Performance of Castor (Ricinus communis L.) Hybrids under Varying Nutrient Regimes in a Simarouba glauca DC.-Based Agrisilvicultural System in the Coastal Plains of Odisha

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Performance of Castor (*Ricinus communis* L.) Hybrids under Varying Nutrient Regimes in a *Simarouba glauca* DC.-Based Agrisilvicultural System in the Coastal Plains of Odisha

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ABSTRACT

A split-plot field experiment was conducted during the 2024–2025 kharif season at Bhubaneswar, Odisha, India, to assess the productivity, energy-use efficiency, and carbon sequestration potential of castor (Ricinus communis L.) hybrids grown within a two-year-old Simarouba glauca DC.-based agrisilvicultural system. Four castor hybrids (ICH-66, PCH-111, ICH-5, and DCH-177) were evaluated in the main plots, while four fertilizer regimes (F_1: 0:0:0, F_2: 50:25:25, F_3: 60:30:30, and F_4: 70:35:35 kg NPK ha^{-1}) were assigned to subplots. The results revealed significant effects of both hybrid selection and nutrient management on tree growth, intercrop productivity, biomass accumulation, carbon storage, energy dynamics, and economic returns. Among the tested hybrids, ICH-5 exhibited superior compatibility with Simarouba glauca, recording the highest tree height (283.25 cm) and collar girth (20.03 cm) at 30 months after planting. The same hybrid also produced the longest primary spikes (21.95 cm), maximum capsules per spike (57.08), and highest seed yield (1860.33 kg ha^{-1}). Greater biomass accumulation under the ICH-5-based system enhanced total organic carbon stock (11.70 t C ha^{-1}) and equivalent atmospheric CO_2 assimilation (42.94 t CO_2 ha^{-1}). Energy and economic analyses further confirmed the superiority of ICH-5, which achieved the highest energy-use efficiency (5.73), energy productivity (0.22 kg MJ^{-1}), gross return (Rs. 100720 ha^{-1}), and benefit–cost ratio (2.33). Progressive increases in fertilizer application significantly improved growth, yield, energy recovery, and profitability, with the F_4 treatment (70:35:35 kg NPK ha^{-1}) recording the highest economic efficiency (B:C ratio 2.37). Overall, the study demonstrated that integration of the castor hybrid ICH-5 with Simarouba glauca under balanced fertilization of 70:35:35 kg NPK ha^{-1} provides an effective strategy for enhancing productivity, energy efficiency, profitability, and carbon sequestration in the coastal plains region of Odisha.

Keywords: *Ricinus communis* ; *Simarouba glauca* ; Castor hybrids ; Energy-use efficiency; Sustainable agrisilvicultural systems; and Climate-resilient agriculture

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INTRODUCTION

The increasing pressure on agricultural systems due to climate change, declining soil fertility, resource degradation, and the need for sustainable intensification has accelerated interest in integrated land-use systems capable of simultaneously enhancing productivity and environmental resilience. Conventional monocropping systems often exhibit low resource-use efficiency and greater vulnerability to climatic variability, particularly under marginal production environments. In this context, agroforestry has emerged as an ecologically sustainable approach that integrates trees with agricultural crops to improve productivity, ecosystem stability, and long-term soil health (Das et al., 2025; Zhou et al., 2023). Agroforestry systems are widely recognized for their ability to enhance nutrient cycling, conserve soil moisture, improve biodiversity, and restore degraded lands while maintaining economic returns to farmers (Mesfin and Haileselassie, 2022; Bhatt et al., 2024).

Among various agroforestry practices, agrisilvicultural systems have gained considerable importance because of their dual capacity to provide ecological and economic benefits. The integration of perennial tree species with annual crops enables efficient utilization of available resources across temporal and spatial scales, thereby improving overall system productivity and resilience. Tree components act as long-term carbon sinks through biomass accumulation and belowground carbon storage, whereas intercrops provide immediate economic returns and contribute to system sustainability. Several studies have demonstrated that agroforestry systems exhibit greater biomass productivity, carbon sequestration potential, and ecological stability than conventional agricultural systems (Chauhan et al. 2019; and Zhou et al., 2023). Consequently, identification of suitable tree-crop combinations remains essential for optimizing biological efficiency and farm profitability under diverse agro-climatic conditions.

Simarouba glauca DC., commonly known as paradise tree or Lakshmi Taru, is a multipurpose evergreen species valued for its adaptability to degraded and marginal soils, drought tolerance, and high biomass production potential. The species has attracted increasing attention because of its industrial importance as a biodiesel-producing tree owing to its high oil content. In addition, *Simarouba glauca* has shown considerable potential for carbon sequestration and ecosystem restoration under tropical environments (Sarkar and Das, 2020. Its deep rooting system, perennial canopy structure, and ability to perform under low-input conditions make it a suitable candidate for sustainable agroforestry development in the Eastern and South-Eastern Coastal Plains Zone of Odisha.

Castor (*Ricinus communis* L.) is an important non-edible oilseed crop cultivated extensively in tropical and subtropical regions because of its adaptability to diverse agro-climatic conditions and high industrial demand. Castor oil possesses wide applications in pharmaceuticals, lubricants, cosmetics, polymers, and biofuel industries, resulting in growing commercial importance worldwide Jat & Desai (2021). Agronomically, castor is considered suitable for integration within agroforestry systems because of its drought tolerance, relatively short duration, and ability to perform under marginal environmental conditions. However, the productivity of castor under tree-based systems largely depends on genotype adaptability and nutrient availability, which influence biomass production, assimilate partitioning, and resource-use efficiency.

Although the individual performance of *Simarouba glauca* and castor has been investigated extensively, information regarding their combined performance within agrisilvicultural systems remains limited. In particular, limited research is available on the influence of castor hybrid selection and nutrient management on productivity, biomass accumulation, carbon sequestration, energy-use efficiency, and economic performance within *Simarouba*-based systems. Understanding these interactions is especially important in the coastal plains region of Odisha, where sustainable production systems capable of improving resource-use efficiency and climate resilience are increasingly required.

The present study was undertaken to evaluate the performance of different castor hybrids under varying fertilizer levels in a *Simarouba glauca*-based agrisilvicultural system. The study specifically aimed to assess growth and yield responses, biomass accumulation, carbon sequestration potential, energy-use efficiency, and economic returns in order to identify a suitable crop–nutrient combination for sustainable agroforestry production under the Eastern and South-Eastern Coastal Plains Zone of Odisha. However, limited information is available regarding the combined influence of castor hybrid selection and graded nutrient management on productivity, biomass accumulation, carbon sequestration, energy-use efficiency, and economic performance within *Simarouba glauca*-based agrisilvicultural systems under the coastal plains conditions of Odisha.

