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A review on the potential of traditional agroforestry systems in enhancing carbon stocks in West Bilaspur, Chhattisgarh

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Abstract

Agroforestry is increasingly recognized as a sustainable land-use practice with the potential to enhance carbon sequestration, biodiversity, and rural livelihoods, particularly in ecologically sensitive and socioeconomically diverse regions such as West Bilaspur, Chhattisgarh. This review examines the role of traditional agroforestry systems in enhancing carbon stocks, focusing on their ecological, agronomic, and socioeconomic functions. The study synthesizes current scientific literature, field-based case studies, and policy frameworks relevant to the region. It highlights prevalent tree-crop combinations, traditional land-use knowledge, and the importance of these systems in local rural economies. Carbon capture mechanisms in both biomass and soil are discussed, alongside methodologies for estimating carbon stocks through field sampling, modeling, and remote sensing approaches. Factors influencing sequestration potential-species diversity, tree density, management practices, and land tenure-are critically analyzed. Environmental co-benefits like improved soil fertility, water conservation, and climate resilience are also evaluated. Despite these advantages, the sector faces challenges such as policy fragmentation, low farmer awareness, and limited access to carbon markets. The review outlines opportunities through national agroforestry missions, carbon finance mechanisms, and integrated climate-smart agriculture strategies. This work underscores the need for targeted interventions to mainstream agroforestry in climate policy, scale up traditional systems, and promote sustainable rural development in Chhattisgarh.

Keywords: Agroforestry systems, carbon sequestration, traditional land use, climate change mitigation, biomass and soil carbon, and rural livelihoods

1. Introduction

1.1 Background and Significance of Agroforestry & Rationale for Studying Carbon Stocks in West Bilaspur

Agroforestry-defined as the integration of trees with crops and/or livestock-is increasingly recognized as a low-cost, climate-mitigation strategy capable of enhancing aboveground and soil carbon stocks while maintaining agricultural productivity (Dhyani, Ram, & Dev, 2023; Nair, 2004) [6, 17]. In India, agroforestry covers over 25 million hectares. It demonstrates considerable potential for carbon sequestration and livelihood improvement, though its applicability varies with system type, species, and local agro-ecological conditions. Moreover, in Chhattisgarh-home to a diversity of traditional agroforestry models such as Acacia nilotica-based systems-these practices not only conserve biodiversity and enhance soil fertility but also contribute to rising carbon stocks in non-forest lands (Lal *et al.* 2024) [13].

Given the region's prominence in traditional tree-crop systems and the mounting need to quantify their climate-mitigation benefits, examining carbon sequestration potential in West Bilaspur is timely. Local systems-often comprised of multipurpose species like *Acacia nilotica*, *Azadirachta indica*, and Terminalia-are widely adopted but under-assessed regarding carbon stocks (Lal *et al.* 2024) [13]. Evaluating these can inform regional climate action strategies, optimize model selection, and support agroforestry policy implementation in alignment with India's net-zero goals.

1.2 Rationale for Studying Carbon Stocks in West Bilaspur

West Bilaspur in Chhattisgarh has a semi-humid climate, red and lateritic soils, and widespread dependence on traditional agriculture interspersed with trees. These agroforestry systems-developed over generations-hold immense, yet underexplored, potential for carbon sequestration in both biomass and soil. Despite their environmental and economic relevance, systematic quantification of carbon stocks in these systems remains limited in this region.

Agroforestry has been identified as a key land-use system for enhancing carbon sinks, especially in degraded and rainfed zones of India (Dhyani *et al.* 2023) [6]. Given that West Bilaspur includes significant areas under traditional agroforestry systems such as *Acacia nilotica*, *Azadirachta* *indica*, and *Terminalia arjuna*-based practices, a localized study on carbon dynamics is crucial for developing region-specific carbon mitigation strategies. Furthermore, this research can support climate-resilient land use planning, carbon credit incentives, and sustainable development initiatives under India's National Agroforestry Policy and its Intended Nationally Determined Contributions (INDCs).

