C in future decades (19). Such alterations will have dramatic consequences across all regions, impacting ecosystems and human societies (20, 21). The severity of climate change consequences is directly linked to the cumulative carbon dioxide (CO₂) emissions from human activities such as fossil-fuel burning, deforestation and

land use and land cover changes (LULCC) (22–26). This highlights the urgent need for effective mitigation strategies that can reduce greenhouse gas emissions and mitigate climate change-related effects such as rising sea levels, more frequent and intense natural disasters, as well as food and health system disruptions (27). Consequently, the study quantified the potential carbon stock for the Sohawal and Rudauli blocks of Ayodhya district, Uttar Pradesh, which possess a diverse and prevalent agroforestry system. The evaluation focused on tree growth parameters, girth at breast height (GBH), tree height, crown length, crown diameter, above-ground biomass (AGB), below-ground biomass (BGB) and soil organic carbon (SOC).

Materials and Methods

Climatic and edaphic conditions

The climatic and edaphic state, in the centre of India, features long hot dry summers from late March to mid-June with an average temperature of 32 °C (90 °F). Winters range from early November to late January and the mean temperature is around 16 °C (61 °F), although winters are colder. Spring is short in February and early

March. Ayodhya's annual average temperature is about 28 °C (82 °F). The physiography of the Ayodhya district is mostly plain. The primary soil is loam, sandy loam and clay at the experiment site. Northern blocks feature clays in the soil, whereas sandy soils are more frequent in the southern blocks. Annual rainfall in Uttar Pradesh is between 84 and 170 cm on average. Ayodhya receives

around 1067 mm of rainfall annually, with approximately 86 rainy days. The monsoon season lasts until October.

Site selection

The prevalent agroforestry systems were identified through a field survey using stratified random sampling (Table 1). Two

Table 1. Structure and composition of prevalent agroforestry systems of Sohawal and Rudauli blocks in Ayodhya district, Uttar Pradesh

Major systems (Sohawal and Rudauli)		Systems types	Woody perennials	Spacing (m) plant to plant	No. of trees per ha.	Intercrops	Age of woody plants
Agri-Silviculture (AS)	12	Eucalyptus + Wheat (on boundary)	Eucalyptus	3 x 3	1111	Broadcasted	6
	5	Eucalyptus + Mustard (on boundary)	Eucalyptus	3 x 3	1111	Broadcasted	6
	2	Eucalyptus + Potato (on boundary)	Eucalyptus	3 x 3	1111	25 x 40 (cm)	6
	3	Teak + Wheat (on boundary)	Teak	4 x 4	625	Broadcasted	8
	4	Mango + Wheat	Mango	10 x 10	100	Broadcasted	10
Agri-Horticulture (AH)	3	Mango + Mustard	Mango	10 x 10	100	Broadcasted	10
	2	Indian gooseberry + Wheat	Indian gooseberry	6 x 6	278	Broadcasted	8
Silvi-Horticulture (SH)	2	Eucalyptus + Mango	Mango	10 x 10	100	10 x 10	6