MATERIALS AND METHODS

Experimental site and soil characteristics

The field experiment was conducted during the kharif season of 2024–2025 at the experimental farm of the All India Coordinated Research Project (AICRP) on Agroforestry, Odisha University of Agriculture and Technology (OUAT), Bhubaneswar, Odisha, India. The experimental site is located at 20°17′ N latitude and 85°49′ E longitude at an altitude of 65.75 m above mean sea level. The region experiences a tropical humid and sub-humid climate characterized by warm summers and mild winters.

During the experimental period (July 2024–January 2025), the site received a total rainfall of 1164.1 mm. The mean maximum and minimum temperatures ranged from 33.6°C to 28.1°C and 26.3°C to 15.3°C, respectively, while relative humidity varied between 53 and 96%.

Prior to the initiation of the experiment, representative soil samples were collected from 0–15 cm and 15–30 cm depths and analyzed following standard laboratory procedures described by Tandon (2005). The experimental soil was classified as loamy sand, comprising 77.4% sand, 14.1% silt, and 8.8% clay. The soil was acidic in reaction (pH 4.45) with an electrical conductivity of 0.40 dS m^{-1}. Soil organic carbon was determined following the method of Walkley and Black (1934), while available nitrogen, phosphorus, and potassium were estimated using the methods described by Subbiah and Asija (1956), Olsen et al. (1954), and Tandon (2005), respectively. The soil contained 1.24% organic carbon, 202.24 kg available nitrogen ha^{-1}, 14.31 kg available phosphorus ha^{-1}, and 175.35 kg available potassium ha^{-1}.

Experimental design and treatment details

The experiment was conducted in an established two-year-old *Simarouba glauca* DC.-based agrisilvicultural system and laid out in a split-plot design with three replications. Four castor hybrids, namely ICH-66, PCH-111, ICH-5, and DCH-177, were assigned to the main plots, while four fertilizer levels constituted the subplot treatments: F_1 (0:0:0 kg NPK ha^{-1}), F_2 (50:25:25 kg NPK ha^{-1}), F_3 (60:30:30 kg NPK ha^{-1}), and F_4 (70:35:35 kg NPK ha^{-1}). The combination of four hybrids and four fertilizer levels resulted in sixteen treatment combinations replicated thrice.

The *Simarouba glauca* trees were maintained at a spacing of 5 m × 5 m, while castor was planted between tree rows at a spacing of 90 cm × 60 cm.

Crop establishment and agronomic management

The experimental field was prepared to a fine tilth through repeated ploughing followed by removal of weeds and crop residues. Farmyard manure (FYM) was uniformly incorporated at 5 t ha^{-1} before sowing. Nitrogen, phosphorus, and potassium were supplied through urea, diammonium phosphate (DAP), and muriate of potash (MOP), respectively, according to the treatment schedule.

Castor hybrids were sown during July 2024 between the established tree rows. All experimental plots received uniform intercultural operations, including hand weeding and other recommended agronomic practices. The crop was grown entirely under rainfed conditions.

Growth and yield observations

Five plants from each treatment plot were randomly selected and tagged for recording periodic growth observations. Plant height was measured from the ground surface to the terminal growing point and expressed in centimeters. The number of leaves and branches per plant were recorded manually at different growth stages, while collar diameter was measured using a digital caliper.

Leaf area was estimated using ImageJ software through analysis of scanned leaf samples. Leaf area index (LAI) was computed using the following relationship:

$$LAI = \frac{\text{Leaf area}}{\text{Ground area}}$$

At maturity, observations on spike length, number of capsules per spike, seed yield, stalk yield, harvest index, and oil content were recorded. Harvest index was calculated using the formula proposed by Donald and Hamblin (1976):

$$HI(\%) = \frac{\text{Economic yield}}{\text{Biological yield}} \times 100$$

Oil content of castor seed was estimated using Nuclear Magnetic Resonance (NMR) spectroscopy.

Biomass estimation and carbon sequestration assessment

Aboveground biomass (AGB) of *Simarouba glauca* was estimated using the allometric equation described by Chave et al. (2014):

$$AGB = 0.1245D^{2.4163}$$

where AGB represents aboveground biomass (kg tree^{-1}) and Ddenotes diameter at breast height (cm).

Belowground biomass (BGB) was estimated using the root-to-shoot conversion factor suggested by Cairns et al. (1997):

$$BGB = AGB \times 0.26$$

Total biomass (TB) was estimated as:

$$TB = AGB + BGB$$

Carbon stock in tree biomass was estimated assuming 47% carbon concentration in dry biomass following IPCC (2006):

$$C_{tree} = TB \times 0.47$$

Carbon contribution from crop biomass was estimated according to the method described by Lal (2004):

$$C_{crop} = B_{crop} \times 0.45$$

where B_{crop}represents crop biomass. Total carbon stock within the agrisilvicultural system was estimated as:

$$C_{total} = C_{tree} + C_{crop}$$

Equivalent atmospheric CO_2 assimilation was estimated using the molecular weight conversion factor described by IPCC (2006):

$$CO_2 = C_{total} \times 3.67$$

Energy analysis

Energy input and output of the agrisilvicultural system were estimated using standard energy equivalents described by Singh et al. (2019) and Devasenapathy et al. (2001). Energy input (EI) was calculated as:

$$EI = \sum(Q_i \times EE_i)$$

where $Q_i$represents the quantity of input used and EE_idenotes the corresponding energy equivalent.

Energy output (EO) was estimated as:

$$EO = \sum(Y_i \times EE_i)$$

where $Y_i$represents crop or biomass yield.

Energy-use efficiency (EUE), energy productivity (EP), and energy intensity (ENI) were calculated using the following relationships:

$$EUE = \frac{EO}{EI}$$
$$EP = \frac{Y}{EI}$$
$$ENI = \frac{EI}{Y}$$

where Ydenotes economic yield.

Economic analysis

Economic performance of the agrisilvicultural system was evaluated in terms of gross return, net return, and benefit-cost ratio following standard farm management procedures (Mead et al. 2003). Gross return (GR) was estimated using the prevailing market price of produce:

$$GR = Y \times MP$$

where Yrepresents crop yield and MPdenotes market price.

Net return (NR) was calculated as:

$$NR = GR - CC$$

where CCrepresents the cost of cultivation.

