The role of agroforestry in carbon sequestration and climate adaptation: A review

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Abstract

Agroforestry is a holistic land-use approach that combines trees, crops, and livestock to improve ecosystem services, biodiversity, and productivity and ensure economic and environmental resilience. This review examines the major contribution of agroforestry in climate change mitigation through carbon sequestration and promoting climate adaptation. Through sequestering atmospheric carbon in biomass and soil, agroforestry systems are a cost-effective method to mitigate greenhouse gases and enhance ecological stability. In addition, these systems play a role in climate adaptation through improved soil health, water retention, erosion reduction, and biodiversity promotion, thereby contributing to agricultural sustainability. The review critically assesses different agroforestry practices, their efficiency in carbon sequestration, and their role in climate adaptation. Also, it elaborates on the primary challenges including land tenure security, policy constraints, and socio-economic limitations and then suggests possible solutions and policy measures to enhance broad-based agroforestry uptake and adoption.

Keywords: Agroforestry, carbon sequestration, climate adaptation, sustainable agriculture, climate change mitigation

Introduction

Global food security, biodiversity, and ecological stability are threatened by climate change, resulting in unpredictable weather patterns, more frequent occurrence of extreme climatic events, and soil erosion (Muluneh, 2021) [69]. Conventional agricultural systems are responsible for deforestation, soil degradation, and carbon emissions, thus worsening climate threats. Agroforestry, as a multi-functional land-use system, comes as a solution by blending woody perennials with crops and livestock to improve ecological, economic, and social benefits (Jain, 2025) [37]. This integrated system not only enhances sustainable food production but also offers numerous ecosystem services, such as soil conservation, enhanced water use efficiency, and increased carbon sequestration (Powlson *et al.*, 2011) [90]. Through enhancing biodiversity and minimizing farming systems' vulnerability to climate change, agroforestry is important in mitigation and adaptation approaches (Mulatu, and Hunde, D. 2019) [68]. This review examines the contribution of agroforestry to carbon sequestration and climate adaptation, highlighting its ability to counteract climate change while promoting long-term agricultural sustainability (Mbow *et al.*, 2014) [64]. It also identifies policy support, farmer training, and technological innovation as critical in maximizing agroforestry practices for optimal climate benefits (Ntawuruhunga *et al.*, 2023) [85].

Climate change is a serious environmental issue that has become international in recent years (Boykoff, 2011) [15]. Rarely does a day pass without news about it making it to the headlines (Washington, 2013) [117]. Huge efforts, ranging from conferences and debates to research projects, action plans, and so forth, are being made on all fronts around the globe at all times to understand the intricacies and severity of human-caused climate change, search for adaptation techniques, and counteract its negative effects. Therefore, global climate change, commonly referred to as global warming, is still a serious environmental issue impacting human life and the earth (Nair *et al.*, 2010) [79].

Carbon (C) is a vital element in all living things and the basic building block of life on Earth

(Bertrand *et al.*, 2021) [13]. It occurs in several forms, such as soil organic matter, plants, animals, geological deposits, atmospheric carbon dioxide (CO_2), and dissolved in seawater (Lal, 2008) [55]. More attention is now being paid to the function of various land-use systems in stabilizing atmospheric CO_2 levels, lowering emissions, and improving carbon sequestration in agroforestry systems (Lorenz, and Lal, 2014) [61]. Agroforestry has been identified as a means of reducing CO_2 emissions and enhancing carbon sinks (Pandey, 2002) [89]. Natural ecosystems are the largest carbon reservoirs in vegetation and soil, but much of these ecosystems has been degraded, especially in developing and underdeveloped countries (Upadhyay *et al.*, 2005) [109]. Restoration of these degraded and deforested lands to their natural forested condition is not likely (Vásquez-Grandón *et al*, 2018) [112]. Thus, the transformation of low-biomass land uses like croplands and fallows into carbon-rich tree-based systems like plantation forests and agroforestry becomes more and more significant (Gupta *et al.*, 2017) [28].

Agroforestry systems (AFS), totaling about one billion hectares in several ecological regions, are important carbon sequestration systems (Nair *et al.*, 2012) [76]. Land-use systems with woody perennials have a high capacity for capturing and storing atmospheric CO_2 in vegetation, soil, and biomass products (Kaur *et al.*, 2023) [44]. Agricultural system management for carbon sequestration has been suggested as one of the partial solutions to climate change (Morgan *et al.*, 2010) [67]. Perennial vegetation establishment and maintenance for carbon capture is cost-effective compared to many other options and entails little or no environmental or health risks. Perennial crops have a greater efficacy than annuals in directing more carbon to below-ground biomass and tend to be longer in the growing season, which also expands their carbon sequestration capabilities (Morgan *et al.*, 2010; Oelbermann *et al.*, 2006; Jose, 2009) [67, 87, 41].

Agroforestry offers an unparalleled opportunity for synergistic climate change adaptation and mitigation (Keprate, *et al.*, 2024) [46]. While these systems are not explicitly intended for carbon sequestration, several recent studies offer convincing evidence of their ability to sequester carbon in aboveground biomass (Mutuo *et al.*, 2005; Verchot *et al.*, 2007) [73, 113], (Nair *et al.*, 2009) [78], and belowground biomass (Nair *et al.*, 2009) [78]. Agroforestry is highly promising for carbon storage owing to its multi-species plant composition, soil-enriching potential, and suitability for agricultural landscapes. It also contributes to the environment indirectly by minimizing pressure on natural forests and avoiding soil erosion (Montagnini, 2004) [65].