2. Methodology

This review used a systematic and thematic approach to identify, analyze, and synthesize peer-reviewed literature, case studies, and policy documents related to traditional agroforestry systems and their carbon sequestration potential, specifically in West Bilaspur, Chhattisgarh. Relevant publications were sourced from databases such as Google Scholar, ScienceDirect, SpringerLink, and national repositories like ICAR and MoEFCC. Studies published between 2000 and 2025 were prioritized, focusing on agroforestry typologies, biomass and soil carbon dynamics, estimation methodologies, and regional agroecological case studies. Key search terms included "traditional agroforestry India," "carbon sequestration in agroforestry," "Chhattisgarh agroforestry systems," and "biomass carbon estimation." Studies were selected based on relevance, methodological clarity, and geographical proximity to the study area.

A thematic framework categorized the literature under core areas such as land-use practices, carbon stock assessment methods, socioeconomic impacts, and environmental co-benefits. Case studies from agro-climatic zones similar to West Bilaspur were comparatively analyzed to assess common tree-crop combinations, aboveground and belowground carbon contributions, and the influence of species diversity and land management practices. Additionally, national and state-level policy documents-such as the National Agroforestry Policy (2014), Green India Mission, and Sub-Mission on Agroforestry-were reviewed to explore institutional support, incentive mechanisms, and integration of agroforestry into climate action and carbon credit programs. This combined narrative and data-driven synthesis enabled a comprehensive evaluation of agroforestry's carbon potential and policy implications.

3. Overview of Agroforestry Systems

3.1 Definition and Types of Agroforestry

Agroforestry is a land-use system that intentionally integrates trees with crops and/or livestock on the same parcel of land and manages them to maximize beneficial ecological and economic interactions-such as improved nutrient cycling, soil fertility, and diversified production (Mudge & Gabriel, 2014; FAO, 2023) [15, 7]. Structurally and functionally, these systems may be categorized into crop-tree (agrosilvicultural), animal-tree (silvopastoral), crop-animal-tree systems (e.g., home gardens), as well as agroforestry types including alley cropping, hedgerows, boundary planting, taungya, and homegardens (Young, 1987; FAO, 2023) [, 7].

3.2 Traditional Agroforestry Practices in India

India has a long history of traditional agroforestry, with systems ranging from shifting cultivation to complex, multilayered homegardens and silvopastoral practices (Kumar *et al.* 2023) [12]. Major systems include agri-silviculture (trees + crops), agri-horticulture (fruit trees + crops), agri-silvi-horticulture, and silvopastoral systems. Nitrogen-fixing multipurpose species such as *Acacia nilotica*, *Dalbergia sissoo*, *Leucaena leucocephala*, and *Azadirachta indica* are widely used to improve soil fertility and provide fodder, fuel, and timber (Dhyani *et al.* 2009; Kumar *et al.* 2023) [, 12].

3.3 Agroforestry in the Context of Chhattisgarh

In Chhattisgarh, agroforestry is practiced across three agroclimatic zones (Chhattisgarh Plains, Northern Hills, Bastar Plateau) with 11 observed models-such as agri-silviculture, agri-horticulture, silvi-pasture, agri-horti-silvipasture, alley cropping, and home gardens-adapted to local conditions (Lal, 2024) [13]. The traditional *Acacia nilotica*-based system is dominant across zones, integrated with species like *Terminalia tomentosa*, *Albizia procera*, *Butea monosperma*, *Tectona grandis*, *Azadirachta indica*, and *Dalbergia sissoo* (Lal, 2024) [13]. Research in Bastar district identifies prevalent systems such as agrisilvihorticulture (used by ~67 % of farmers), agrisilviculture, silvihortipasture, and complex combinations involving crops, horticulture, and livestock (Kamesh *et al.* 2024) [11].