The benefit-cost ratio was computed as:

$$B:C = \frac{GR}{CC}$$

Statistical analysis

Experimental data were analyzed using analysis of variance (ANOVA) appropriate for a split-plot design following the procedure described by Gomez and Gomez (1984). Treatment effects were tested at the 5% level of significance, and mean comparisons were performed using the least significant difference (LSD) test at $P < 0.05$.

RESULTS

Growth and Structural Development of *Simarouba glauca*

The structural development of *Simarouba glauca* was significantly altered by both the choice of companion castor hybrid and the intensity of mineral fertilization (Table 1). Main-plot analysis revealed a distinct growth hierarchy among the evaluated crop combinations. Intercropping with the hybrid ICH-5 demonstrated superior vegetative compatibility, driving peak tree height and collar girth values at 30 MAP. Conversely, the lowest growth metrics were consistently restricted to the PCH-111 crop association, with similar limiting trends observed for both lateral crown spread and total branch proliferation.

Sub-plot nutrient management treatments showed a gradual, positive response to fertilizer intensification. Progressive NPK applications steadily enhanced cambial and vegetative activity over the unfertilized control. Accordingly, the highest fertilizer regime (F_4: 70:35:35 kg NPK ha^{-1}) optimized overall tree development, recording the maximum structural height, collar girth, crown width, and branch numbers across all fertilizer levels.

Treatments	Tree height (cm)	Collar girth (cm)	Crown spread (cm)
Main plot (Castor hybrids)			
V1 – ICH-66	263.03	19.87	214.83
V2 – PCH-111	229.60	19.17	180.06
V3 – ICH-5	283.25	20.03	232.06
V4 – DCH-177	261.50	19.81	200.27
S.Em (±)	0.41	0.17	—
LSD (P = 0.05)	1.43	0.60	—
Sub plot (NPK levels)			
F1 – 0:0:0	256.87	19.60	203.68
F2 – 50:25:25	257.50	19.60	204.24
F3 – 60:30:30	260.06	19.74	206.42
F4 – 70:35:35	261.75	19.85	209.71

Table 1. Growth performance and structural attributes of *Simarouba glauca* DC. at 30 MAP as influenced by different castor hybrids and fertility levels

Agronomic Yield Attributes and Performance of Castor Hybrids

Castor agronomic attributes and canopy development varied significantly by hybrid and fertilization level (Table 2). Main-plot analysis identified hybrid ICH-5 as the top vegetative and economic performer under the tree canopy, yielding the maximum plant height, branch number, and seed yield at harvest. Morphological variance was limited to DCH-177, which recorded significantly higher leaf area and leaf area index values during the late growth stages.

Reproductive yield components followed similar genotypic trends. Hybrid ICH-5 maximized primary sink parameters, producing the highest spike length and capsule counts per spike. Conversely, PCH-111 exhibited distinct dry matter partitioning trade-offs, prioritizing vegetative development to record peak stalk yield at the expense of seed production. Harvest index parameters peaked in hybrid ICH-66, while oil content was optimized under the DCH-177 association.

Treatments	**Spike length (cm)**	**Capsules spike^{-1}**	**Seed yield (kg ha^{-1})**	**Stalk yield (kg ha^{-1})**	**Harvest index (%)**
Main plot (Castor hybrids)					
V1 – ICH-66	20.45	55.76	1768.25	2636.67	40.14
V2 – PCH-111	18.51	52.93	1670.25	6678.00	20.01
V3 – ICH-5	21.95	57.08	1860.33	2975.25	38.47
V4 – DCH-177	19.28	53.81	1756.92	4224.17	29.37
S.Em (±)	0.05	0.06	4.88	17.44	0.05
LSD (P = 0.05)	0.18	0.22	16.90	60.34	0.17
Sub plot (NPK levels)					
F1 – 0:0:0	19.49	54.62	1714.17	4120.83	31.65
F2 – 50:25:25	19.88	54.82	1750.67	4125.08	31.88
F3 – 60:30:30	20.22	54.99	1783.42	4131.83	32.15
F4 – 70:35:35	20.61	55.14	1807.50	4136.33	32.31
S.Em (±)	0.05	0.02	2.49	1.84	0.04
LSD (P = 0.05)	0.14	0.07	7.27	5.38	0.13

Table 2. Yield attributes and yield of castor hybrids as influenced by different varieties and fertility levels in an agrisilvicultural system

Sub-plot fertilizer intensification from F_1 to F_4 step-incremented all primary growth and yield attributes, with the highest regime (F_4: 70:35:35 kg NPK ha^{-1}) maximizing seed output. The comparative variation in primary agronomic yield traits among the four castor hybrids is shown in Figure 1.