The interactions among the species of an ecosystem are affected by anthropogenic variables of space, resources, and time (Hautier *et al.*, 2015) [30]. When a number of species compete for the same combinations of resources, it might pose potential threats to carbon sequestration (Lal, 2008) [56]. Trees in agroforestry systems, however, can act as vital sinks for carbon because of their fast growth and high productivity (Lorenz, and Lal, 2014) [61]. Hence, encouraging agroforestry can be a useful method for resolving land-use issues and preventing CO_2-caused global warming (Naizheng, 2016) [83]. The degree of carbon sequestration attained is mainly dependent on the structure (Kumar *et al.*, 2011) [53], function, and type of agroforestry system, which in turn are controlled by environmental and socio-economic factors (Ramachandran Nair *et al.*, 2009) [95]. Tree species choice and system management also control the carbon storage potential in agroforestry systems (Albrecht & Kandji, 2003) [7].

Carbon is an essential element present in all living things and most inorganic substances (Nair, 2012) [77]. It is the main building block of life and the environment (Kaim *et al.*, 2013) [42]. Living things consist of different elements, the most common of which are oxygen, carbon, hydrogen, nitrogen, calcium, and phosphorus (Ochiai, and Ochiai, 2011) [86]. Of these, carbon is best suited to create vital life-sustaining molecules like sugars, starches, fats, and proteins (Nair, 2023) [75]. Together, these carbon-containing compounds make up virtually half of the planet's vegetation dry mass (Adams, and Adams, 2010) [3]. Aside from its biological importance, carbon also exists in non-biological parts of the environment such as rocks, fossil fuels (oil, natural gas, and coal), and the atmosphere (Kambale *et al.*, 2010) [43].

Carbon cycle is the flow of carbon from one reservoir or storage system to another in the Earth's system, including the atmosphere, lithosphere, hydrosphere, and biosphere (Ussiri *et al.*, 2017) [111]. Being a process that involves biological systems, it is a biogeochemical cycle. The carbon cycle is the transfer of carbon between land, oceans, and the atmosphere (Crisp *et al.*, 2022) [17].

Carbon dioxide (CO_2) is emitted into the atmosphere from multiple sources, including anthropogenic activities like fossil fuel combustion, deforestation (Yoro *et al.*, 2020) [118], cement manufacturing, biomass burning, agricultural activities, and land use changes related to croplands expansion (Andres *et al.*, 2012) [9]. Wildfires also emit CO_2 each year, CO_2 is taken away from the atmosphere in two main processes (Tkemaladze, and Makhashvili, 2016) [107]. photosynthesis by terrestrial and ocean organisms and by oceans' absorption (Kiang *et al.*, 2016) [49]. Consequently, both terrestrial and oceanic ecosystems are carbon sources and sinks. Natural processes in the past kept them in balance, but human-added carbon emissions have upset this balance, causing rising atmospheric CO_2 levels and the sequestration of a considerable amount of this anthropogenic carbon in the oceans (Khatiwala *et al.*, 2013) [48].

Carbon is held in a number of reservoirs, which include the atmosphere, soil, vegetation, fossil fuels, oceans, and the Earth's crust (Naeem *et al.*, 2023) [74]. When considering Earth as a system, these reservoirs are referred to as carbon pools, stocks, or storage units because they contain substantial amounts of carbon (Senjam *et al.*, 2020) [99]. The movement of carbon from one reservoir to another is known as carbon flux. Fluxes are typically measured as the rate of carbon transfer over a specific period (Hertel *et al.*, 2009) [31]. Within the integrated Earth system, these fluxes link different reservoirs, forming cycles and feedback mechanisms (Ward *et al.*, 2012) [116].

This review emphasizes the potential of agroforestry systems for carbon sequestration and calls for research to estimate their efficacy, determine their multiple advantages, and understand their ability to generate synergies among climate change mitigation, adaptation, and community resilience strengthening.

Motive of the Review

The main purpose of this review is to integrate current research on agroforestry's contribution to carbon sequestration and climate adaptation, offering insights into its advantages, challenges, and opportunities. Through the presentation of empirical evidence and case studies, the review aims to motivate policymakers, researchers, and farmers to embrace agroforestry as a climate-smart agricultural practice. The research also seeks to underscore the necessity of additional research and policy assistance to maximize agroforestry systems for maximum socio-economic and environmental gains.

Carbon Sequestration Potential of Agroforestry

Agroforestry contributes significantly to carbon sequestration through the capture and storage of atmospheric carbon dioxide (CO2) in biomass and soil (Lorenz, and Lal, 2014) [61]. Incorporating trees, shrubs, and perennial vegetation into agricultural ecosystems increases carbon sequestration through various mechanisms such as aboveground biomass accumulation (Abbas *et al.*, 2017) [2], root biomass production, and enrichment of soil organic carbon. Perennial plants and trees take up CO_2 by photosynthesis and store carbon in their roots, stems, branches, and leaves (Handa *et al.*, 2020) [29]. Furthermore, litterfall and root turnover help in long-term carbon storage in the soil, enhancing soil organic matter content and fertility (Ghale *et al.* 2022) [26].

Various agroforestry systems, including alley cropping, silvopasture, windbreaks, home gardens, and multistrata systems, play a significant role in carbon sequestration (Nair *et al.*, 2021) [80]. Research shows that Agroforestry systems (AFS) such as parklands, live fences, and homegardens had substantial C stocks, but only accumulated 0.2-0.8 Mg C ha^{-1} $year^{-1}$in soil, making them effective measures for carbon capture and storage (Luedeling *et al.*, 2011) [62]. The efficiency of carbon sequestration is influenced by several factors, such as tree species, planting density, soil type, climate, and management (Jandl *et al.*, 2007) [38]. Deep-rooted trees sequester more carbon in the subsoil, while leguminous trees increase nitrogen fixation, thus supporting carbon buildup (Lebrazi, and Fikri-Benbrahim, 2022) [59].

