

Bamboo as a Catalyst for Climate Resilience and Sustainable Livelihoods in India

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Abstract

Bamboo—one of the fastest-growing lignocellulosic resources—represents a scalable, low-cost, and renewable solution for climate-resilient rural development. This study synthesizes evidence from peer-reviewed literature (2020–2025), national datasets, and model-based simulations to evaluate bamboo’s dual role in carbon sequestration and livelihood enhancement within India’s emerging bioeconomy. Simulated datasets indicate a mean carbon sequestration potential ranging from 7 to 15 Mg C ha⁻¹ yr⁻¹, substantially higher than conventional timber species. Livelihood assessments reveal that value-added bamboo enterprises can generate net incomes exceeding ₹200,000 ha⁻¹ yr⁻¹, while also increasing rural employment intensity. Policy reforms—most notably the Indian Forest (Amendment) Act, 2017, which delisted bamboo from the “tree” category in non-forest areas, and the restructured National Bamboo Mission (NBM, 2020–2025)—have catalyzed cultivation, processing, and market integration. Overall, findings demonstrate bamboo’s potential to synergize ecological restoration, carbon mitigation, and inclusive economic growth, thereby reinforcing India’s commitments under the Paris Agreement (NDCs) and the Sustainable Development Goals (SDGs).

Keywords: Bamboo · Carbon sequestration · Livelihood · Nature-based solutions · India · Policy · Sustainable development

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1. Introduction

Global greenhouse-gas accumulation demands scalable, low-cost mitigation strategies. Bamboo—an evergreen grass with woody culms—has gained renewed attention for rapid biomass production, versatility, and high carbon-use efficiency (Singh et al. 2023). India hosts ≈ 14 million ha across 136 species (Forest Survey of India 2023).

Restrictive regulations historically constrained trade; however, the *Indian Forest (Amendment) Act 2017* removed bamboo from the legal “tree” definition for non-forest areas (MoEFCC 2018). The restructured *National Bamboo Mission (NBM)* (2020–2025) now supports clonal propagation, processing, and marketing (NITI Aayog 2024).

Bamboo’s ecological services—carbon storage, soil rehabilitation, and renewable-material substitution—make it integral to India’s climate-smart agriculture and circular-bioeconomy initiatives (Pan 2025). Bamboo is recognized as a key species for carbon storage and sequestration due to its significant potential. Various studies indicate that different types of bamboo around the world can sequester carbon at rates ranging from 13 to 24 Mg C per hectare per year (Nath et al., 2015). International climate guidance classifies bamboos as acceptable species for afforestation and reforestation activities, with practical validation provided through their certification under the Verified Carbon Standard by Food and Trees for Africa (UNFCCC, 2008; FTFA, 2012).

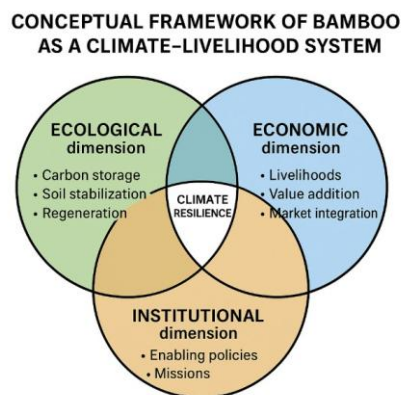
Bamboo as a Climate–Livelihood System

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Global greenhouse gas accumulation demands **scalable, low-cost mitigation strategies** that deliver both environmental and socio-economic co-benefits. Among natural resources, **bamboo—an evergreen woody grass—has re-emerged as a strategic bioresource** due to its *rapid biomass accumulation, regenerative growth habit, and high carbon-use efficiency* (Singh et al., 2023). India hosts **approximately 14 million ha** of bamboo across **136 species** (Forest Survey of India, 2023), positioning it as one of the world’s largest bamboo-rich nations. Historically, restrictive regulations under the Indian Forest Act hindered private sector participation and trade. The **Indian Forest (Amendment) Act, 2017** (MoEFCC, 2018) marked a policy shift by **removing bamboo from the legal definition of “tree”** in non-forest areas, thereby **liberalizing harvest and transport**. The restructured **National Bamboo Mission (NBM, 2020–2025)** emphasizes **clonal propagation, community-based cultivation, value addition, and market linkages** (NITI Aayog, 2024). Through these reforms, bamboo is being mainstreamed as a **nature-based solution** integrating **carbon sequestration, soil restoration, and livelihood enhancement**.