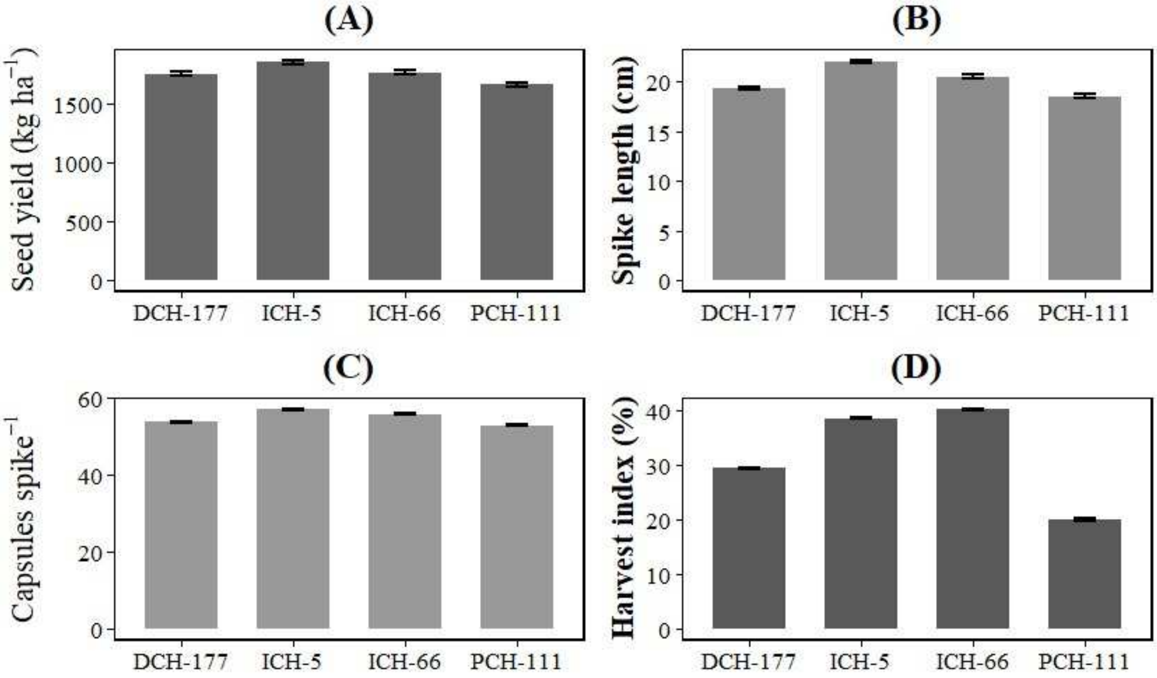

Figure 1. Influence of different castor (*Ricinus communis* L.) hybrids on major agronomic yield attributes and crop performance indices under the canopy of *Simarouba glauca* DC.: (A) seed yield (kg ha^{-1}), (B) spike length (cm), (C) number of capsules $spike^{-1}$, and (D) harvest index (%). Error bars represent the standard error of the mean (± SE) across experimental replications.

Biomass Partitioning and System-Level Carbon Sequestration

Substantial variation in aboveground biomass accumulation and associated carbon sequestration potential was observed among the evaluated treatments (Figure 2). Intercropping with the castor hybrid ICH-5 exhibited a pronounced positive influence on overall system productivity, resulting in the highest woody tree biomass (9210.02 kg ha^{-1}) and intercrop biomass production (15682.43 kg ha^{-1}). Consequently, the ICH-5-based agrisilvicultural system recorded the maximum total carbon stock (11.70 t C ha^{-1}; Figure 2B). The enhanced biomass accumulation further translated into greater atmospheric CO_2 mitigation potential, with the system achieving a maximum equivalent CO_2 assimilation of 42.94 t CO_2 ha^{-1}.

A similar trend was observed across subplot nutrient management treatments, where increasing fertilizer application significantly enhanced vegetative growth and biomass production. The highest fertilizer level (F_4: 70:35:35 kg NPK ha^{-1}) produced the greatest tree biomass accumulation (9020.43 kg ha^{-1}) and increased system carbon stock to 11.45 t C ha^{-1}. The partitioning of aboveground biomass and its contribution to system-level carbon sequestration are illustrated in Figure 2.

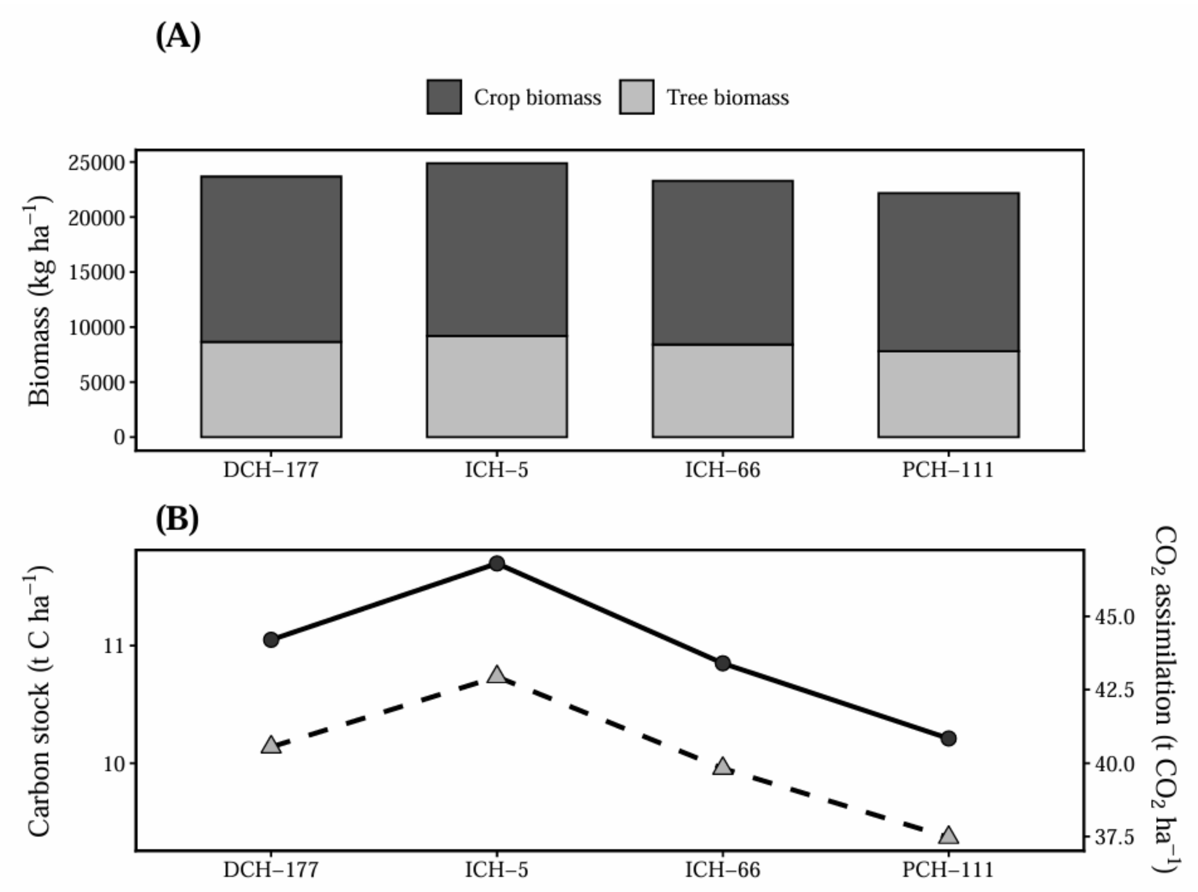

Figure 2. Biomass partitioning and system-level carbon sequestration dynamics in a *Simarouba glauca*–castor agrisilvicultural system across four castor hybrids: (A) stacked aboveground dry biomass production (kg ha^{-1}) partitioned into tree and crop biomass components; (B) total system carbon stock (t C ha^{-1}; primary axis, solid line) and equivalent atmospheric CO_2 assimilation (t CO_2 ha^{-1}; secondary axis, dashed line).

Energy Auditing and System Performance Indices

Energy budgeting provides an important framework for evaluating the efficiency and sustainability of integrated agrisilvicultural systems. The major energy indices were significantly influenced by both castor hybrids and nutrient management levels (Table 3). Among the evaluated hybrids, the ICH-5-based system recorded the highest gross energy output (46508.25 MJ ha^{-1}) and net energy output (38394.17 MJ ha-1). The superior biological productivity of this hybrid also resulted in the maximum output-input ratio (5.73) and energy productivity (0.22 kg MJ^{-1}). In contrast, the hybrid PCH-111 exhibited comparatively lower energy-use efficiency, recording the minimum output-input ratio (4.81) along with the highest energy intensity (4.81 MJ kg^{-1}), indicating relatively greater energy expenditure per unit economic yield produced.