In addition, agroforestry operations enhance soil microbial activity, increasing carbon stabilization and minimizing soil respiration losses (Fahad *et al.*, 2022) [23]. The integration of perennial crops and soil conservation practices reduces the incidence of soil erosion, hence the loss of carbon from agricultural land (Hussain *et al.*, 2021) [32]. Proper agroforestry design, species composition, and intensively managed sustainable land use practices are critical to the optimization of the carbon sequestration capability of these systems (Kumar *et al.*, 2023) [54]. By incorporating agroforestry into climate mitigation plans, agricultural landscapes can be transformed into substantial carbon sinks while, at the same time, contributing various co-benefits including intensified biodiversity, strengthened water cycling, and enhanced farmer resilience to climate change (Pandey *et al.*, 2002) [89].

Table 1: different Agroforestry system enhances carbon sequestration

Agroforestry System	**Description**
Agri-Silvicultural Systems	Combining trees with crop cultivation to improve soil fertility and reduce dependency on chemical inputs.
Home Gardens	Small-scale agroforestry systems that enhance biodiversity, sequester carbon, and ensure food security.
Riparian Buffer Systems	Establishing tree and shrub buffers along streams and rivers to prevent soil erosion, improve water quality, and enhance carbon sequestration.
Forest Farming	Cultivating high-value crops such as medicinal plants and spices under tree canopies to optimize land use and carbon storage.
Alley Cropping	Planting rows of trees or shrubs alongside agricultural crops to provide shade, act as a windbreak, and facilitate nutrient cycling, while crops benefit from reduced soil erosion and improved microclimate. Certain trees also contribute to nitrogen fixation.
Silvopasture	Integrating trees, forage crops, and grazing livestock. Trees provide shade, forage, and shelter for livestock while enhancing soil fertility. Additionally, silvopasture generates income from timber and non-timber forest products.
Windbreaks and Shelterbelts	Rows or blocks of trees planted to reduce wind speed, protect agricultural fields, and minimize soil erosion. They create a favorable microclimate, conserve soil moisture, and mitigate wind-related damage to crops and livestock.
Riparian Forest Buffers	Vegetated areas along water bodies like streams, rivers, and wetlands that filter runoff, stabilize soil, and improve water quality. They also provide wildlife habitats, help control flooding, and reduce nutrient and pollutant runoff.

There are different cropping systems in India that help sequester carbon by increasing soil organic carbon (SOC) and encouraging good land management practices (Swarup *et al.*, 2019) [106]. These cropping systems, both conventional and new, in addition to sequestering carbon, also enhance soil health, water storage, and general agricultural output (Dhyan *et al.*, 2016) [20]. Some of the prominent cropping systems practiced in India, which are capable of carbon sequestration, are listed below:

Table-2: Different agroforestry system having carbon sequestration potential.

Region	**Agroforestry system**	**Tree species**	**No. of trees/ha**	**Age (year)**	**CSP (Mg C/ha/yr)**	**References**
		Acacia farnesiana	170	2	2.42	
		Cassia montana	154	2	1.84	
		Prosopis juliflora	138	2	1.16	
		Acacia nilotica	106	2	5.70	
	Agrisilviculture	*Albizia procera*	312	7	3.70	Newaj and Dhyani (2008) [117]
		Acacia pendula	1666	5.3	0.43	Rai *et al.* (2002) [128]
		Leucaena leucocephala	11111	4	2.77	Rao *et al.* (1991) [135]
			6666	4	1.90	
			4444	4	14.42	Prasad *et al.* (2012) [126]
			10000	4	15.51	
		Casuarina equisetifolia	833	4	1.57	Viswanath *et al.*(2004) [170]
		Delbergia sissoo		11	1.47	NRCAF (2007)
		Emblica officinalis		8	1.58-1.62	Swamy *et al.* (2003) [155]
		Hardwickia binnata		8	1.07-1.10	
		Colophospermum mopane	8	0.59-0.66		

	Silvipasture	*Acacia nilotica* +Natural pasture	312	5	1.9-5.4	Rai *et al.* (2001)
		Acacia nilotica +Established pasture	312	5	5.9	
		Dalbergia sissoo+Natural pasture	312	5	2.5	
		Dalbergia sissoo+Established pasture	312	5	3.44	
		Hardwickia binnata+Natural pasture	312	5	3.24	
		Hardwickia binnata+Established pasture	312	5	3.40	
Tropical	Home garden	Mixed tree species	667	71	1.60	Saha *et al.* (2009) [138]
	Block plantation	*Eucalyptus* spp.		7-10	3.71	Ajit *et al.* (2014) [6]
		Acacia mangium	5000	6.5	12.59	Kunhamu *et al.* (2011) [75]
			2500	6.5	9.94	
			1250	6.5	9.51	
			625	6.5	6.37	

(Source, Dhyan *et al.*, 2016) [20]

Agroforestry and Its Role in Carbon Sequestration

Agroforestry is well known to be an economically sound and ecologically sustainable method of reducing climate change (Raj *et al.*, 2019) [94]. It combines trees, crops, and livestock in a multi-functional land-use system that increases biodiversity, soil health, and climate resilience (Assèdé *et al.*, 2024) [10]. Its most important environmental advantage is carbon sequestration—the capture and storage of atmospheric carbon dioxide (CO_2) in plant biomass and soil organic matter (Nair *et al.*, 2015) [82].