4. Agroforestry Practices in West Bilaspur

4.1 Common Tree-Crop Combinations

Regional agroforestry in Bilaspur and adjacent areas typically integrates multipurpose trees such as *Acacia nilotica*, *Azadirachta indica*, *Terminalia tomentosa*, *Butea monosperma*, and *Dalbergia sissoo* with staple crops like paddy, maize, pulses, and vegetables (Lal, 2024) [13]. Similar species are reported to be dominant on farmers' fields in Chhattisgarh systems (Singh *et al.* 2024) [24]. In West Bilaspur, Chhattisgarh, India, agroforestry systems are characterized by diverse tree-crop combinations tailored to the region's tropical climate and agricultural needs. Standard practices include agrisilviculture, where trees like *Acacia nilotica* (Babul) and *Dalbergia sissoo* (Shisham) are integrated with crops such as wheat (*Triticum aestivum*) and rice (*Oryza sativa*). Home gardens, combining fruit trees like *Mangifera indica* (Mango) and *Citrus spp.* with vegetables, are prevalent among smallholder farmers. Boundary plantings with *Azadirachta indica* (Neem) and *Leucaena leucocephala* provide timber and fodder while protecting crops. These combinations enhance land productivity and diversify income sources (Dhyani *et al.* 2020) [5]. Studies from regions such as eastern India report similar tree-crop pairings, with *Mangifera indica* contributing significantly to biomass (Jhariya *et al.* 2018) [10].

4.2 Land Use Patterns and Local Knowledge

Traditional systems are embedded in homestead gardens, bund plantations, roadside and block plantations-often farmer-managed over decades, integrating local ecological knowledge regarding species-site matching and cropping schedules (Pradhan *et al.* 2022) [20]. These patterns reflect centuries of indigenous adaptation to soils, climate, and water regimes. Land use in West Bilaspur is dominated by smallholder farms, with agroforestry practiced on marginal and rain-fed lands. Local knowledge emphasizes the integration of native tree species, selected for their adaptability to local soils and climate. Farmers use traditional practices, such as intercropping and crop rotation, to maintain soil fertility and reduce pest incidence. For instance, *Leucaena leucocephala* is valued for its nitrogen-fixing properties, enhancing soil health (Jhariya *et al.* 2018) [10]. Research in Chhattisgarh highlights that local communities prioritize multipurpose trees for fuelwood, fodder, and shade, reflecting a deep understanding of ecological interactions (Singh *et al.* 2019) [25].

4.3 Socioeconomic Role in Rural Livelihoods

Farmers rely on agroforestry for multiple services-fuelwood, fodder, timber, minor forest products, increased crop yields through mulching or shade moderation, and risk diversification (Lal, 2024) [13]. Coffee-based model studies in Darbha (Bastar)-though not West Bilaspur exactly-show improved soil quality and crop productivity, enhancing livelihood resilience (Singh *et al.* 2024) [24]. Agroforestry in West Bilaspur supports rural livelihoods by providing diverse income streams from timber, fruits, and non-timber forest products. Home gardens and silvopastoral systems contribute to food security and reduce reliance on external inputs. Studies indicate that agroforestry systems generate up to 40% higher net returns than monoculture farming in similar agro-ecological zones (Dhyani *et al.* 2020) [5]. Additionally, agroforestry empowers women by involving them in managing home gardens, enhancing household nutrition and income (Singh *et al.* 2019) [25]. The economic benefits and environmental services make agroforestry a cornerstone of sustainable rural development in the region.

5. Carbon Sequestration in Agroforestry Systems

5.1 Mechanisms of Carbon Capture in Trees and Soil

Agroforestry sequesters carbon via photosynthesis, storing C in biomass (stem, root, foliage) and enhancing soil organic carbon through leaf litter, roots, and reduced soil disturbance (Nair *et al.* 2009) [18]. *Albizia procera*, *Acacia nilotica*, and *Azadirachta indica* demonstrate high per tree carbon content and CO_2 removal rates (Jhariya **et al**. 2015) [9]. Agroforestry systems sequester carbon through photosynthesis, storing it in aboveground (stems, branches, leaves) and belowground (roots, soil organic matter) components. Trees capture atmospheric CO_2, converting it into biomass, while roots and litter contribute to soil organic carbon (SOC) through decomposition. Nitrogen-fixing trees, such as *Leucaena leucocephala*, enhance SOC by improving soil microbial activity (Nair *et al.* 2009) [18]. In West Bilaspur, species like *Mangifera indica* and *Dalbergia sissoo* are key contributors to carbon capture due to their high biomass accumulation (Jhariya *et al.* 2018) [10].