Subplot nutrient treatments followed a similar trend, with progressive improvement in energy-use indices observed from F_1 to F_4. Although higher fertilizer application increased total input energy, the associated enhancement in biomass and seed production compensated for these additional inputs and improved overall energy recovery. The highest fertilizer level, F_4 (70:35:35 kg NPK ha^{-1}), recorded the maximum gross energy output (46968.93 MJ ha^{-1}), net energy output (38288.81 MJ ha^{-1}), and energy productivity (0.24 kg MJ^{-1}). The positive response of energy-use efficiency under higher fertility regimes suggests that increased nutrient availability substantially enhanced biological conversion efficiency within the *Simarouba glauca*–castor agrisilvicultural system.

Treatment	Gross energy output (MJ ha⁻¹)	Energy input (MJ ha⁻¹)	Net energy output (MJ ha⁻¹)	Energy productivity (kg MJ⁻¹)	Energy intensity (MJ kg⁻¹)	Output-input ratio
Main plot: Castor hybrids						
ICH-66	44216.34	8045.28	36171.06	0.20	5.01	5.49
PCH-111	42508.76	8835.42	33673.34	0.19	4.81	4.81
ICH-5	46508.25	8114.08	38394.17	0.22	4.52	5.73
DCH-177	45186.42	8588.66	36597.76	0.21	4.89	5.26
SEm (±)	248.36	52.14	216.48	0.01	0.09	0.08
LSD (P = 0.05)	745.22	156.38	649.12	0.02	0.27	0.24
Sub plot: Fertility levels						
F_1 (40:20:20 kg NPK ha⁻¹)	41885.62	7652.16	34233.46	0.18	5.48	4.52
F_2 (50:25:25 kg NPK ha⁻¹)	43892.74	7992.34	35900.40	0.20	5.02	4.88
F_3 (60:30:30 kg NPK ha⁻¹)	45672.48	8210.42	37462.06	0.21	4.76	5.12
F_4 (70:35:35 kg NPK ha⁻¹)	46968.93	8680.12	38288.81	0.24	4.38	5.41
SEm (±)	215.18	44.26	198.44	0.01	0.07	0.06
LSD (P = 0.05)	628.54	129.31	580.06	0.02	0.21	0.18

Table 3. Energy budget and performance indices of the *Simarouba glauca*–castor agrisilvicultural system as influenced by hybrids and fertility level

Crop Economic Viability and Financial Returns

The financial returns of the agrisilvicultural system were driven entirely by the castor intercrop due to the pre-bearing establishment phase of the *Simarouba glauca* canopy (Table 4). Main-plot analysis revealed a distinct economic hierarchy among the evaluated hybrids. The hybrid ICH-5 demonstrated clear financial superiority, generating the highest gross and net monetary returns. This enhanced productivity culminated in a peak benefit-cost ratio (B:C) of 2.33, whereas the lower seed yield of PCH-111 resulted in a baseline B:C ratio of 2.14.

Sub-plot nutrient management treatments showed a strong, positive economic response to fertilizer intensification. Although step-increasing NPK application from F_1 to F_4 elevated the total cost of cultivation, the economic value of the incremental seed yield significantly outpaced the chemical input expenses. Consequently, the F_4 treatment (70:35:35 kg NPK ha^{-1}) optimized net farm returns across the system, yielding a maximum sub-plot net return and a peak B:C ratio of 2.37.

Treatments	**Total cost of cultivation (Rs ha⁻¹)**	**Gross return (Rs ha⁻¹)**	**Net return (Rs ha⁻¹)**	**Benefit–cost ratio**
Main plot (Castor hybrids)				
V1 – ICH-66	43027	99305	56278	2.30
V2 – PCH-111	43012	92238	49226	2.14
V3 – ICH-5	43047	100720	57673	2.33
V4 – DCH-177	43022	95634	52612	2.22
Sub plot (NPK levels)				
F1 – 0:0:0	43009.17	96954.58	53923.33	2.08
F2 – 50:25:25	43054.75	96967.25	53941.67	2.23
F3 – 60:30:30	43093.33	96983.33	53954.33	2.31
F4 – 70:35:35	43138.75	96993.33	53970.42	2.37

Table 4. Economic analysis of the *Simarouba glauca*–castor agrisilvicultural system as influenced by hybrids and fertility levels

Inter-Trait Correlation Metrics

Pearson's correlation analysis revealed a strong degree of association among productivity, biomass, carbon, energy, and economic variables within the evaluated agrisilvicultural system (Figure 3). Seed yield maintained strong positive correlations with net return ($r = 0.97$), benefit–cost ratio ($r = 0.94$), and total biomass production ($r = 0.90$). Biomass accumulation also exhibited close association with carbon assimilation ($r = 0.88$) and energy productivity ($r = 0.88$), indicating that treatments with higher dry matter production contributed simultaneously to greater carbon capture and improved energy-use efficiency.

The positive clustering among yield, biomass, economic return, and carbon-related parameters suggests a coordinated system response under improved hybrid performance and nutrient management. In contrast, comparatively moderate associations observed among certain secondary traits indicate that not all variables contributed equally to overall system productivity. The absence of strong negative correlations further suggests that enhancement of agronomic productivity did not occur at the expense of ecological or economic performance within the studied *Simarouba glauca*–castor agrisilvicultural system.