Agroforestry systems sequester carbon by storing carbon in aboveground (trees, shrubs, and crops) and belowground biomass (roots and soil organic matter) (Lorenz, and Lal, 2014) [61]. Agroforestry systems also reduce greenhouse gas (GHG) emissions by increasing soil carbon storage, minimizing soil disturbance, and reducing methane (CH_4) and nitrous oxide (N_2O) emissions from agricultural soils (Kim *et al.*, 2016) [50]. The sequestration capacity of agroforestry varies with a number of factors, such as tree species choice (Prasad *et al.*, 2012), management regimes (Newaj *et al.*, 2001), soil, and climate.

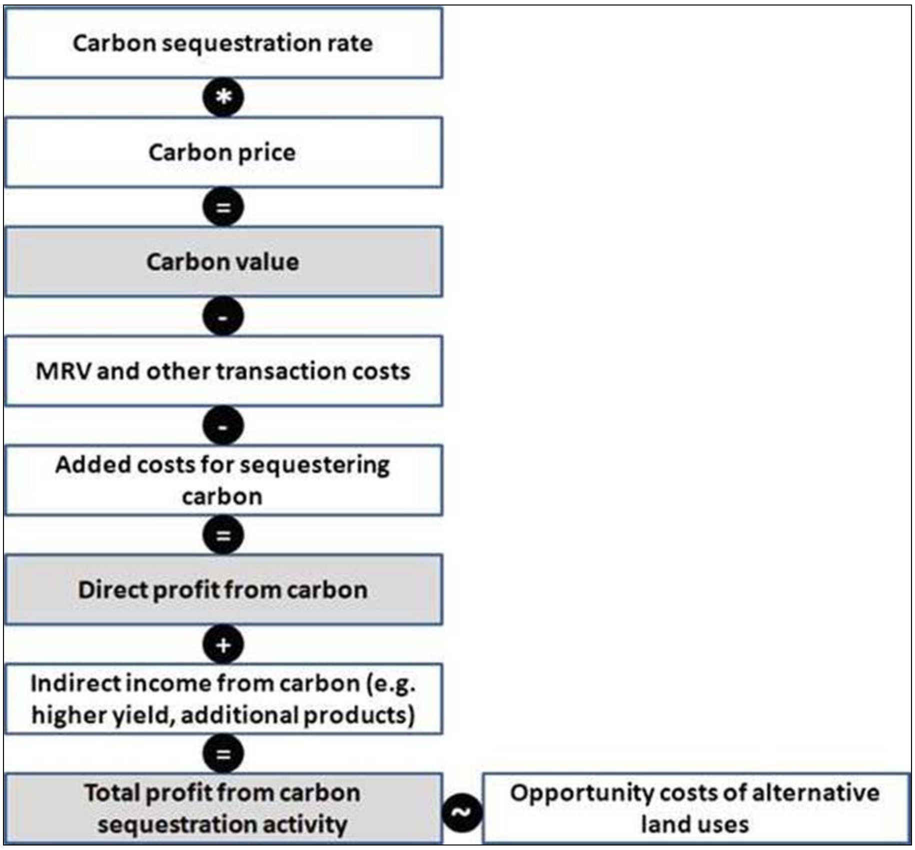

Fig 1: Economic viability of agroforestry systems for carbon sequestration

Agroforestry presents a unique opportunity to achieve multiple environmental, economic, and social benefits while addressing climate change mitigation and adaptation (Jhariya *et al.*, 2019) [40]. By promoting carbon sequestration in biomass and soils, reducing GHG emissions, and enhancing ecosystem resilience, agroforestry plays a crucial role in sustainable land management (Pancholi *et al.*, 2023 [88]. Effective adoption of agroforestry systems must be supported through policy, economics, and capacity-building programs for farmers and land managers to encourage large-scale uptake (Shrestha *et al.*, 2018) [101]. Research and extension service strengthening will further maximize agroforestry's potential to be a flagship strategy for ensuring long-term climate sustainability.

Agroforestry is a useful method for both avoiding and adapting to climate change by lowering atmospheric CO_2 concentrations and enhancing carbon sequestration in biomass and soils (IPCC. (2021) [35]. Incorporating trees into agricultural fields can enhance soil fertility, increase water holding capacity, and stabilize yields while decreasing exposure to climate-related stresses. The root systems of trees in agroforestry avoid soil deterioration by minimizing erosion, enhancing water infiltration, and solidifying the soil (Ghale *et al.*, 2022) [26]. Agroforestry biomass is a renewable energy source of fuelwood, fodder, food, fiber, construction materials, shade, and medicinal crops that sustains rural livelihoods (Dagar, and Tewari, 2017) [19]. Agroforestry has the potential to reduce reliance on shifting/slash-and-burn farming. For example, a single hectare of well-planned agroforestry land is capable of replacing 5-10 hectares of land under conventional shifting cultivation, saving forests and preventing land degradation (Bishaw *et al.*, 2013) [14]. Urban agroforestry efforts help produce biomass at the local level, provide cleaner air, and raise the public's appreciation of the virtues of tree planting in urban areas (Akanwa *et al.*, 2020) [6]. Agroforestry helps in the production of renewable energy through the supply of biomass for bioenergy. Through fossil fuel substitution, agroforestry can potentially avoid the emission of about 17 million metric tons of carbon every year globally (Evans, 1992). Agroforestry is a viable solution for the rehabilitation of wastelands and degraded lands and increasing tree cover beyond forests, thereby alleviating human pressure on natural forests in various agro-ecological regions of India (Dagar, and Gupta, 2016) [18]. Based on the IPCC (2000) special report, the conversion of unproductive grasslands and croplands into agroforestry systems has the maximum potential for sequestering atmospheric CO_2 while at the same time enhancing land productivity. Agroforestry promotes soil organic carbon by the addition of leaf litter, root biomass, and microbial life (Solanki, and Arora, 2015) [104]. Deep-rooting trees in agroforestry systems also promotes nutrient cycling by tapping deeper layers of the soil and releasing the nutrients into use for crop production.