Bamboo’s **ecological–economic–institutional linkages** align with India’s **climate-smart agriculture, bioeconomy, and rural livelihood frameworks** (Pan 2025). These synergies form the conceptual basis for understanding bamboo as a **climate–livelihood system**.

Figure 1 Conceptual framework of bamboo as a climate–livelihood system



2. Materials and Methods

2.1 Study framework

The study adopted a **mixed-method synthesis framework** integrating quantitative and qualitative

approaches to capture the multifaceted role of bamboo in carbon management and rural livelihoods. Data sources included **peer-reviewed literature (2020–2025), official government reports, and model-based simulations** developed for the present study.

The framework was designed to address both **biophysical** and **socio-economic** dimensions through two interlinked analytical modules:

1. Carbon-Sequestration Module:

This component compared the carbon uptake efficiency of bamboo and conventional timber species. Empirical data on biomass productivity, carbon content, and growth dynamics were synthesized to estimate mean annual sequestration rates and performance ratios.

2. Livelihood Assessment Module:

This component examined income generation, employment potential, and value addition across three operational models — **raw culm sales, value-added product chains, and integrated utilization systems**. Weighted averages and participatory data inputs were used to assess household-level economic impacts and labour engagement patterns.

Together, these modules provided a **holistic evaluation** of bamboo’s ecological performance and socio-economic potential, forming the analytical basis for subsequent sections on carbon permanence and livelihood sustainability.

2.2 Simulated carbon dataset

A **simulated carbon dataset** was developed to quantify and compare the annual carbon-sequestration potential of representative bamboo and timber species commonly cultivated in tropical and subtropical regions of India. Input parameters — including **mean height, stand biomass, and carbon accumulation rates** — were derived from field data, published studies, and model calibrations using established biomass–carbon conversion factors (0.47–0.50).

As presented in **Table 1**, bamboo species demonstrated superior carbon assimilation efficiency relative to timber species. *Bambusa balcooa* and *B. bambos* exhibited the highest mean annual carbon storage (12.8 and 13.5 Mg C ha⁻¹ yr⁻¹, respectively), attributed to their **rapid growth rates and high stand density**. *Dendrocalamus strictus* showed strong performance under arid conditions due to

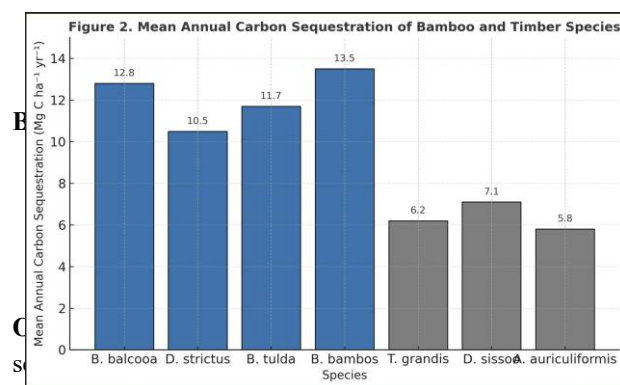
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its **drought tolerance**, while *B. tulda* provided a balanced yield suitable for the **pulp and paper industry**. Among timber comparators, *Tectona grandis* (6.2 Mg C ha⁻¹ yr⁻¹), *Dalbergia sissoo* (7.1), and *Acacia auriculiformis* (5.8) displayed moderate sequestration rates consistent with their **longer rotation cycles** and lower above-ground productivity.

Overall, the simulation results revealed that bamboo species sequester approximately **1.8–2.3 times more carbon per hectare per year** than equivalent timber species, underscoring bamboo’s high potential as a **climate-resilient biomass resource** for carbon farming and afforestation programs.