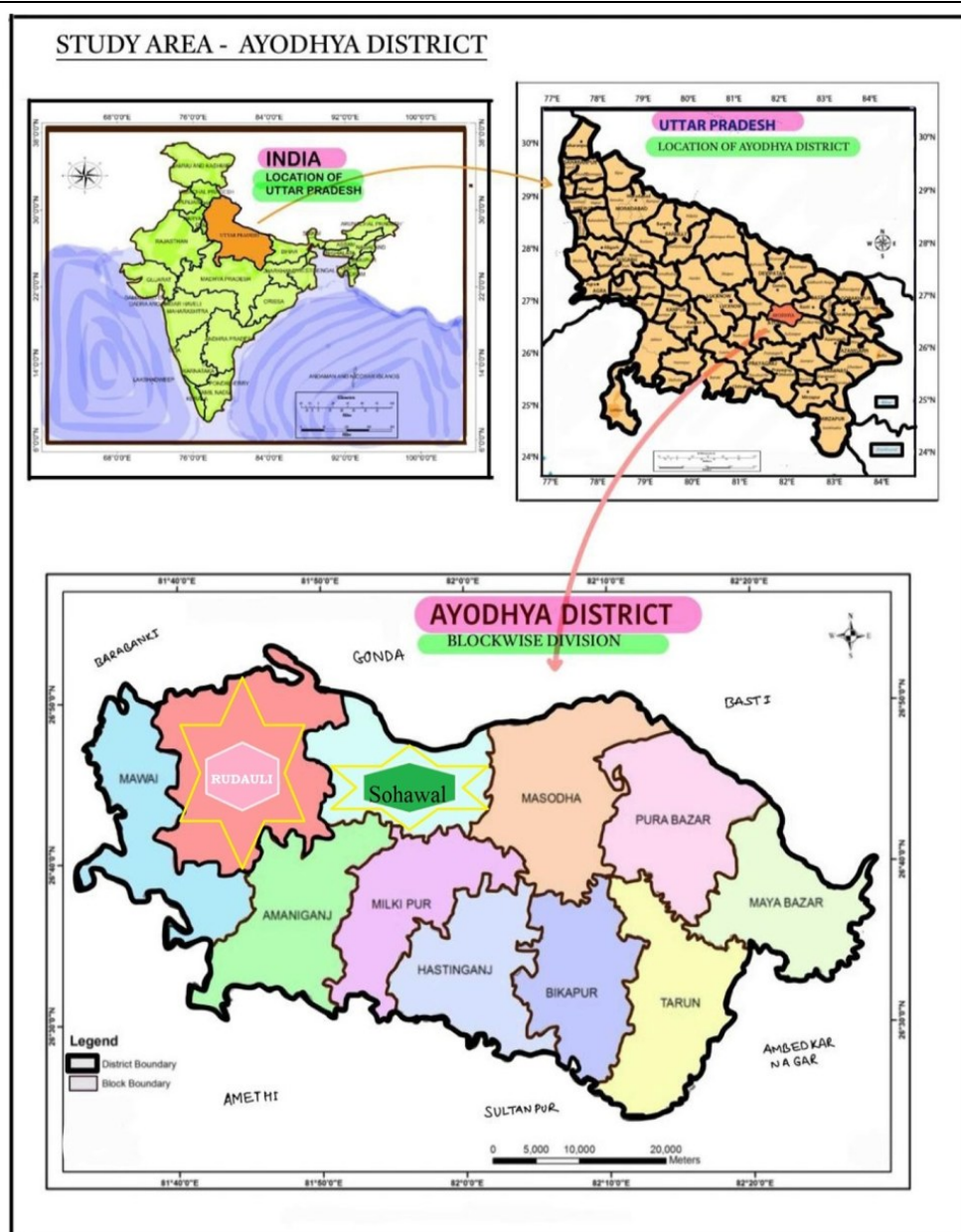


Fig. 1. Map showing the location of experimental blocks of Ayodhya district, Uttar Pradesh.

blocks - Sohawal and Rudauli (Fig. 1) were selected from the Ayodhya district, with five villages chosen from each block.

Tree growth attributes

Tree height (m)

It was measured from ground level to the tip of the apical bud using a Ravi Altimeter, recorded from ten trees per agroforestry system.

Bole height (m)

The distance from ground level to the first living crown-forming branch, was recorded from ten trees per system.

Tree GBH (cm)

Girth at breast height (1.37 m above ground) was measured using a measuring tape on ten trees randomly selected from each agroforestry system.

Standing volume of trees (m³)

Tree volume was calculated using the formula:

$$\text{Volume (m}^3\text{)} = (g^2/4\pi) \times l$$

where $\pi = 3.14$, g = GBH (m) and l = tree height (m).

Table 2. Wood specific gravity of different agroforestry tree species in Ayodhya district, Uttar Pradesh

Sr. No	Species	Specific gravity	References
1.	Eucalyptus	0.42	(34, 35)
2.	Teak	0.57	(34, 35)
3.	Mango	0.39	(34, 35)
4.	Indian gooseberry	0.60	(34, 35)

AGB

It was estimated by multiplying the tree volume by the specific gravity of that species (Table 2).

$$\text{AGB} = \text{Volume} \times \text{Specific Gravity}$$

BGB

It was estimated as one-fourth of the AGB, using the default factor 0.25 (28, 29)

$$\text{BGB} = \text{AGB} \times 0.25$$

Total system biomass

It was calculated as the sum of AGB and BGB (30)

$$\text{Total biomass} = \text{AGB} + \text{BGB}$$

Carbon stocks

It was estimated using the IPCC previously used method (31)

$$\text{Carbon stock} = \text{Tree biomass} \times 0.5$$

Soil sample collection

Composite soil samples were randomly collected from a depth of 0–15 cm. Samples were oven-dried at 70 °C for 24 hrs and sieved using a 2 mm mesh for further analysis.

Electrical conductivity (dSm⁻¹)

It was measured using a digital conductivity meter in a 1:2 soil-to-water suspension (32). For this, 20 g of soil was mixed with 50 mL of distilled water in a 100 mL beaker. The SOC was estimated using the rapid titration method (33).

