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Evaluation of agroforestry systems for carbon sequestration in Konkan Region

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Abstract
Agroforestry, a nature-based solution offers multifaceted benefits for sustainable development and climate change mitigation. Major objective of this study was to explores and evaluates the agroforestry systems for carbon sequestration in Konkan Region of Maharashtra state. Present study was conducted at the Research Farm of the AICRP on Agroforestry, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Dist Ratnagiri, in the year 2024. The highest carbon stock, carbon sequestration and carbon credits was was recorded in T_6 - Mango based AFS which was 126.35 t/ha, 463.70 t/ha and 463.70 credit/ha respectively and lowest was reported in T_2 - Malabar neem based AFS with 4.68 t/ha,17.17 t/ha and 17.17 credits/ha respectively. The study concludes that agroforestry systems, especially those involving Mango, Coconut, Asana, bamboo, and economically, it offers farmers an incentive to adopt sustainable practices through access to carbon markets for agroforestry farmers of the region. Strategic species selection, proper spacing, and management practices are essential to optimize both productivity and climate mitigation benefits.

Keywords: Agroforestry systems, carbon sequestration, carbon stock, carbon credits, climate change mitigation

Introduction
Climate change, caused by the increasing concentration of greenhouse gases (GHGs) such as carbon dioxide (CO_2) in the atmosphere, has emerged as one of the most critical global challenges of the 21st century. Among various strategies to mitigate climate change, carbon sequestration, the process of capturing and storing atmospheric carbon, plays a pivotal role (IPCC, 2021). Agroforestry, a nature-based solution, offers multifaceted benefits for sustainable development and climate change mitigation. It enhances farmers' adaptive capacity to climate change while delivering ecological, social, and economic advantages (Telwala, 2022) [37].

Agroforestry systems act as carbon sinks through the accumulation of biomass in above-ground (trees, crops) and below-ground (roots) components, as well as through the enhancement of soil organic carbon (Nair *et al.*, 2009; Montagnini & Nair, 2004) [29, 25]. These systems are recognized for their potential to mitigate climate change, improve land productivity, enhance biodiversity, and strengthen livelihood resilience, especially in tropical and subtropical regions (Jose, 2009) [17]. However, the carbon sequestration potential of agroforestry systems varies depending on species composition, tree density, age, soil type, climatic conditions, and management practices (Nair, 2011) [28].

Agroforestry in India is increasingly recognized for its role in enhancing sustainable agriculture, rural livelihoods, and climate resilience. According to estimates, about 25.32 million hectares, or approximately 8.2% of the total geographical area, are under agroforestry practices (Dhyani & Handa, 2013) [8]. Maharashtra is among the leading states in India for agroforestry adoption, with an estimated 1.61 million hectares area under agroforestry (Panwar *et al.*, 2022) [32]. The state practices diverse agroforestry systems tailored to its varied agro-climatic zones, from the semi-arid Deccan Plateau to the humid Konkan coast (Ilorkar *et al.*, 2011) [13]. The Maharashtra State Forest Policy (2008) targets increasing tree cover to 33%, encouraging tree planting on private farmlands and non-forest lands.

The National Agroforestry Policy (NAP) of 2014 aims to promote agroforestry through improved quality planting material, tree insurance, simplified regulations, and enhanced marketing opportunities (Chavan *et al.*, 2015) [3]. It recognizes agroforestry's potential to achieve agricultural sustainability, optimize productivity, and mitigate climate change impacts (GOI, 2015). Agroforestry is also a significant element of India's Nationally Determined Contributions (INDCs) under the Paris Agreement, which are designed to establish an additional carbon sink of 2.5 to 3.0 billion tonnes of CO_2 equivalent per year through forest and tree cover by 2030 (UNFCCC, 2015). Further, afforestation and tree-based systems for climate mitigation are highlighted by the National Action Plan on Climate Change (NAPCC) through the Green India Mission.