Strategies for Climate Change Mitigation through Agroforestry

Preserving and sustaining current carbon stocks in forests, grasslands, and agroforestry systems by avoiding deforestation, soil erosion, and loss of biomass (Khan *et al.*, 2024) [47]. Augmenting the sequestration of carbon by adding additional tree cover, building up soil organic matter, and stimulating deep-rooted perennials that sequester carbon in biomass and soils (Morari *et al.*, 2019) [66]. Substituting the renewable energy form from biomass agroforestry to fuel substitutes fossil fuels or the use of wood as a sustainably produced alternative for energy-intensive construction materials (Irache Cabello, 2023) [36]. The first two approaches result in increased total carbon stocks, but they can lead to increased emissions in the future if not properly managed through land-use changes or decomposition of biomass. The third approach, however, offers a long-term sustainable option, where carbon sequestration is ensured to go on indefinitely (IPCC, 2001).

Agroforestry systems have an important contribution to carbon sequestration by incorporating trees within agricultural landscapes (Kay *et al.*, 2019) [45]. Agroforestry systems enhance carbon storage by several mechanisms:

Tree Biomass: Trees within agroforestry systems uptake atmospheric carbon dioxide during photosynthesis and store it in their leaves, branches, and trunks. Above-ground biomass is an important carbon sink, lowering atmospheric carbon content efficiently (Atangana *et al.*, 2014) [11].

Below-Ground Carbon Sequestration: Agroforestry increases carbon sequestration in the soil as tree roots grow deep into the ground, leaving behind organic matter and building up soil carbon content (Dissanayaka *et al.*, 2024) [21]. The process also increases soil fertility and general ecosystem well-being.

Litter and Mulch Contribution: Tree leaves, twigs, and organic residues fall to the ground and enrich the soil organic content. As they break down over time, they release carbon into the ground, which goes towards long-term carbon storage (Nair *et al.*, 2021) [81].

Agroforestry Interactions: The association of trees with crops or livestock promotes positive interactions. For example, tree shade can promote the growth of crops, minimizing dependence on chemical fertilizers and irrigation, thus reducing the carbon intensity of farming (Aba *et al.*, 2017) [1].

Table 3: Different tree species Boost Carbon Sequestration

Tree Species	Key Characteristics
Eucalyptus species	High growth rate, long lifespan, tolerant of various climates.
Poplar species	Fast-growing, adaptable to different soil types.
Black locust (*Robinia pseudoacacia*)	Nitrogen-fixing, enhances soil fertility.
Balsam fir (*Abies balsamea*)	Cold-tolerant, grows in diverse soil conditions.
Red maple (*Acer rubrum*)	Hardy, fast-growing, tolerates various environments.

India's trees have a high Carbon Sequestration Potential (CSP) due to the rich diversity of climatic zones, soils, and forest species available in the nation (Kumar, and Kunhamu, 2021). [52] Trees are important for sequestering atmospheric CO2, storing it as biomass aboveground and belowground, and adding organic carbon to soil (Dhyan *et al.*, 2016) [20]. Carbon sequestration potential differs according to factors such as species of tree, age, forest category, management, and ecological factors.

Table 4: Different tree species having carbon sequestration potential

Region	Agroforestry system	Tree species	No. of trees/ha	Age (year)	CSP (Mg C/ha/yr)	References
Himalaya	Block plantation	*Eucalyptus tereticornis*	2500	3.5	4.40	Dhyani *et al.* (1996) [5]
			2777	2.5	5.90	
		Tectona grandis	570	10	3.74	Negi *et al.* (1995) [116]
			500	20	2.25	
			494	30	2.87	
		Cedrus deodara	100	19	2.47	Wani *et al.* (2014) [171]
		Acacia/Dalbergia/Prosopis		6	1.13-3.08	Kaur *et al.* (2002) [44]