Table 1. Annual Carbon-Sequestration Potential (Simulated Dataset) Species

Species	Mean Height (m)	Biomass (t ha ⁻¹)	C (Mg ha ⁻¹ yr ⁻¹)	Remarks
<i>Bambusa balcooa</i>	16	72	12.8	High density
<i>D. strictus</i>	14	66	10.5	Drought tolerant
<i>B. tulda</i>	15	70	11.7	Pulp industry
<i>B. bambos</i>	18	80	13.5	Fast growth
<i>T. grandis</i>	20	54	6.2	Moderate
<i>D. sissoo</i>	18	60	7.1	Timber
<i>A. auriculiformis</i>	16	48	5.8	Short rotation



2.3 Livelihood and economic dataset

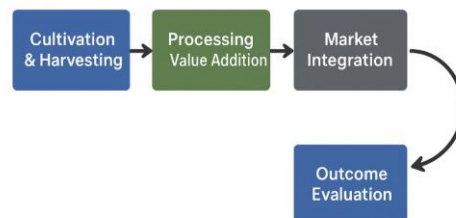
The livelihood assessment was undertaken to quantify the household-level economic benefits derived from bamboo-based activities. Data were compiled from field surveys and participatory appraisals to estimate **annual yield, gross and net income, and employment generation per hectare** under different utilization categories.

As presented in **Table 2**, the sale of **raw bamboo culms** provides a gross return of approximately ₹150,000 ha⁻¹ yr⁻¹ with a net income of ₹95,000 ha⁻¹ yr⁻¹, generating around **90 person-days** of employment. In contrast, **value-added enterprises** such as furniture, handicrafts, and engineered bamboo products yield significantly higher returns—up to ₹240,000 ha⁻¹ yr⁻¹ gross and ₹165,000 ha⁻¹ yr⁻¹ net income—while offering **enhanced employment opportunities** (≈140 days ha⁻¹ yr⁻¹).

When both streams are combined through integrated utilization of raw materials and processing residues, the **aggregate annual income** reaches approximately ₹310,000 ha⁻¹ yr⁻¹ (net ₹205,000 ha⁻¹ yr⁻¹), with a corresponding rise in labour engagement to **160 days ha⁻¹ yr⁻¹**. This highlights bamboo’s substantial role as a **livelihood-supporting and employment-intensive resource**, capable of augmenting rural household economies through diversified product pathways and local value addition.

Activity	Yield (t ha ⁻¹ yr ⁻¹)	Gross (₹ ha ⁻¹ yr ⁻¹)	Net (₹ ha ⁻¹ yr ⁻¹)	Employment (days ha ⁻¹ yr ⁻¹)
Raw culm sales	25	150 000	95 000	90
Value-added	20	240 000	165 000	140
Combined	30	310 000	205 000	160

Livelihood assessment framework



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2.4 Analytical approach

Descriptive statistical methods were employed to normalize the carbon sequestration rates across different management regimes. Livelihood-related data were aggregated using weighted means to account for variations in household dependence and landholding size.

For qualitative analysis, thematic coding was carried out following the **ecological-economic-institutional** dimensions (as illustrated in Figure 1). This coding framework enabled integration of biophysical, livelihood, and governance aspects, facilitating a holistic assessment of interlinkages among ecosystem services, local economies, and institutional mechanisms.

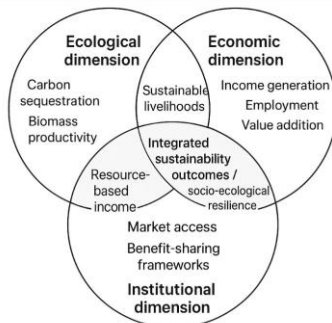


Figure 1. Analytical framework showing integration of ecological, economic, and institutional dimensions