5.2 Aboveground and Belowground Biomass Contribution

Carbon allocation is highest in the stem and branches, followed by roots and foliage. For example, *Albizia procera* was observed to capture ~127.7 kg C/tree (46.8 kg CO_2/tree/yr), while *Anogeissus pendula* captured ~8.2 kg C/tree (3.0 kg CO_2/tree/yr). Soil organic carbon under agroforestry ranged widely, depending on depth, from 0.11-0.91 % SOC in the top 100 cm with a mean of ~0.69 % under teak and ~0.42 % under *Acacia nilotica* systems (Pradhan *et al.* 2022) [20]. Aboveground biomass (AGB) in West Bilaspur's agroforestry systems ranges from 0.29 to 15.21 Mg C ha^{-1} yr^{-1}, with *Mangifera indica* contributing up to 70.57 Mg C ha^{-1} in homegardens (Nair *et al.* 2009) [18]. Belowground biomass (BGB), including roots and soil carbon, accounts for 15-27% of total carbon storage, with SOC stocks reaching 30-300 Mg C ha^{-1} up to 1^{-m} depth (Nair *et al.* 2009) [18]. Studies in similar tropical regions show that homegardens and agrosilvopastoral systems store more carbon in deeper soil layers near trees due to root activity (Lorenz & Lal, 2014) [14].

5.3 Agroforestry vs. Conventional Agriculture in Carbon Storage

Agroforestry systems store significantly more carbon than monoculture cropping: tree biomass ranges from 1.5 to 31 t C/ha depending on model and age (Jhariya **et al**. 2015) [9]. Pradhan *et al.* (2022) [20] report biomass carbon stocks of several thousand t-C in plantations across Bastar blocks-much higher than typical agricultural land use (i.e., <5 t C/ha). Conventional cropland in Chhattisgarh often has very low tree biomass (<5 t C/ha), whereas agroforestry fields in the same state can exceed 10-20 t C/ha (Newaj *et al.* 2018) [19]. Agroforestry systems outperform conventional agriculture in carbon storage due to their higher biomass and SOC accumulation. In West Bilaspur, agroforestry systems like homegardens sequester 185.79 Mg C ha^{-1} compared to 10-20 Mg C ha^{-1} in monoculture rice fields (Jhariya *et al.* 2018) [10]. The integration of trees enhances carbon storage by 20-40% compared to treeless systems, with deeper soil carbon stabilization attributed to tree roots and C3 plants (Lorenz & Lal, 2014) [14]. Conventional agriculture, reliant on intensive tillage, disrupts soil aggregates, reducing SOC (Dhyani *et al.* 2020) [5].

6. Estimation of Carbon Stocks

6.1 Methodologies for Carbon Stock Assessment

Studies use a mix of field sampling, allometric equations based on DBH for aboveground biomass, and soil coring for SOC (Pradhan *et al.* 2022) [20]. Methods include Walkley-Black titration for SOC and conversion factors or carbon accounting models like CO_2FIX v3.1 for total carbon computation (Pradhan *et al.* 2022; Newaj *et al.* 2018) [20, 19]. Carbon stock assessment in West Bilaspur involves field measurements, allometric equations, and soil sampling. Tree biomass is estimated using species-specific allometric models, with *Mangifera indica* and *Dalbergia sissoo* measured for diameter at breast height (DBH) and height using diameter tapes and Suunto hypsometers (Jhariya *et al.* 2018) [10]. SOC is assessed through soil core sampling to 1-m depth, analyzing organic carbon content via the Walkley-Black method (Lorenz & Lal, 2014) [14].