		Acacia/Dalbergia/Prosopis		6	0.25-2.05	
	Agrihortipasture	*Malus domestica,*			1.15	AICRPAF (2006) [5]
		Prunus persica etc.				
	Hortipasture	*Prunus persica* etc.			1.08	
	Agrisilviculture	*Dendrocalamus hamiltonii*	1000	7	15.91	Kaushal *et al.* (2014) [63]
		Populus deltoides	500	8	12.02	Singh and Lodhiyal (2009) [149]
	Grove	*Bambusa* spp.	11033 (culm)	4	19.14	Nath and Das (2012) [111]
	Silvipasture	*Grewia optiva, Morus*			2.17	AICRPAF (2006) [5]
		alba etc.				
	Farm forestry	*Acacia catechu*		30	1.5	Hooda *et al.* (2007) [46]
		Pinus spp.		30	7.1	
		Mixed plantation		30	5.9	
		Mangifera indica		30	1.7	
		Kinnow		30	0.2	
Indo- Gangetic	Agrisilviculture	*Leucaena leucocephala*	10666	6	10.48	Mittal and Singh (1989) [90]
		Populus deltoides	400	7	1.98	Rizvi *et al.* (2011) [136]
			400	7	2.48	
			740	7	9.40	Chauhan *et al.* (2010) [16]
	Block plantation	*Acacia nilotica*	1250	7	2.81	Kaur *et al.* (2002) [44]
		Dalbergia sissoo	1250	7	5.37	
		Prosopis juliflora	1250	7	6.50	
Humid and sub-humid	Agrisilviculture	*Gmelina arborea*	592	5	3.23	Swamy and Puri (2005) [154]
	Forest plantation	*Eucalyptus* spp.		6	2.18	Bala *et al.* (2012) [15]
	Block plantation	*Gmelina arborea*		6	4.01-5.01	Swamy *et al.* (2003) [155]
	Silviculture	*Tectona grandis*	444	20	3.32	Negi *et al.* (1990) [115]
		Gmelina arborea	452	20	3.95	
Arid and	Block plantation	*Albizia procera*	312	10	1.79	Rai *et al.* (2000) [134]
semi-arid		*Albizia amara*	312	10	1.00	
		Acacia pendula	312	10	0.95	
		Dalbergia sissoo	312	10	2.55	
		Dichrostachys cinerea	312	10	1.05	
		Emblica officinalis	312	10	1.55	
		Hardwickia binata	312	10	0.58	
		Melia azaderach	312	10	0.49	
		Leucaena leucocephala	2500	9	10.32	Rao *et al.* (2000) [134]
		Eucalyptus camaldulensis	2500	9	8.01	
		Dalbergia sissoo	2500	9	11.47	
		Albizia lebbeck	625	9	0.62	
		Acacia albida	1111	9	0.82	
		Acacia tortilis	1111	9	0.39	
		Acacia auriculiformis	2500	9	8.64	
		Eucalyptus tereticornis	320	2	13.86	Pragason and Karthik (2013) [124]

(Source, Dhyan *et al.*, 2016) [20]

Optimizing Tree Planting for Carbon Sequestration

Trees planted in close proximity can form a dense canopy, minimizing sunlight penetration and curbing the growth of invasive cover vegetation, thus ensuring optimal carbon storage (Negash, 2021) [84]. Trees planted at strategic points can act as windbreaks, minimizing soil erosion and air pollution. Shelterbelts also shield crops from wind damage, promoting agricultural resilience.

Agroforestry and Carbon Sequestration

The initial aim of farmers and government institutions in encouraging agroforestry has been to develop rural livelihoods while meeting diverse basic requirements including food, fuel, wood, and fodder (Sahoo *et al.*, 2022) [96]. Nevertheless, with the changing times of climate change, agroforestry has assumed important economic and environmental significance as a technique to counteract the negative consequences of greenhouse gases (GHGs). The Kyoto Protocol allowed industrialized countries with GHG reduction obligations to invest in mitigation activities in developing and least-developed countries through the Clean Development Mechanism (CDM). This offer is a beneficial opportunity for agroforestry practitioners, especially resource-poor farmers (Nair *et al.*, 2009) [78].

The Intergovernmental Panel on Climate Change (IPCC, 2007) [33] emphasized in its special report that the restoration of wastelands and grasslands to agroforestry systems holds very high potential for absorbing atmospheric CO_2, besides other direct advantages. Because CO_2 accounts for around 77% of the total anthropogenic GHG emissions, lowering the concentration of CO_2 in the atmosphere is very important. Carbon sequestration is the process of capturing CO_2 from the atmosphere and sequestering it for the long term using natural processes (e.g., vegetation and soil) or engineered methods (Schrag, 2007) [98]. Of all the natural processes, agroforestry is a useful method that contributes to carbon sequestration, climate change mitigation, and adaptation at the same time. Although agroforestry systems (AFS) are not deliberately cultivated to sequester carbon, several recent research papers provide ample evidence of their functioning as carbon captors and storers in aboveground biomass (Murthy *et al.*, 2013) [70] as well as belowground biomass (Nair *et al.*, 2009) [78].

Carbon sequestration by cropping system

The carbon sequestration potential in different cropping systems in India is different based on the nature of the system and management practices (Srinivasarao *et al.*, 2020) [105]. Monoculture, mixed cropping, agroforestry, and integrated systems have different capacities to trap and store carbon in soils and plant biomass (Fahad *et al.*, 2022) [23].

Agroforestry systems, for instance, have a very high carbon sequestration potential because of the integration of trees, crops, and occasionally livestock (Murthy *et al.*, 2013) [71]. These systems can sequester carbon above and below the ground, raising soil organic matter considerably. In the same manner, systems involving the integration of crops with livestock (such as silvopastoral systems) can also sequester carbon because the incorporation of organic matter from both plant and animal origins improves soil fertility and allows for improved carbon retention (Mayer *et al.*, 2022) [63].

Conservation agriculture like no-till, crop rotation, and cover cropping also contribute to the enhancement of soil organic carbon by minimizing soil disturbance and enhancing decomposition of organic matter (Francaviglia *et al.*, 2023) [25]. In contrast, intensive monoculture cropping systems generally have lower carbon sequestration capacity as a result of lower soil organic matter and higher carbon emissions from activities like tillage and chemical fertilization (Jarecki *et al.*, 2003) [39].

In general, tree and other perennial-based diversified cropping systems, as well as minimum soil disturbance practices, are better at increasing carbon sequestration in Indian agro-ecosystems. These systems can play a significant role in mitigating climate change by sequestering large quantities of atmospheric carbon dioxide (Dhyan *et al.*, 2016) [20].