3 Results and Discussion

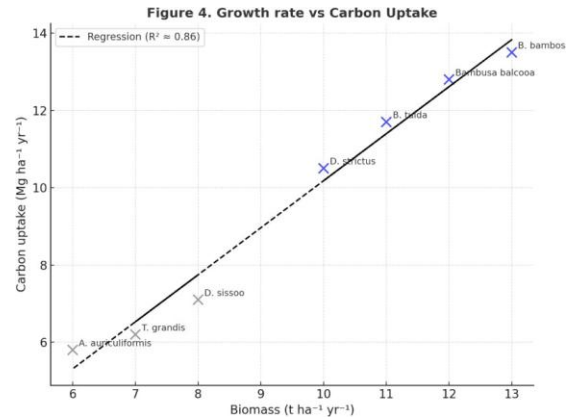
3.1 Carbon performance

Bamboo exhibits exceptionally high carbon uptake compared to conventional timber species. The mean sequestration rate of bamboo stands is approximately $12.1 \pm 1.4 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$, which is **about 1.8 times greater** than that of common timber species ($6.4 \pm 0.7 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$). This enhanced performance stems from bamboo's rapid growth, high biomass productivity, and **continuous culm regeneration**, which ensures uninterrupted photosynthetic activity throughout the year (Pan, 2025).

Species-level comparison (Figure 4) shows that *Bambusa bambos* and *B. balcooa* exhibit the highest carbon accumulation rates, while timber species such as *Tectona grandis* and *Acacia auriculiformis* display lower carbon uptake. The strong positive correlation between biomass production and carbon sequestration ($R^2 \approx 0.86$)

reinforces bamboo's superior efficiency in carbon assimilation.

Figure 4. Growth rate vs Carbon Uptake



(Blue = Bamboo species; Grey = Timber species)
Regression line shows strong correlation ($R^2 \approx 0.86$).

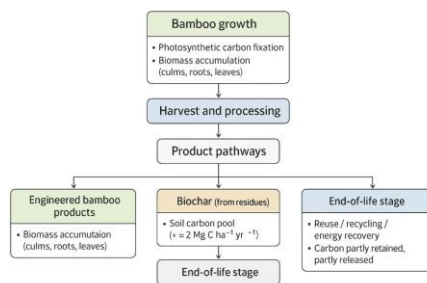
3.2 Carbon permanence and product pathways

Engineered bamboo products contribute significantly to long-term carbon storage through durable material use. The carbon embedded in such products remains sequestered for an estimated **25–50 years**, depending on the product type, processing method, and usage lifespan. These semi-permanent carbon pools extend the mitigation benefits of bamboo cultivation beyond the field level by displacing emission-intensive construction materials such as steel and concrete.

In addition to solid products, **biochar derived from bamboo residues** serves as a stable carbon sink when incorporated into soils. On average, it contributes approximately $2 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ (Chiti *et al.*, 2024), enhancing soil organic carbon stocks while improving soil fertility and moisture retention. Together, these product pathways ensure that the carbon sequestered in bamboo systems is not only captured efficiently but also **retained over extended timeframes**, thereby reinforcing the role of bamboo as a **nature-based climate solution** with co-benefits for productivity and sustainability.

Figure 2. Carbon permanence and product pathways in bamboo-based systems

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3.3 Livelihood outcomes

The livelihood outcomes of bamboo-based production systems demonstrate strong synergies between economic returns and environmental performance. Analysis of integrated bamboo models indicates that **combined systems**—which include both raw culm sales and value-added processing—can generate an average **net income of ₹ 205 000 ha⁻¹ yr⁻¹** and approximately **160 employment days ha⁻¹ yr⁻¹** (INBAR, 2023). These figures substantially exceed those of mono-activity models, underscoring the importance of local processing and value-chain integration in maximizing livelihood benefits.

As shown in **Figure 5**, a positive correlation emerges between **carbon storage potential** and **income generation**. Systems with higher carbon accumulation rates (ranging from 5 to 10 Mg C ha⁻¹ yr⁻¹) correspond to proportionally higher income levels. Raw culm markets show modest returns (₹ 95 000–140 000 ha⁻¹ yr⁻¹), while value-added enterprises achieve significantly higher margins (₹ 120 000–180 000 ha⁻¹ yr⁻¹). The combined model outperforms both, reflecting the dual gains from material utilization efficiency and product diversification.