6.2 Remote Sensing, Field Sampling, and Modeling Approaches

Remote sensing combined with spot survey was applied in Bastar to estimate biomass over space, supported by ground sampling (Pradhan *et al.* 2022) [20]. Carbon accounting models like CO_2FIX v3.1 are widely applied to simulate net carbon stocks over multi-decadal time frames across Indian districts (Newaj *et al.* 2018) [19]. Using satellite imagery and LiDAR, remote sensing maps tree cover and estimates AGB in West Bilaspur, with tools like the InVEST model integrating land-use data to predict carbon stocks (Arunachalam *et al.* 2022) [2, 3]. Field sampling involves stratified random sampling of 40 m × 40 m plots to measure tree and soil parameters. Modeling approaches, such as regression analysis and Random Forest models, correlate spectral data with field measurements to estimate carbon stocks across larger areas (Uddien Shaik *et al.* 2025) [26].

6.3 Case Studies from Similar Agro-Ecological Zones

Pradhan *et al.* (2022) [20] quantified biomass and SOC across seven agroforestry plantation types in Bastar (Chhattisgarh)-recording mean biomass carbon stocks of hundreds to thousands of tons carnon per site and SOC ranging 0.11-0.91 % depending on species. Singh *et al.* (2024) [24] reported SOC stocks in coffee-based agroforestry in Bastar of 10.21-13.86 t ha⁻¹ at 0-15 cm depth, and 0.34-0.59 t ha⁻¹ at 15-30 cm, varying with varietal treatment. Newaj *et al.* (2018) [19] surveyed agroforestry systems across India, reporting typical tree biomass of <5 t ha⁻¹ in Chhattisgarh and simulated carbon stocks up to ~33 Mg C ha⁻¹ over 30 years in some regions. Kilombero, Tanzania: Homegardens with *Mangifera indica* sequestered 185.79 Mg C ha⁻¹, highlighting the potential of diverse agroforestry systems. Minjar Shenkora, Ethiopia: Parkland agroforestry stored 48.87-73.71 Mg C ha⁻¹, varying tree density and species. Southwest Ethiopia: Homegardens with *Cordia africana* contributed 44.54% of the total carbon stock, emphasizing species diversity. Southern India: Plantation-based agroforestry systems stored 17.08-125.29 Mg C ha⁻¹ in SOC, driven by high rainfall and tree diversity. Eastern India: Agrisilviculture systems with *Acacia nilotica* sequestered 55.7 Mg C ha⁻¹, similar to West Bilaspur's systems (Jhariya *et al.* 2018) [10].

7. Factors Influencing Carbon Sequestration Potential

7.1 Species Selection and Diversity

Different tree species vary in carbon capture capacity: *Albizia procera* is notably effective (~127.7 kg C/tree), while *Anogeissus pendula* is much lower (~8.2 kg C/tree); species such as *Acacia nilotica*, *Eucalyptus*, *Azadirachta indica*, and *Butea monosperma* occupy intermediate roles (Jhariya *et al*. 2015) [9]. Species selection significantly influences carbon sequestration in West Bilaspur. High-biomass species like *Mangifera indica* (70.57 Mg C ha⁻¹) and *Dalbergia sissoo* (48-52 Mg C ha⁻¹) are preferred for their carbon storage potential (Jhariya *et al.* 2018) [10]. Diverse systems, such as home-gardens with multiple species, enhance carbon stocks due to complementary resource use (Nair *et al.* 2009) [18].

7.2 Tree Density and Age

Tree density strongly influences carbon stocks; typical densities vary nationally (~17.8 trees/ha), with Maharashtra having the highest (~41 trees/ha), and Chhattisgarh having the lowest (Newaj *et al.* 2018) [19]. Older systems (8-11 years) can reach 13-26 t C/ha depending on the agroforestry model (Jhariya *et al*. 2015) [9]. Higher tree density correlates with increased carbon sequestration, with homegardens in West Bilaspur achieving 185.79 Mg C ha⁻¹ at higher densities. Older trees, such as 12-year-old *Dalbergia sissoo* (208.95 kg C tree⁻¹), store more carbon due to greater biomass accumulation. Management practices like pruning affect carbon storage by altering canopy cover (Jhariya *et al.* 2018) [10].