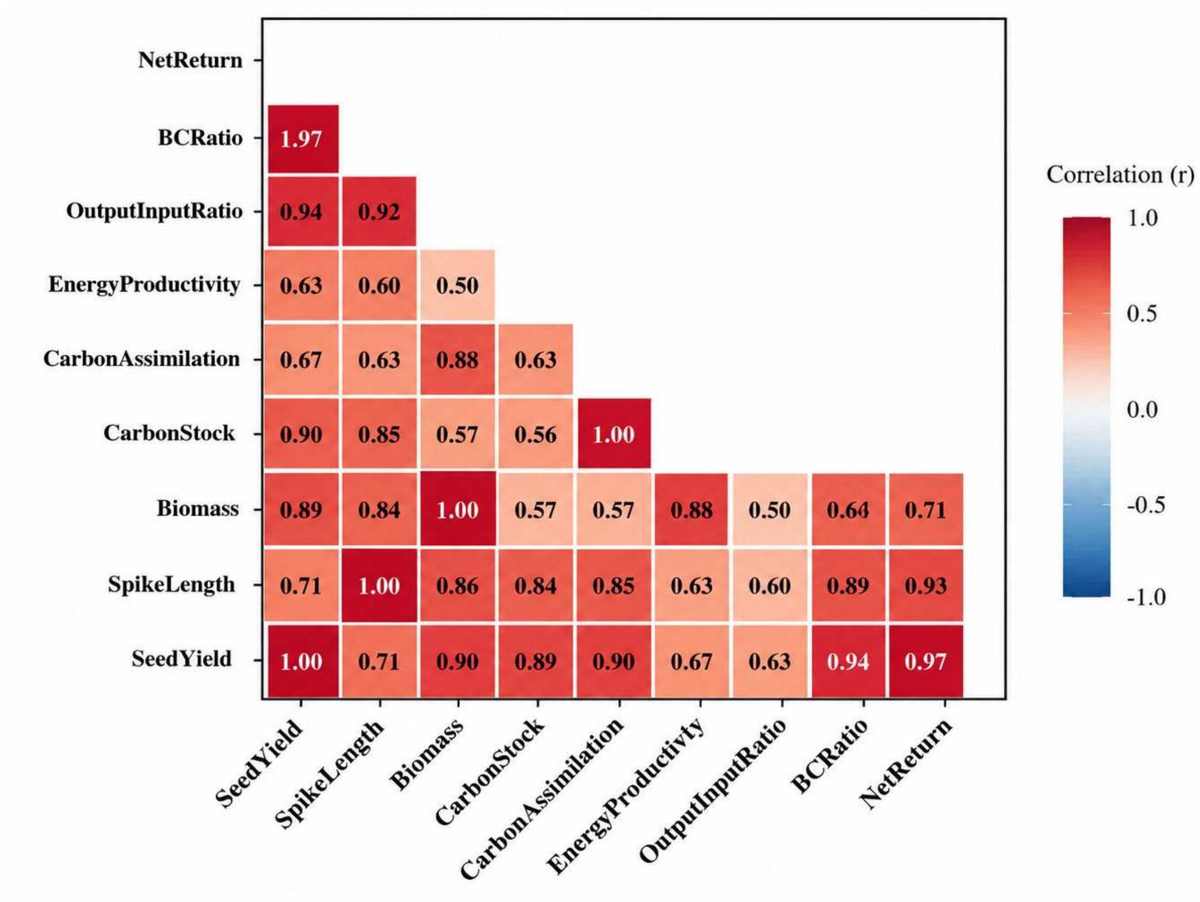

Figure 3. Pearson correlation matrix (r) illustrating the relationships among agronomic yield traits, biomass accumulation, carbon sequestration, energy-use efficiency, and economic variables within the *Simarouba glauca*–castor agrisilvicultural system. Color intensity represents the strength and direction of correlation coefficients, ranging from positive (red) to negative (blue) associations.

DISCUSSION

Interspecific Tree–Crop Compatibility and Vegetative Growth Dynamics

The growth performance of *Simarouba glauca* was significantly influenced by both castor hybrids and fertilizer levels. Trees associated with the ICH-5 hybrid recorded greater tree height, collar girth, and crown spread than those grown with the other hybrids, indicating comparatively better compatibility between the tree and intercrop components within the agrisilvicultural system. Variations among castor hybrids in canopy architecture, rooting behaviour, and nutrient demand may have altered interspecific competition for light, water, and nutrients, thereby influencing overall tree growth dynamics. These observations are consistent with earlier reports by Chauhan et al. (2019), Fahad et al. (2022), and Dhyani et al. (2016), who also observed enhanced biomass accumulation and improved tree vigour under balanced tree–crop interactions in agroforestry systems.

The progressive improvement in growth parameters with increasing fertilizer levels further highlights the importance of nutrient availability in regulating tree development. Nitrogen promotes chlorophyll synthesis and vegetative growth, phosphorus enhances root establishment and energy transfer, while potassium supports assimilate translocation and stem strengthening. The combined application of

NPK therefore likely improved nutrient uptake efficiency and photosynthetic activity, resulting in enhanced vegetative performance of the system. Improved growth responses under balanced fertilization may additionally be associated with enhanced soil physicochemical properties and nutrient cycling, as demonstrated by Mesfin and Haileselassie (2022), Zhou et al. (2023), and Newaj et al. (2020) in nutrient-enriched tropical agroforestry systems.

Genotypic Variance, Resource Allocation, and Sink Efficiency in Castor

Significant variation in castor growth and yield attributes among the evaluated hybrids indicates substantial genotypic differences in adaptability and resource-use efficiency under agroforestry conditions. Hybrid ICH-5 recorded greater spike length, higher capsule number per spike, and superior seed yield, reflecting improved reproductive efficiency and more effective assimilate partitioning toward economic yield under the tree canopy environment. In contrast, PCH-111 produced greater stalk biomass, suggesting relatively higher assimilate allocation toward vegetative structures rather than reproductive sinks. The observed variability in castor productivity and biomass partitioning among hybrids agrees with the genotype-dependent responses reported by Alexopoulou et al. (2015) and Jat & Desai (2021).

Higher fertilizer application significantly enhanced castor productivity, with F_4 (70:35:35 kg NPK ha^{-1}) recording the maximum seed yield and associated yield attributes. Increased nutrient availability likely promoted leaf expansion, chlorophyll formation, photosynthetic efficiency, and dry matter accumulation, thereby improving reproductive development. Enhanced canopy growth under nitrogen application may have increased radiation interception, while phosphorus and potassium likely facilitated energy transfer and assimilate translocation toward sink tissues. Comparable responses of castor to balanced fertilization were reported by Jat et al. (2022), who observed substantial improvements in seed yield and nutrient-use efficiency under higher NPK levels.

The increase in harvest index observed under the productive hybrids further suggests improved assimilate partitioning toward economic yield. Enhanced reproductive efficiency under optimized nutrient management has likewise been documented in integrated agroforestry systems by Newaj et al. (2020) and Das et al. (2025), who reported improved crop productivity and more efficient nutrient-use dynamics under tree–crop combinations.