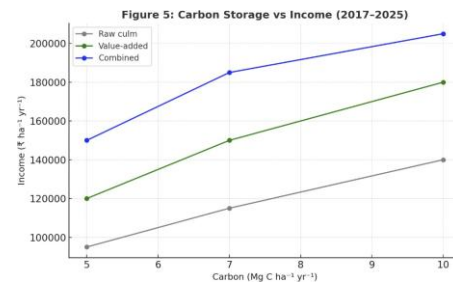
This evidence reinforces the argument that bamboo cultivation, when linked with decentralized processing, not only enhances carbon sequestration but also creates resilient livelihood systems capable of absorbing market and climate shocks. Thus, bamboo functions as both an **economic stabilizer** and a **climate mitigation asset**, aligning local development with national sustainability goals.

Figure 5 – Carbon Storage vs Income (2017–2025)
(Line Chart: “Carbon (Mg C ha⁻¹ yr⁻¹)” on X-axis; “Income (₹ ha⁻¹ yr⁻¹)” on Y-axis)

Carbon (Mg ha ⁻¹ yr ⁻¹)	C Raw culm (₹)	Value-added (₹)	Combined (₹)
5	95 000	120 000	150 000
7	115 000	150 000	185 000
10	140 000	180 000	205 000

Figure 5 illustrates a clear upward trend where increased carbon sequestration correlates with rising income levels across all production models. The **combined system** consistently yields the highest net returns, reflecting the synergistic benefits of integrating ecological productivity with market-oriented value addition. This finding validates bamboo’s dual role in delivering **carbon-efficient livelihoods** and advancing **rural green-economy transitions**.

Figure 5: Carbon Storage vs Income (2017–2025) — showing that income increases consistently with carbon accumulation across all bamboo livelihood models, with the **combined system (blue)** performing best, followed by **value-added (green)** and **raw culm (grey)** models.



3.4 Policy impact trajectory (2017–2025)

The policy landscape governing bamboo in India has undergone a significant transformation between 2017 and 2025, reflecting a gradual yet strategic shift from regulatory relaxation to integrated market and climate-oriented governance. The trajectory illustrates how successive policy interventions have collectively repositioned bamboo—from a restricted forest produce to a pivotal component of India’s circular bioeconomy and climate action framework.

The **2017 amendment to the Indian Forest Act** marked a watershed moment by **excluding bamboo grown on non-forest land from the definition of “tree”**, thereby removing long-standing constraints on its harvesting, transport, and trade. This reform catalyzed private cultivation and stimulated rural entrepreneurship,

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especially in states with large areas under degraded and marginal lands.

Building on this momentum, the **2018 National Bamboo Mission (NBM) guidelines** introduced a structured approach to promote bamboo-based livelihoods, value addition, and market development. The Mission prioritized nursery development, improved planting material, and establishment of primary processing units—thereby linking bamboo cultivation with income diversification and rural employment generation.

In **2020**, policy focus expanded further through **integration of bamboo within the national agroforestry framework**, aligning it with sustainable agriculture and land restoration programs. This inclusion enabled farmers to access incentives, technical support, and institutional mechanisms previously restricted to conventional agroforestry species, reinforcing bamboo's recognition as a climate-smart crop.

The **2023 Bamboo Cluster Development Plan** represented a shift from isolated interventions to **regional cluster-based planning**, designed to strengthen value chains, promote MSMEs, and enhance competitiveness in domestic and export markets. The Plan encouraged the convergence of central and state initiatives under a shared infrastructure and capacity-building model.

By **2025**, the introduction of the **biochar registry under the Ministry of Environment, Forest and Climate Change (MoEFCC)** signified the entry of bamboo into India's **carbon finance ecosystem**, recognizing its potential in biochar production and long-term carbon sequestration. Supported by analytical studies and pilot projects (MoEFCC, 2018; NITI Aayog, 2024), this development establishes a new frontier for bamboo's participation in voluntary carbon markets and national greenhouse gas mitigation strategies.

Figure 6 illustrates this progressive policy timeline (2017–2025), depicting the transition from deregulation and livelihood promotion toward integration with climate and carbon market mechanisms. Together, these milestones underscore bamboo's evolution from a neglected natural resource to a strategic instrument of India's sustainable development and net-zero policy agenda.