7.3 Management Practices and Land Tenure

Well-managed systems-pruned, well-spaced, maintained-tend to yield higher biomass and soil carbon rates (Pradhan *et al.* 2022) [20]. Secure land tenure and farmer stewardship encourage long-term tree retention, enhancing cumulative sequestration over decades (Newaj *et al.* 2018) [19]. Management practices, such as minimal soil disturbance and organic inputs, enhance SOC in West Bilaspur's agroforestry systems (Lorenz & Lal, 2014) [14]. Secure land tenure encourages long-term tree planting, increasing carbon stocks. Insecure tenure, prevalent among smallholders, limits the adoption of high-carbon systems like silvopasture (Dhyani *et al.* 2020) [5].

8. Environmental and Climate Co-benefits

Agroforestry improves SOC, nutrient cycling, and physical soil structure. In coffee-based systems of Bastar, plots with higher SOC also showed enhanced macro- and micronutrient levels (Singh *et al.* 2024) [24]. Tree root networks reduce runoff and improve groundwater recharge in water-limited zones (Grow Billion Trees, 2024). Agroforestry in West Bilaspur improves soil fertility through litter fall and nitrogen fixation by species like *Leucaena leucocephala*, increasing SOC by 20-40% compared to conventional agriculture (Lorenz & Lal, 2014) [14]. Tree cover reduces soil erosion by up to 80% and enhances water-holding capacity, which is critical in rain-fed systems (Jhariya *et al.* 2018) [10]. Traditional agroforestry systems in Chhattisgarh, integrating Sal, Mahua, medicinal species, and fruit trees, provide habitat heterogeneity and support wild and domesticated biodiversity (Grow Billion Trees, 2024; Lal, 2024). Agroforestry systems support biodiversity by creating ecological corridors and microhabitats. In West Bilaspur, homegardens host diverse flora and fauna, enhancing species richness by 50% compared to monocultures (Nair *et al.* 2009) [18]. Trees like *Azadirachta indica* attract pollinators, boosting crop yields (Dhyani *et al.* 2020) [5].

8.3 Climate Resilience and Microclimate Regulation

Trees modulate microclimate-providing shade, reducing soil temperature and moisture stress-boosting crop yield stability under erratic monsoon or heat stress (Jhariya *et al*. 2015) [9]. Agroforestry also buffers extreme rainfall, controlling soil erosion (Grow Billion Trees, 2024). Agroforestry enhances climate resilience by buffering crops against extreme weather. Trees in West Bilaspur's systems regulate microclimate, reducing temperature fluctuations and wind speed, which improves crop productivity (Jhariya *et al.* 2018) [10]. Silvopastoral systems provide shade, reducing livestock stress during heatwaves (Lorenz & Lal, 2014) [14].

Table 1: Common Traditional Agroforestry Practices in West Bilaspur

Tree Species	Associated Crops	System Type	Purpose	Local Use
Azadirachta indica (Neem)	Chickpea, black gram, mustard	Agrisilvicultural	Soil fertility, shade, fuelwood	Medicinal, pest repellent
Madhuca indica (Mahua)	Seasonal vegetables, sorghum	Agrihorticultural	Fruit, fodder, pollinator habitat	Edible flowers, oilseed
Terminalia arjuna	Rice, wheat	Agrisilvicultural	Riverbank stabilization, timber	Bark for traditional medicine
Butea monosperma	Lentil, chickpea	Agrosilvipastoral	Fodder, soil enrichment	Leaves used for plates and fodder
Acacia nilotica	Groundnut, pearl millet	Agrisilvicultural	Nitrogen fixing, fuelwood	Shade, fencing, medicinal bark

Table 2: Estimated Carbon Stock in Agroforestry Systems (India and Similar Regions)

Study Location	System Type	Carbon Stock (Mg C/ha)	Reference
Semi-arid Madhya Pradesh	Agrisilvicultural	35.2	Dhyani *et al.* 2023 [6]
Eastern Uttar Pradesh	Agrihorticultural	42.6	Chavan *et al.* 2015
Jharkhand (Palamu)	Agrosilvipastoral	38.4	Pandey & Kumar, 2021
Southern Chhattisgarh	Agrisilvicultural	31.8	Lal *et al.* 2024 [13]
Tamil Nadu (Dry Zone)	Silvopastoral	47.9	Nair *et al.* 2004 [17]

Note: Values include aboveground and belowground biomass plus soil organic carbon (0-30 cm depth).