Biomass Scaling and System-Level Ecological Carbon Sinks

The greater biomass accumulation observed under the ICH-5-based agrisilvicultural system directly contributed to higher carbon stock and CO_2 assimilation potential. Biomass production is a major determinant of carbon sequestration because carbon storage generally increases proportionally with dry matter accumulation. Consequently, the higher tree and crop biomass recorded under the ICH-5 and F_4 treatments resulted in enhanced system-level carbon accumulation and greater atmospheric CO_2 mitigation potential. These findings are consistent with the relationships between biomass productivity and carbon sequestration reported by Sarkar and Das (2020) and Chauhan et al. (2019) in *Simarouba glauca*-based agroforestry systems.

Agroforestry systems are increasingly recognized as efficient ecological carbon sinks because both tree and crop components contribute to aboveground and belowground carbon storage. Enhanced carbon accumulation under integrated systems may additionally improve soil organic matter status and nutrient recycling, thereby supporting long-term ecosystem sustainability. Evidence from diversified agroforestry systems by Zhou et al. (2023), Bhatt et al. (2024), and Mesfin and Haileselassie (2022) likewise demonstrated improvements in soil carbon accumulation and ecosystem resilience.

The positive association between fertilizer application and carbon accumulation observed in the present study may be attributed to improved vegetative growth and greater photosynthetic activity under balanced nutrient management. Increased nutrient availability likely enhanced biomass production and carbon assimilation efficiency across the system. Comparable observations were made by IPCC (2019), Das et al. (2025), and Nair et al. (2021), who highlighted the role of productive agroforestry systems in climate-change mitigation and ecological restoration.

Energy-Use Optimization and Biological Input-Output Efficiencies

Energy analysis revealed that the ICH-5-based system produced greater gross energy output, net energy output, and output–input ratio than the other treatments. The superior energy efficiency observed under this treatment was primarily associated with higher seed yield and biomass production relative to the total energy inputs. Greater biological productivity enhances energy recovery from the system, thereby improving overall energy-use efficiency. These findings support earlier observations by Jat & Desai (2021) and Dhyani et al. (2016), who demonstrated that integrated nutrient management and productive crop combinations improve energetic efficiency in agroforestry systems.

Although fertilizer application increased total input energy consumption, the corresponding improvement in crop productivity compensated for the additional energy expenditure and enhanced overall system efficiency. The higher output–input ratio recorded under F_4 suggests that balanced nutrient application increased productivity sufficiently to offset fertilizer-associated energy costs. This trend further reinforces the importance of balanced nutrient management in improving energy productivity and resource-use efficiency, as emphasized by Jat & Desai (2021) and Zhou et al. (2023).

The improved energy performance of the agroforestry system may additionally be attributed to enhanced nutrient cycling, biomass recycling, and ecological buffering associated with tree-based production systems. Such integrated systems are generally considered more energetically and ecologically efficient than conventional monocropping systems, as also reported by Das et al. (2025) and Mesfin and Haileselassie (2022).

Economic Returns and Farm Livelihood Sustainability

Economic analysis indicated that the ICH-5-based system generated greater gross return, net return, and benefit–cost ratio than the other hybrids due to its superior yield performance and higher productivity. The enhanced profitability observed under this hybrid highlights the importance of selecting compatible intercrop combinations within agroforestry systems to maximize economic returns and improve production efficiency. Comparable economic advantages of productive castor hybrids under integrated systems have also been documented by Alexopoulou et al. (2015), Rathore et al. (2022), and Jat et al. (2022).

Although higher fertilizer application increased cultivation costs, the corresponding improvement in productivity compensated for the additional expenditure and enhanced net returns under the F_4 treatment. Balanced nutrient management likely improved resource-use efficiency and economic recovery through increased seed yield and biomass production. Similar responses were reported by Jat & Desai (2021), who observed greater profitability in castor-based production systems under balanced fertilizer application and improved nutrient management.

The higher economic return associated with greater biomass accumulation and carbon assimilation further indicates that *Simarouba glauca*-based agrisilvicultural systems can simultaneously deliver ecological and economic benefits. Agroforestry systems capable of improving productivity while contributing to carbon sequestration are increasingly recognized as important strategies for climate-resilient and sustainable agriculture (IPCC, 2019; Zhou et al., 2023; Das et al., 2025). This broader role of integrated agroforestry systems in enhancing long-term farm sustainability, ecosystem services, and livelihood security has also been emphasized by Chauhan et al. (2019).

CONCLUSION

The present investigation highlighted the potential of *Simarouba glauca*–castor based agrisilvicultural systems as a sustainable land-use approach for the coastal plains region of Odisha. Integration of castor hybrids within the established tree system not only improved overall productivity but also enhanced carbon sequestration potential, energy-use efficiency, and economic returns. Among the evaluated hybrids, ICH-5 consistently performed better in terms of growth, yield attributes, biomass accumulation, and resource-use efficiency, indicating its better adaptability and compatibility under the agroforestry environment.

Balanced nutrient management also played a crucial role in improving system performance. Application of 70:35:35 kg NPK ha^{-1} significantly enhanced crop productivity, biomass production, and profitability, while simultaneously contributing to greater carbon accumulation and energy recovery. The combined effect of the ICH-5 hybrid and higher fertilizer level created a more productive and biologically efficient system capable of utilizing available resources effectively under rainfed conditions.

Beyond yield and economic benefits, the study emphasizes the ecological significance of integrated agroforestry systems in improving long-term sustainability. The higher biomass and carbon assimilation observed in the present study demonstrate the potential of tree-based production systems to contribute toward climate-change mitigation while supporting farmer livelihoods. Thus, integration of the castor hybrid ICH-5 with *Simarouba glauca* under balanced fertilization may be considered a promising strategy for achieving productive, profitable, and environmentally resilient agriculture in the Eastern and South-Eastern Coastal Plains Zone of Odisha.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. The datasets were generated as part of a controlled field experiment and are not publicly available due to ongoing analyses related to complementary manuscripts derived from the same experimental trial. The R codes used to analyze the data and to generate the figures can be found here

https://drive.google.com/file/d/1WNL1dvjlYqz7VzBOOm0mAdRykDwQi-DK/view?usp=drive_link

Declaration of generative AI use

Microsoft copilot is used to suggest how should we analyze the data set. Grammarly is used at times to improve grammar. In general, the use of AI is very negligible.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization: G.T ; M.R.N.
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Field investigation and data collection: G.T.
Data analysis and visualization J.N. ; G.T.
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Ethics Approval and Consent to Participate

Not applicable.