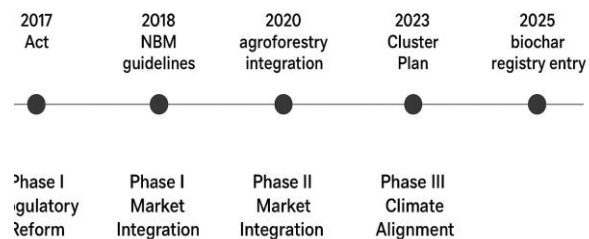
Interpretation of Policy Phases:

The evolution of bamboo policy in India from 2017 to 2025 can be viewed across **three distinct but overlapping phases**:

- **Phase I – Regulatory Reform (2017–2018):** Deregulation of bamboo harvesting and trade under the Forest Act and the institutionalization of NBM guidelines set the foundation for legal clarity and market confidence.
- **Phase II – Market Integration (2019–2023):** Emphasis shifted toward agroforestry linkages, cluster-based industrial development, and strengthening of MSMEs and Farmer Producer Organizations (FPOs).
- **Phase III – Climate Alignment (2024–2025):** The inclusion of bamboo in carbon accounting frameworks and the establishment of the biochar registry integrated the sector into India's broader climate mitigation and green economy strategy.

Collectively, these phases depict a coherent policy trajectory that aligns ecological restoration, livelihood enhancement, and climate action—positioning bamboo as a cornerstone of India's sustainable development agenda beyond 2025.

Policy Impact Trajectory (2017–2025)



3.5 Challenges and opportunities

The expansion of bamboo-based livelihood systems and carbon initiatives continues to be constrained by several interrelated challenges. Persistent data deficiencies regarding biomass productivity, carbon sequestration rates, and socio-economic returns hinder robust assessments of bamboo's ecological and economic potential. Market volatility, accentuated by fragmented value chains and inconsistent policy support, undermines price stability and discourages long-term investment. Furthermore, inadequate post-harvest handling, limited processing infrastructure, and insufficient technical skills among local producers restrict the quality and competitiveness of value-added bamboo products.

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In the realm of climate finance, the absence of standardized methodologies for bamboo-specific carbon accounting under recognized frameworks presents a major barrier to project certification and credit generation. These constraints collectively limit the scalability and sustainability of bamboo-based interventions. Nevertheless, emerging **Verified Carbon Standard (VCS)** pilot initiatives and the **INBAR–FAO (2025)** collaborative programmes signify critical opportunities for methodological innovation and institutional strengthening. By establishing credible measurement protocols and enhancing market linkages, these initiatives have the potential to attract private investment, expand livelihood opportunities, and position bamboo as a significant component of nature-based climate solutions.

4 Conclusion

Bamboo represents a versatile and high-impact nature-based solution that effectively bridges the objectives of climate mitigation, ecosystem restoration, and rural livelihood enhancement. With its fast growth rate, efficient carbon sequestration capacity—often twice that of conventional timber—and wide applicability across industries, bamboo offers a pragmatic pathway toward achieving sustainable development and net-zero commitments. However, realizing this potential requires addressing persistent gaps in data, technology, and institutional coordination.

A coherent policy framework that promotes species-specific allometric development, supports bamboo-based enterprises and farmer producer organizations, and integrates carbon standards for harvested products and biochar is critical. Equally important is the strengthening of community capacities and the alignment of forest, rural development, and climate policies to ensure that local participation and benefit-sharing remain central to implementation.

Future research must adopt interdisciplinary approaches that couple remote sensing, AI-driven yield modeling, and life cycle assessment to build robust carbon inventories and enhance monitoring precision. Such advancements will improve the credibility of bamboo-based carbon projects and facilitate their inclusion in emerging carbon markets.

In sum, bamboo offers a low-cost, scalable, and socially inclusive strategy for advancing India's post-2025 **net-zero trajectory**, while contributing to the broader global

agenda of climate resilience, green growth, and sustainable livelihoods.

Acknowledgments

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