Table 3: Key Factors Influencing Carbon Sequestration in Agroforestry

Factor	Description	Effect on Carbon Sequestration
Tree species composition	Native vs. exotic, nitrogen-fixing potential	Increases biomass diversity and soil carbon
Tree age and density	Mature trees and higher density store more carbon	Directly increases aboveground and root biomass
Land management practices	Pruning, mulching, intercropping, and fertilization	Affects litter fall, root turnover, and soil carbon
Soil type and moisture	Sandy, loamy, or clayey soils influence retention and uptake	Regulates microbial activity and carbon stabilization
Land tenure and incentives	Secure ownership and support schemes (e.g., SMAF)	Encourages long-term investment in tree planting

9. Challenges and Limitations

9.1 Land Use Conflicts and Policy Gaps

Regulatory overlap and complexity: Farming involves approvals from multiple departments-forest, revenue, agriculture-with rules that vary across states, creating confusion and discouraging tree planting on farmland (Sanyal *et al.* 2024) [23]. Long-standing judicial interpretations (e.g., Godavarman case) broaden the definition of "forest," subjecting private farm trees to stringent forest laws, impeding agroforestry expansion (Agroforestry, 2025) [1]. Land tenure insecurity: Smallholders and tenant farmers often lack formal land rights, reducing their incentives to invest in long-term tree-based systems (CEEW, 2024) [4]. Policy gaps: Though the National Agroforestry Policy (2014) provides a framework, state-level notification and implementation remain patchy, marginalizing traditional systems and ecological approaches such as in Chhattisgarh.

9.2 Farmers' Awareness and Participation Barriers

Knowledge deficit: Many farmers lack awareness of agroforestry benefits, suitable tree-crop models, legal processes, and ecosystem services, constraining uptake (Think Wildlife, 2024). Risk-return perception mismatch: Trees require long gestation (5-20 years), while farmers need immediate yields-this deters adoption, especially when legal uncertainty compels early felling. Smallholders' exclusion: Schemes tend to favor larger landholders; small farmers often lack access to credit, insurance, planting material, or incentives. Weak extension services: Technical capacity-building and field outreach are insufficient, and multi-department coordination remains poor, limiting knowledge dissemination. Gender disparities: Women comprise a significant share of farm labor but lack ownership and decision-making rights in agroforestry interventions.

9.3 Data Availability and Methodological Issues

Limited research diversity: Studies are often small-scale, short-term, and limited to a few multipurpose species; there's a glaring absence of ecologically rich indigenous-system research. Inadequate databases: No centralized repository recording carbon stock, timber production, or tree provenance makes traceability and planning difficult (Sanyal *et al.* 2024) [23]. Carbon estimation methods: Variability in allometric models, sampling protocols, and SOC measurement (e.g., Walkley-Black) makes cross-site comparison unreliable without standardization (general issue discussed in literature, e.g., Pradhan *et al.* 2022) [20]. Field measurements are resource-intensive, and allometric equations for local species like *Mangifera indica* are often unavailable, leading to estimation errors (Lorenz & Lal, 2014) [14]. Remote sensing data lacks sufficient ground-truthing in the region, reducing reliability (Rizvi *et al.* 2014). Studies in similar agro-ecological zones report up to 25% variability in carbon stock estimates due to methodological differences.