Table 5: Carbon sequestration by different cropping system in India

Cropping system	Carbon sequestration(Mg/ha/yr)		References
	NPK	INM	
Rice-Wheat	0.22	0.34	Ghosh *et al.* (2009) [38]
Rice-Wheat	0.15	0.05	Mandal *et al.* (2007) [86]
Rice-Wheat	0.07	0.11	Yadav *et al.* (2000) [174]
Rice-Wheat	0.34	0.11	Yadav *et al.* (2000) [174]
Rice-Wheat	0.13	0.18	Prasad and Sinha, (2000) [125]
Rice-Wheat	0.17	0.05	Yadav *et al.* (2000) [174]
Rice-Wheat	0.10	0.03	Yadav *et al.* (2000) [174]
Rice-Wheat	0.05	0.45	Yadav *et al.* (2000) [174]
Rice-Wheat	0.04	0.06	Yaduvanshi and Swarup (2005) [175]
Rice-Rice	0.26	0.04	Nayak *et al.* (2009) [113]
Rice-Lentil	0.12	0.15	Srinivasarao *et al.* (2012) [153]
Rice-Mustard-Sesame	0.56	0.06	Mandal *et al.* (2007) [86]
Rice-Berseem	0.04	0.09	Majumdar *et al.* (2008) [84]
Rice-Wheat-Jute	0.07	0.05	Manna *et al.* (2005) [87]
Soybean-Wheat	0.10	0.29	Kundu *et al.* (2007) [74]
Soybean-Wheat	0.06	0.01	Manna *et al.* (2005) [87]
Soybean-Wheat	0.14	0.14	Behra *et al.* (2007) [16]
Soybean-Wheat-Maize	0.02	0.12	Hati *et al.* (2007) [43]
Maize-Wheat	0.04	0.40	Sharma *et al.* (1998) [144]
Maize-Wheat-Cowpea	0.06	0.31	Rudrappa *et al.* (2006) [137]
Maize-Chickpea	0.02	0.02	Vineela *et al.* (2008) [168]
Sorghum-Wheat	0.26	0.31	Manna *et al.* (2005) [87]
Sorghum-Castor	0.11	0.28	Sharma *et al.* (2005) [143]
Cotton-Sorghum	0.31	0.23	Venugopalan and Pundrikakshud (1998) [165]
Finger millet-Maize- Cowpea	0.10	0.10	Murugappan *et al.* (1998) [98]
Cassava	0.60	0.58	John *et al.* (1998) [56]
Pearlmillet	0.06	0.05	Srinivasarao *et al.* (2009) [152]

(Source, Dhyan *et al.*, 2016) [20]

Soil carbon sequestration

Soil carbon sequestration in agroforestry systems is an extremely effective approach to climate change mitigation (Ghale *et al.*, 2022) [26]. Agroforestry, which combines trees, crops, and occasionally livestock on the same land, enhances the sequestration of carbon in soils through several mechanisms (Shi *et al.*, 2018) [100].

Tree species in agroforestry add more organic matter to the soil. Since trees lose their leaves, twigs, and roots, and these decay adding organic carbon content to the soil, soil structure and fertility is improved with good conditions for the microbial processes, which promote sequestration of carbon Lorenz, and Lal, 2014) [61]. The large root systems of trees in agroforestry systems extend deeper into the ground, sequestering carbon below the ground. The deep roots also inhibit soil erosion and allow for the upward transport of nutrients, which can improve overall soil health and carbon storage (Usharani *et al.*, 2019) [110]. Agroforestry systems tend to enhance the supply of nutrients by recycling organic matter (Sileshi *et al.*, 2020) [102]. Some tree species have the ability to fix nitrogen in the soil, further improving the growth of crops and other vegetation, enhancing the overall carbon sequestration capacity (Koutika *et al.*, 2021) [51]. Agroforestry minimizes the use of extensive tillage, which tends to disturb soil organic carbon pools. Through less disturbance to the soil, these systems conserve the carbon that is already in the soil (Baah-Acheamfour *et al.*, 2014) [12]. Tree cover in agroforestry benefits moderates temperature and soil moisture, thereby maintaining an environment ideal for the sequestration of carbon. An enhanced microclimate facilitates both soil microbial activity responsible for sequestrating carbon and plant development (Lasco *et al.*, 2014) [58]. The carbon sequestered in the wood of trees and in the soil can be kept stored for long durations, particularly in well-designed agroforestry systems. With time, the gradual buildup of organic matter contributes to a stable carbon pool (Sahoo *et al.*, 2022) [96]. Certain agroforestry practices including alley cropping, silvopasture, and riparian buffers sequester high amounts of soil carbon (Udawatta *et al.*, 2017) [108]. These practices involve integrating trees with crops or livestock, which increase carbon storage in plant biomass and soil (Lal, 2020) [57]. Overall, agroforestry systems not only present a sustainable option for soil carbon sequestration increase but also present several co-benefits such as biodiversity conservation, increased water retention, and enhanced agricultural productivity (Fahad *et al.*, 2022) [23]. Therefore, they are a key tool in the fight against climate change globally.