Results and Discussion

Girth at breast height

The average tree GBH varied across the agroforestry systems in Sohawal and Rudauli blocks of Ayodhya district. In Sohawal, the Agri-Horticulture (AH) systems with Mango + Mustard and Mango + Wheat recorded the highest GBH (107 cm and 105 cm respectively) (Table 3). In Rudauli, the AH system with Mango + Wheat showed the highest GBH (103.4 cm). These results indicated significant differences in GBH among systems, with superior growth in AH systems likely due to complementary growth habits, efficient resource use and favourable microclimatic conditions. Similar observations earlier reported that tree girth and diameter measurements are important predictors of AGB in tropical dry evergreen forests of peninsular India (34). A related study in the Bundelkhand region also reported significant variation in tree diameters under different land-use systems, including species like *Acacia nilotica*, *Emblia officinalis*, *Tectona grandis* and *Psidium guajava* (35, 36). Notably, GBH is a key parameter for estimating tree basal area, showing a direct correlation with volume and biomass production.

Tree height (m)

Tree height followed the same pattern as tree GBH across the agroforestry systems in the Sohawal and Rudauli blocks. In Sohawal, the AS systems with Eucalyptus + Wheat and Teak + Wheat recorded the highest average heights (12.58 m and 11.85 m respectively), while in Rudauli, the AS system with Eucalyptus + Mustard showed the tallest trees (16.10 m) (Table 3).

These results indicate significant differences in tree height among the systems. Superior growth in AS systems is likely due to synergistic interactions, improved soil structure and complementary nutrient use (37). Tree height generally increases rapidly during early growth stages and stabilises over time (38). Growth is further influenced by genetic, physiological and morphological responses to environmental factors as well as site and climate conditions (39).

Tree volume (m³)

The AH system with Mango + Wheat (0.67 m³) was the highest tree volume in the Sohawal, followed closely by Mango + Mustard (0.66 m³). In Rudauli, the volume of AS with Eucalyptus + Mustard was higher (0.68 m³) than Teak + Wheat (0.58 m³). The Silvi-Horticulture (SH) system with the Eucalyptus + Mango had moderate tree volume in both blocks (0.29 m³). The mango-based systems outperformed in Sohawal; however, the eucalyptus-based systems took advantage in Rudauli.

Above-ground biomass (Mg ha⁻¹)

The AS system with the Eucalyptus + Wheat obtained the highest AGB (17.48 Mg ha⁻¹), compared to Eucalyptus + Potato (13.75 Mg ha⁻¹). The highest AGB for Rudauli was in Eucalyptus + Mustard (31.87 Mg ha⁻¹), followed by Teak + Wheat (20.57 Mg ha⁻¹). The SH system (Eucalyptus + Mango) had relatively low AGB values in Sohawal (1.21 Mg ha⁻¹) and Rudauli (1.12 Mg ha⁻¹) (Table 3). These are species-specific differences related to biomass productivity. For example, *Terminalia arjuna* reported its tree yield at the age of 10 to be as high as 470.99 kg per tree, reflecting high potential of trees and enhancing carbon sequestration and forest health.

Below-ground biomass (Mg ha⁻¹)

The experimental results showed substantial diversity in underground biomass between tree species and AF system. In Sohawal, the highest BGB value was obtained in the Eucalyptus + Wheat (AS) system (4.37 Mg ha⁻¹), then Eucalyptus + Potato (3.44 Mg ha⁻¹). Rudauli showed results for Eucalyptus + Mustard (AS) that came first (7.97 Mg ha⁻¹), followed by Teak + Wheat (5.14 Mg ha⁻¹). The SH system with Eucalyptus + Mango recorded relatively low BGB in both Sohawal (0.30 Mg ha⁻¹) and Rudauli (0.28 Mg ha⁻¹), indicating a lower root biomass contribution in mixed-species horticulture systems. These results highlight significant variations in tree volume across species and agroforestry systems, with species nature, density, stand structure, soil characteristics, environmental factors (humidity, air temperature) and other cultural practices affecting overall volume and biomass (40–44).

