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Growth performance and carbon sequestration of poplar-based agroforestry systems in temperate plains

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Abstract
Agroforestry systems that pair fast-growing tree species with seasonal crops offer a dual benefit that neither monoculture farming nor pure forestry can match on its own: agricultural income and carbon storage operating on the same piece of land. This research quantified the growth performance, biomass production, and carbon sequestration potential of seven-year-old poplar (Populus deltoides) plantations intercropped with wheat, mustard, and turmeric at the Agriculture Campus of IGNTU, Amarkantak, Madhya Pradesh, during 2021-2023. Sole poplar accumulated the highest tree biomass at 124.6 t/ha and total carbon stock of 58.7 t/ha. However, the poplar-wheat combination achieved the highest total system carbon sequestration rate of 10.24 t CO_2/ha/yr and a land equivalent ratio (LER) of 1.32, indicating 32% greater land-use efficiency than growing trees and crops separately. Soil organic carbon in the top 30 cm was also highest under poplar-wheat (38.6 t/ha) compared to sole crops (22.4 t/ha). These results position poplar-based agroforestry as an effective land use strategy for combining food production with climate change mitigation in the temperate plains of central India.

Keywords: Poplar, carbon sequestration, agroforestry systems, temperate plains, tree-crop interaction, biomass production, land equivalent ratio, Populus deltoides, soil organic carbon, climate mitigation

Introduction

Picture a farmer's field where rows of tall poplar trees stand above a carpet of ripening wheat, the two crops sharing sunlight, water, and soil nutrients in a system that produces timber, grain, and stored carbon all at once. This scenario describes poplar-based agroforestry, which has expanded rapidly across northern and central India over the past two decades [1]. Poplar (Populus deltoides) is favored because of its fast growth, straight bole, deciduous habit that allows winter light to reach intercrops, and strong market demand for plywood and packaging material [2].

Carbon sequestration by agroforestry systems is increasingly recognized in national greenhouse gas inventories and climate policy frameworks [3]. Tree biomass acts as a long-term carbon sink, while litter inputs and root turnover build soil organic carbon stocks beyond what annual crops can achieve alone [4]. Estimates suggest that agroforestry systems in India sequester 0.5-3.5 t C/ha/yr depending on species, density, and management [5]. But site-specific data from the temperate highland-plain transition zone of Madhya Pradesh remain thin. This research aimed to compare biomass accumulation, carbon partitioning, and system-level carbon sequestration rates across four poplar-based land use configurations to identify the most productive and carbon-efficient option for this region.

Carbon Accounting Methodology

Total system carbon stock was calculated as the sum of above-ground biomass carbon (tree + crop), below-ground biomass carbon (estimated as 26% of above-ground tree biomass using the root-shoot ratio of Cairns *et al.* [6]), litter carbon, and soil organic carbon to 30 cm depth. Biomass was converted to carbon using a factor of 0.47 for woody tissues and 0.43 for herbaceous biomass. The annual CO_2 sequestration rate was derived by dividing the total carbon stock increment over the measurement period by the number of years and multiplying by 3.67 (the molecular weight ratio of CO_2 to C). These calculations follow IPCC Tier 2 guidelines for land use change reporting [7].

Material and Methods

Material

The research was conducted at the Agriculture Campus of Indira Gandhi National Tribal University, Amarkantak, Madhya Pradesh (22.67° N, 81.75° E, elevation 1,048 m). The site has a subtropical highland climate with mean annual rainfall of 1,650 mm and mean temperature of 22.4 °C. Soil is red lateritic (Typic Haplustalfs) with clay loam texture, pH 5.8, and organic carbon 0.94%. Four land use systems were evaluated: sole poplar plantation (8 m × 3 m spacing), poplar + wheat (cv. GW-322), poplar + mustard (cv. Pusa Bold), poplar + turmeric (cv. Suroma), and sole crop rotation (wheat-mustard) as the control. Trees were seven years old at the start of measurements. Each system occupied four replicate plots of 0.1 ha in a randomized block design [8].