Consent for Publication

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REFERENCES

1. Alexopoulou, E., Papatheohari, Y., Zanetti, F., Tsiotas, K., Papamichael, I., Christou, M., Namatov, I., & Monti, A. (2015). Comparative studies on several castor (Ricinus communis L.) hybrids: Growth, yields, seed oil and biomass characterization. *Industrial Crops and Products*, *75*, 8–13.
2. Bhatt, K., Agrawal, S.B., Dwivedi, B.S., Gupta, D., Priya, S., Malviya, P., & Ray, M.A. (2024). Comparative Analysis of Soil Physico-Chemical Properties Across Different Land-Use Systems. *International Journal of Plant & Soil Science*.
3. Cairns, M. A., Brown, S., Helmer, E. H., & Lugo, A. E. (1997). Root biomass allocation profiles and root-to-shoot conversion factors in tropical, temperate, and boreal forest ecosystems. *Oecologia*, 111(1), 1–11.

4. Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B.C., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C., Henry, M., Martínez-Yrízar, A., Mugasha, W.A., Muller-Landau, H.C., Mencuccini, M., Nelson, B.W., Ngomanda, A., Nogueira, E.M., Ortiz-Malavassi, E., Pélissier, R., Ploton, P., Ryan, C.M., Saldarriaga, J.G. and Vieilledent, G. (2014), Improved allometric models to estimate the aboveground biomass of tropical trees. Glob Change Biol, 20: 3177-3190.
5. Chauhan, S. K., 1, Singh, S., Sharma, S., Sharma, R., Saralch, H. S., Regional Research Station, ICAR-CAZRI, Leh-194101, India, & Punjab Agricultural University, Ludhiana-141004, India. (2019). Tree biomass and carbon sequestration in four short rotation tree plantations. In *Range Mgmt. & Agroforestry* (Vol. 40, Issue 1, pp. 77–82).
6. Das, J., Sharma, U., Sankhyan, N., Sharma, S., Chauhan, V., Parida, S., & R, A. A. (2025). Integrating millets into agroforestry systems: A climate-smart strategy for sustainable land use and livelihood improvement with special emphasis on India. *Trees Forests and People*, *22*, 101087.
7. Devasenapathy, P., Senthilkumar, G., & Shanmugam, P. (2001). Energy management in crop production. *Indian Journal of Agronomy*, *54*(1), 80–90.
8. Dhyani, S. K., Ram, A., & Dev, I. (2016). Potential of agroforestry systems in carbon sequestration in India. *The Indian Journal of Agricultural Sciences*, *86*(9). https://doi.org/10.56093/ijas.v86i9.61348
9. Donald, C., & Hamblin, J. (1976). The biological yield and harvest index of cereals as agronomic and plant breeding criteria. In *Advances in agronomy* (pp. 361–405).
10. Fahad, S., Chavan, S. B., Chichaghare, A. R., Uthappa, A. R., Kumar, M., Kakade, V., Pradhan, A., Jinger, D., Rawale, G., Yadav, D. K., Kumar, V., Farooq, T. H., Ali, B., Sawant, A. V., Saud, S., Chen, S., & Poczai, P. (2022). Agroforestry Systems for Soil Health Improvement and Maintenance. *Sustainability*, *14*(22), 14877.
11. Gomez, K. A., & Gomez, A. A. (1984). *Statistical procedures for agricultural research with special reference to rice*. International Rice Research Institute (IRRI) / John Wiley & Sons.
12. IPCC. (2006). *Guidelines for national greenhouse gas inventories: Vol 4. Agriculture, forestry and other land use*. Institute for Global Environmental Strategies (IGES).
13. IPCC. (2019). *Special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Intergovernmental Panel on Climate Change (IPCC) Secretariat.
14. Jat, A. L., & Desai, A. G. (2021). Growth, Productivity Behavior and Economics of Castor (Ricinus communis L.) Hybrids as Influenced by Different Fertility Levels under North Gujarat Agroclimatic Region. *Annals of Arid Zone*, *59*(3–4).
15. Jat, A. L., Parmar, L. D., Patel, A., Gangwar, G. P., & Castor-Mustard Research Station, S.D. Agricultural University, Sardarkrushinagar. (2022). Performance of Castor (Ricinus

communis L.) Genotypes with Varying Fertility Levels under North Gujarat Agro-climatic Condition. In *Annals of Arid Zone* (Vol. 61, Issue 1, pp. 35–39).

16. Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security networks. *Science*, 304(5677), 1623–1627.
17. Mead, R., Curnow, R. N., & Hasted, A. M. (2003). Statistical methods in agriculture and experimental biology. In *Texts in Statistical Science* (Third Edition).
18. Mesfin, S., & Haileselassie, H. (2022). Evaluation of soil physico-chemical properties as affected by canopies of scattered agroforestry trees on croplands. *South African Journal of Plant and Soil*, *39*(2), 153–162.
19. Nair, P. K. R., Kumar, B. M., & Nair, V. D. (2021). An Introduction to Agroforestry. Four Decades of Scientific Developments, Springer Nature.
20. Newaj, R., Chaturvedi, O.P., Kumar, D., Chavan, S.B., Rajawat, B.S., Yadav, D.K. (2020). Carbon Sequestration Potential of Agroforestry Systems for Rehabilitating Degraded Lands of India. In: Dagar, J.C., Gupta, S.R., Teketay, D. (eds) Agroforestry for Degraded Landscapes. Springer, Singapore.
21. Olsen, S. R., Cole, C. V., Watanabe, F. S., & Dean, L. A. (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate* (USDA Circular No. 939). United States Department of Agriculture.
22. Sarkar, S., & Das, D. K. (2020). Tree biomass and carbon stock assessment in different agroforestry system trees. *International Journal of Chemical Studies*, *8*(4), 3858–3861.
23. Singh, P. &. S. G. &. S. G. (2019). Energy auditing and optimization approach for improving energy efficiency of rice cultivation in south-western Punjab, India. *ideas.repec.org*.
24. Subbiah, B. V., & Asija, G. L. (1956). A rapid procedure for the determination of available nitrogen in soils. *Current Science*, 25(8), 259–260.
25. Tandon,H. L. S., H. L. S. Tandoneditor, 20063011024, English, Book, India, 81-85116-55-5, New Delhi, Methods of analysis of soils, plants, waters, fertilisers & organic manures, (xi + 203 pp.), Fertiliser Development and Consultation Organisation, Methods of analysis of soils, plants, waters, fertilisers & organic manures., (2005)
26. Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science*, 37(1), 29–38.
27. Zhou, J., Sun, T., Shi, L., Kurganova, I., De Gerenyu, V. L., Kalinina, O., Giani, L., & Kuzyakov, Y. (2023). Organic carbon accumulation and microbial activities in arable soils after abandonment: A chronosequence study. *Geoderma*, *435*, 116496.