Total carbon stocks (Mg ha⁻¹)

The Eucalyptus + Wheat system in Sohawal (10.92 Mg ha⁻¹) and the Eucalyptus + Mustard system in Rudauli (19.92 Mg ha⁻¹) recorded the highest carbon stocks (Table 3). Poplar and eucalyptus demonstrate significant carbon sequestration potential of agroforestry systems in the Indo-Gangetic plains of India, with carbon stocks of 212.7 Mg C ha⁻¹ and 237.2 Mg C ha⁻¹ respectively (45). In contrast, the SH system with Eucalyptus + Mango exhibited the lowest carbon stocks in both blocks, 0.76 Mg ha⁻¹ in Sohawal and 0.70 Mg ha⁻¹ in Rudauli. The study measured total carbon pools in different cropping systems. The poplar intercropping system recorded the highest carbon pool at 96.5 t C ha⁻¹, followed by the spruce intercropping system at 75.3 t C ha⁻¹ and the barley sole cropping system at 68.5 t C ha⁻¹. The estimated barley carbon pool was 3.4 t C ha⁻¹ in the sole cropping system and 2.9 t C ha⁻¹ in the intercropping systems (46).

Soil organic carbon (%)

The soil organic carbon (SOC) in the Sohawal and Rudauli blocks varied between 0.21 % and 0.32 %, which demonstrates moderate to high carbon content, with the Teak + Wheat (AS) system accounted for the maximum SOC in both Sohawal (0.31 %) and Rudauli (0.32 %) but Mango + Mustard (AH) in Sohawal (0.21 %) and Eucalyptus + Mango (SH) in Rudauli (0.23 %) showed the minimum SOC. The SOC values tend to decrease due to relatively infrequent organic matter input, alongside an increase in the rate of erosion and oxidation due to tillage; these conditions are also dependent on microclimate changes from land use. SOC is one of the most important indicators of soil quality and enhances water infiltration, retention, bulk density and nutrient supply (47). Tree-based systems improve soil health through deeper root systems supporting organic matter accumulation and the soil aggregate attributes are a valid signal of carbon sequestration (48, 49). Similar dynamics have been confirmed in *Acacia nilotica*-based agroforestry, supporting high carbon sequestration capacity for the Teak + Wheat system in this region of soil (50).

Conclusion

The analysis of carbon stock for dominant agroforestry systems emphasised their significant contribution to climate change mitigation and sustainable land use. The findings suggested that these agroforestry systems were effective in carbon sequestration, with Agri-Silviculture systems proving to be particularly successful in

Table 3. Average girth of different tree species under agroforestry systems in Ayodhya district, Uttar Pradesh

Systems	Tree species	Block name									
		Sohawal		Rudauli		Sohawal		Rudauli		Sohawal	
		Tree GBH (cm)	Tree height (m)	Tree volume (m ³)	AGB (Mg h ⁻¹)	BGB (Mg h ⁻¹)	Total biomass (Mg h ⁻¹)	Carbon stocks (Mg/h ⁻¹)	SOC (%)		
(AS) Eucalyptus + Wheat	Eucalyptus	61.2	12.58	0.37	17.48	4.37	21.85	10.92	12.59	0.28	0.30
(AS) Eucalyptus + Mustard	Eucalyptus	51.7	9.73	0.21	9.65	2.41	12.07	6.03	19.92	0.23	0.26
(AH) Mango + Wheat	Mango	105	7.65	0.67	2.60	0.65	3.25	1.63	1.59	0.22	0.29
(AH) Mango + Mustard	Mango	107	7.51	0.68	2.66	0.66	3.32	1.66	0.79	0.21	0.25
(AS) Teak + Wheat	Teak	61.6	11.85	0.36	12.75	3.19	15.94	7.97	12.86	0.31	0.32
(AH) Indian gooseberry + Wheat	Indian gooseberry	60.2	10.34	0.30	4.94	1.24	6.18	3.09	1.39	0.27	0.28
(AS) Eucalyptus + Potato	Eucalyptus	58.0	11.00	0.29	13.75	3.44	17.18	8.59	9.69	0.26	0.27
(SH) Eucalyptus + Mango	Mango	77.0	6.10	0.29	1.21	0.30	1.51	0.76	0.70	0.24	0.23
SEm±		7.6	0.81	0.06	2.16	0.54	2.70	1.35	2.60	0.01	0.01
CD		18.1	1.92	0.15	5.11	1.28	6.38	3.19	6.14	0.03	0.02
CV		0.3	0.24	0.45	0.75	0.75	0.75	0.75	0.99	0.13	0.10

storing carbon in both living biomass and soil organic matter. The significant variation observed in tree growth traits and soil organic carbon and total carbon stock among different systems and blocks highlight the importance of selecting and managing appropriate agroforestry practices. Agri-Silviculture systems, particularly combining Eucalyptus with wheat or mustard, are promising methods for improving carbon storage. Overall, the study demonstrated that well-managed agroforestry systems enhanced carbon storage potential while supporting sustainable land management.

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Authors' contributions

SK conducted the study under the supervision of AT. RY and AT analysed the data. VK wrote and formatted the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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