Methods

Tree height and diameter at breast height (DBH) were measured on all trees in each plot using a Blume-Leiss hypsometer and diameter tape. Above-ground tree biomass was estimated using the allometric equation developed by Rizvi *et al.* [9] for P. deltoides: $\ln(AGB) = -2.134 + 2.412 \times \ln(DBH)$. Crop biomass was recorded at harvest from 1 m^2 quadrats (four per plot). Litter was collected monthly from 1 m × 1 m traps placed at four positions per plot. Soil samples were taken at 0-15 and 15-30 cm depths in March 2022 and 2023, and SOC was determined by wet oxidation [10]. Land equivalent ratio was calculated as (Yaf/Ys, tree) + (Yaf/Ys, crop), where Yaf is yield in agroforestry and Ys is yield in sole system. Data were analyzed by ANOVA at $P = 0.05$.

Results

Table 1: Biomass production and carbon stocks in poplar-based agroforestry systems

Agroforestry System	Tree Biomass (t/ha)	Crop Biomass (t/ha)	Total Biomass (t/ha)	C Stock (t/ha)
Sole Poplar (8×3 m)	124.6	0	124.6	58.7
Poplar + Wheat	98.3	8.4	106.7	46.2
Poplar + Mustard	86.7	4.8	91.5	40.8
Poplar + Turmeric	78.4	6.2	84.6	36.9
Sole Crops (Control)	0	9.8	9.8	4.2
SEm(±)	4.82	0.46	5.12	2.34
CD (P=0.05)	14.46	1.38	15.36	7.02

Sole poplar had the highest tree biomass (124.6 t/ha) and carbon stock (58.7 t/ha), but the poplar-wheat system produced the most balanced combination of tree and crop output (Table 1). The presence of intercrops reduced tree biomass by 21-37% compared to sole poplar due to below-ground resource competition.

Table 2: Soil organic carbon, litter carbon input, CO_2 sequestration rate, and land equivalent ratio

System	SOC 0-30 cm (t/ha)	Litter C (t/ha/yr)	CO_2 Seq. Rate (t/ha/yr)	LER
Sole Poplar	34.8	3.42	8.64	1.00
Poplar + Wheat	38.6	4.18	10.24	1.32
Poplar + Mustard	36.2	3.84	9.48	1.18
Poplar + Turmeric	37.4	3.96	9.86	1.26
Sole Crops	22.4	1.86	4.12	-
SEm(±)	1.86	0.24	0.68	-
CD (P=0.05)	5.58	0.72	2.04	-

SOC was highest under poplar-wheat at 38.6 t/ha, exceeding sole poplar by 3.8 t/ha, possibly due to additional root and stubble inputs from the wheat crop (Table 2). The CO_2 sequestration rate was highest for poplar-wheat at 10.24 t/ha/yr. All agroforestry systems had LER above 1.0, confirming land use advantage.

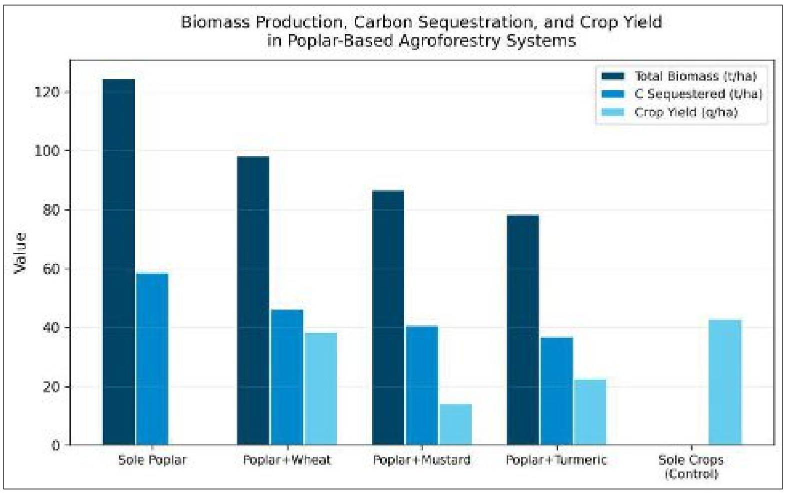

Fig 1: Biomass production, carbon sequestration, and crop yield in poplar-based agroforestry systems compared to sole crops