Table 6: Soil carbon sequestration through agroforestry

Region	Agroforestry system	Tree species	No. of trees/ha	Age (year)	CSP (Mg C/ha/yr)	References
Himalaya	Block plantation	Eucalyptus, Oak etc.		21	0.6-3.98	Devi *et al.* (2013) [26]
Indo-	Agrisilviculture	*Populus deltoides*	38		0.513	Ajit *et al.* (2014) [6]
Gangetic			357	6	1.95	Gupta *et al.* (2009) [41]
			357	6	2.63	
			740	7	1.62	Chauhan *et al.* (2010) [16]
Humid and	Block plantation	*Gmelina arborea*			1.6-2.8	Swamy *et al.* (2003) [155]
Sub-humid		*Ceiba pentandra*			1.3-3.4	
Tropical		*Acacia mangium*	5000	6.5	1.09	Kunhamu *et al.* (2011) [75]
			2500	6.5	1.53	
			1250	6.5	0.36	
			625	6.5	0.82	
All India	Various AFS	Miscellaneous trees	2-51	30	0.003-0.513	Ajit *et al.* 2014(in press) [6]
(All agroclimates)						

Source, Dhyan *et al.*, 2016) [20]

Agroforestry Adaptation to Climate

Agroforestry is an important climate adaptation strategy with several ecological and economic advantages that increase the resilience of agricultural landscapes (Viñals *et al.*, 2023) [114]. Agroforestry combines trees with crops and livestock, enhancing soil health, water retention, and biodiversity, which enables farming systems to resist the negative impacts of climate change (Vinodhini *et al.*, 2023) [115]. Trees offer shade, which lowers heat stress for crops and livestock while reducing evapotranspiration losses, thus enhancing water use efficiency (Jose *et al.*, 2009) [41]. The availability of tree cover with deep roots improves soil structure, avoids erosion, and enhances soil organic matter, leading to better nutrient availability and microbial diversity, the key drivers of plant resilience to floods and droughts (Raheem *et al.*, 2025) [91].

Agroforestry also helps manage microclimates by buffering against temperature extremes and minimizing the effects of extreme climatic events including storms, flash floods, and extended dryness (Muschler, 2016) [72]. Tree-based systems, functioning as windbreaks, reduce wind speed, which shields the crops from lodging and drying up. Agroforestry further recharges the groundwater and safeguards watersheds by minimizing runoff and enhancing rates of infiltration (Singh *et al.*, 2024) [103].

From a financial point of view, agroforestry systems diversify farmers' sources of income through the generation of timber, fuelwood, fodder, fruits, nuts, medicinal plants, and non-timber forest products (Amusa *et al.*, 2024) [8]. Economic diversification of this nature minimizes farmers' exposure to climate-related crop failures and market fluctuations, leading to a more secure livelihood. Integrated agroforestry systems can also act as carbon offset programs, offering farmers economic incentives in the form of carbon credit mechanisms (Lokuge, and Anders, 2022) [60].

Inclusion of agroforestry in climate adaptation is not only boosting agricultural sustainability but also supporting ecosystem restoration in the long term. By promoting mutual benefits between environmental conservation and agricultural productivity, agroforestry offers a nature-based solution for meeting the threats of climate change while ensuring food, income, and ecological stability for generations to come (Gupta *et al.*, 2024) [27].

Opportunities and Challenges

Adoption of agroforestry is constrained by a number of challenges, in spite of its many economic and ecological advantages. Land tenure insecurity is a great constraint where the uncertainty about the ownership of and rights over the land keeps the farmers away from long-term investments in tree-based systems. Besides, poor technical knowledge and inadequate awareness regarding the practice of agroforestry keeps farmers away from its efficient implementation and maintenance. Inadequate extension services and poor training packages further widen the gap, hampering the adaptation of small-scale farmers to conventional farming to adopt integrated agroforestry measures.

Exorbitant initial investment charges and the many years trees need to mature before they start benefiting farmers create monetary constraints, primarily for poor resource farmers. Poor economic rewards for immediate consumption suppress adoption, where farmers value fast productivity more than long-term productivity. In addition, the availability of quality planting material, correct agroforestry species, and finance remains low in much of the landscape, which otherwise limits agroforestry scaling.

Institutional and policy barriers also contribute significantly to the slow adoption of agroforestry. Ineffective policy environments, poor financial incentives, and lack of agroforestry incorporation in national agricultural and climate policy hinder full adoption. Government assistance through subsidies, tax benefits, and market connections for agroforestry goods can help augment farmer investment and participation in these systems.

Widespread challenges notwithstanding, there are various opportunities to enhance agroforestry adoption. Improvements in agroforestry science, enhanced tree-crop-livestock integration methods, and new financing mechanisms like carbon credits and payment for ecosystem services (PES) can encourage farmers. Institutional support, capacity-building initiatives, and farmer cooperatives can facilitate knowledge sharing and technical skills training. Moreover, incorporating agroforestry into national climate plans and land restoration initiatives can offer policy support and economic incentives, making agroforestry a sustainable and scalable option for carbon sequestration and climate resilience.

Conclusion

Agroforestry is a very efficient and sustainable approach to carbon sequestration and climate adaptation with a variety of ecological, economic, and social advantages. Through the integration of trees with crops and livestock, agroforestry promotes biodiversity, increases soil quality, and enhances agricultural resilience to climate change. Agroforestry is an important nature-based solution that not only tackles climate change by capturing carbon but also maintains sustainable production of food and ecosystem resilience.

Though it has great potential, extensive use of agroforestry is hindered by land tenure insecurity, poverty, and inadequate technical knowledge. These obstacles can be overcome with the help of favorable policies, economic incentives, capacity-building, and technology improvement. It is essential to overcome these obstacles for large-scale agroforestry practice worldwide. Governments, researchers, and private sector actors have to work together to mainstream agroforestry in climate action plans and land-use planning.

Future studies must focus on maximizing tree-crop-livestock integration, improving carbon quantification methods, and evaluating the long-term socio-economic effects of agroforestry. In addition, enhancing market access for agroforestry products and carbon credit systems can make it more economically viable for farmers. Through the application of scientific innovation, policy support, and community involvement, agroforestry can become a revolutionary strategy for meeting climate challenges, ensuring food security, and supporting environmental sustainability for generations to come.

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