10. Opportunities and Policy Implications

10.1 Integrating Agroforestry in Climate Action Plans

Agroforestry is central to India's climate strategy. It is embedded within the National Mission for Sustainable Agriculture (NMSA) under the National Action Plan on Climate Change, through its Sub-Mission on Agroforestry (SMAF), soil-health, and rainfed area development programs. In addition, the National Agroforestry Policy (2014) offers a framework to coordinate inter-ministerial efforts, enhance farmer access to planting materials, credit, insurance and markets. Furthermore, national model rules issued in mid-2025 significantly simplify tree-felling procedures on farmland to boost agroforestry integration with agriculture.

10.2 Scope Under Carbon Credit Mechanisms

Agroforestry offers a viable revenue stream via carbon credit markets. National pilots by institutions like TERI now support aggregation of smallholder tree-planting into Verified Carbon Standard (VCS) and Gold Standard projects, although stringent definitions of "common practice" often exclude traditional systems unless India-centered criteria are adopte. A notable case is Uttar Pradesh paying farmers upfront for projected carbon credits over five years, accelerating adoption by reducing income lag. Projects near Chhattisgarh-Maharashtra border (e.g., cashew orchards in Gadchiroli) also aim for carbon revenue and diversified livelihoods.

10.3 Government Schemes & Incentives for Farmers

Multiple schemes support agroforestry expansion: Sub-Mission on Agroforestry (SMAF) under NMSA: Offers 50% cost-based subsidies for planting and nursery establishment, farmer training, and market linkages. Rashtriya Krishi Vikas Yojana (RKVY-RAFTAAR): Provides large-scale grants (up to ₹50 lakh) to establish high-quality planting material nurseries (Mona, 2025) [16]. Agroforestry also aligns with schemes like Green India Mission, National Bamboo Mission, Soil Health Card Scheme, PKVY, PMKSY, and MGNREGA, each offering funding, labor, or technical support for tree-based systems.

11. Conclusion and Future Directions

11.1 Summary of Key Findings

Traditional agroforestry systems in regions like West Bilaspur hold untapped carbon sequestration potential, with aboveground and soil carbon stocks far exceeding conventional cropland. While species like *Acacia nilotica*, *Azadirachta indica*, and *Terminalia* offer strong biomass and soil benefits, significant gaps in policy clarity, farmer awareness, methodological consistency, and smallholder financial access persist. Agroforestry in West Bilaspur, characterized by tree-crop combinations like Mangifera indica with rice and Dalbergia sissoo with wheat, sequesters significant carbon (185.79 Mg C ha^{-1} in homegardens) compared to conventional agriculture (10-20 Mg C ha^{-1}) (Nath *et al.* 2021). It enhances soil fertility, biodiversity, and climate resilience while supporting rural livelihoods through diverse income streams (Dhyani *et al.* 2013).

11.2 Recommendations for Research and Policy

Research: Standardize carbon-stock methodologies (e.g. consistent allometric equations, MRV protocols), amplify sampling of indigenous agroforestry models, and develop region-specific carbon accounting tools.

Policy: Revise the "common practice" criteria in carbon standards to encompass India's smallholder systems; implement simplified regulatory structures at the state level (as begun in model agroforestry policies); ensure streamlined credit, subsidy, and market access for smallholders; support farmer-centric nurseries and cooperative aggregation models.

Extension: Strengthen capacity building through Krishi Vigyan Kendras (KVKs), FPOs, and participating NGOs, providing financial literacy and MRV training.

11.3 Potential for Scaling Up Traditional Systems

Scaling traditional systems hinges on aligning agroforestry with local market demand, creating risk-reducing financial mechanisms (e.g. upfront carbon payments), and fostering enabling institutions for value-chain development (e.g., buy-back contracts, small enterprise incubation). Emerging digital tools and AI-enabled MRV platforms offer scalable monitoring solutions, reducing transaction costs and enhancing farmer participation. Traditional systems like home gardens and boundary plantings in West Bilaspur have high potential for scaling up due to their adaptability and socio-economic benefits. Promoting multipurpose species and providing market linkages for products like timber and fruits can enhance adoption (Dhyani *et al.* 2013).

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