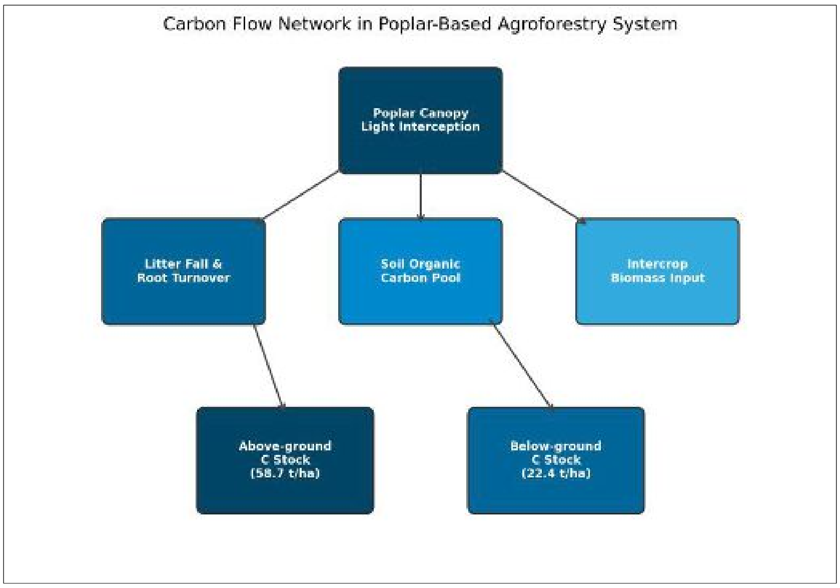

Fig 2: Carbon flow network in poplar-based agroforestry showing pathways from canopy to above-ground and below-ground carbon pools

Comprehensive Interpretation

The poplar-wheat system achieved the highest total CO_2 sequestration while maintaining 89.7% of sole crop wheat yield, making it the best overall system for balancing food production and carbon storage. Tree DBH growth was 12.4 cm/yr in sole plantations but declined to 9.8 cm/yr under intercropping, confirming moderate but manageable competition effects.

Discussion

The LER values of 1.18-1.32 recorded here confirm that poplar agroforestry uses land more efficiently than monocultures, consistent with findings from the Indo-Gangetic plains [1, 2]. The superiority of poplar-wheat over other intercrop combinations reflects the complementary phenology of deciduous poplar and rabi wheat: the tree is leafless during the critical wheat growth period from November to February, minimizing light competition [8]. The higher SOC under agroforestry compared to sole crops (38.6 vs. 22.4 t/ha) supports the argument that continuous litter input and deeper root activity under trees build soil carbon stocks beyond what annual tillage systems can sustain [4].

The CO_2 sequestration rate of 10.24 t/ha/yr for poplar-wheat is at the upper end of estimates for Indian agroforestry systems and has direct relevance for national carbon credit programmes [5]. If even a fraction of the 25 million hectares of cultivable wasteland in India were brought under such systems, the cumulative carbon benefit would be substantial. Farmers benefit simultaneously from timber income at harvest rotation (typically 7-8 years) and annual crop returns [3].

Conclusion

Poplar-based agroforestry systems sequester significantly more carbon than sole crops while maintaining viable crop yields. The poplar-wheat combination performed best overall with 10.24 t CO_2/ha/yr sequestration and an LER of 1.32. Farmers in the temperate plains of central India should consider poplar agroforestry as an economically and environmentally sound alternative to sole cropping, especially on marginal lands where crop returns alone are insufficient.

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