Studying carbon stock and carbon credits in agroforestry is important for multiple reasons. Environmentally, it helps quantify the potential of agroforestry to mitigate greenhouse gas emissions and supports the development of climate-resilient land-use systems. Economically, it offers farmers an incentive to adopt sustainable practices through access to carbon markets. From a policy perspective, it provides scientific data that supports national and international climate commitments, such as India's National Agroforestry Policy (2014) and its Nationally Determined Contributions (NDCs) under the Paris Agreement. Thus, the assessment of carbon stock and understanding of carbon credit mechanisms are crucial for promoting agroforestry as a sustainable land-use option that integrates ecological, economic, and climate goals.

Materials and Methods

The study was conducted during 2024-25 at the Research Farm of the AICRP on Agroforestry, Central Experimental Station, Wakawali, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Ratnagiri (Maharashtra). The experimental site lies in the humid Konkan region (17º 45' N and 73º 26' E longitude having an elevation of 250 meters above mean sea level), characterized by lateritic soils derived from basalt, with >4000 mm annual rainfall and mean temperature ranging between 11-37°C. The experiment was laid out in a Randomized Block Design (RBD) with eight agroforestry treatments and three replications:

Initial status of experiment

The experiment was conducted on a well-established block plantation of selected agroforestry tree species at the Central Experimental Station, Wakavali, under the AICRP on Agroforestry. The details of block plantation in respect to year of plantation, age, row to row and plant to plant spacing is mentioned in Table 1 During the investigation year 2024-25, annual intercrops were freshly sown under agroforestry system to evaluate biomass accumulation and carbon sequestration potential of trees and intercrops.

Table 1: Details of block plantation

Treatments	Tree component under AF	Spacing (m)	Year of plantation	Age of plantation (Years)
T_1	*Bridelia retusa*	10 x 5	2013	12
T_2	*Melia dubia*	5 x 5	2022	3
T_3	*Dendrocalamus stocksii*	10 x 10	2007	18
T_4	*Santalum album*	5 x 5	2013	12
T_5	*Melia dubia*	10 x 5	2015	10
T_6	*Mangifera indica*	10 x 10	2004	21
T_7	*Anacardium occidentale*	10 x 10	2006	19
T_8	*Cocus nucifera*	10 x 10	1999	26

Tree growth parameters (height, DBH, crown spread, and density) were recorded. Tree biomass was estimated using species-specific volume/allometric equations (ISFR, 2021; Chave *et al*., 2014; Kaushal *et al*., 2016) [4, 19]. Wood density values from literature were used, and a biomass expansion factor (BEF) of 1.3 was applied. Below-ground biomass was assumed to be 25% of above-ground biomass (IPCC, 2006). Intercrop biomass was measured destructively from 1 m^2 plots by drying and weighing shoot and root components. Tree carbon stock was calculated using 0.50 × total dry biomass, while intercrop carbon content was estimated by the ash method. The total CO_2 sequestration was obtained by multiplying carbon stock by 3.67. Carbon credits were computed as 1 t CO_2 = 1 carbon credit, valued at $20 (₹1500) per credit as per market rate (Kumar *et al*., 2024) [20]. Data on biomass, carbon stock, carbon sequestration, and carbon credits were statistically analyzed using ANOVA as per Gomez and Gomez (1984) [12].

Results and Discussion

Biomass, Carbon stock and Carbon sequestration by intercrop

Total intercrop biomass (sum of shoot and root biomass) was significantly affected by the agroforestry systems. The highest total biomass was recorded in T_8 - Coconut based AFS (7.98 t/ha), and Lowest total biomass values were recorded in T_4 - Sandal based AFS (1.69 t/ha) (Table 2).

The carbon stock in intercrops under different agroforestry systems varied significantly depending on species combination and biomass allocation. The maximum carbon stock was recorded under T_8 - Coconut based AFS (Coconut + Turmeric) with 4.12 t/ha, while the lowest total carbon stock was recorded in T_4 - Sandal based AFS (Sandal + Jackfruit) 0.86 t/ha. The significantly maximum carbon sequestration in the intercrop was 15.13 t/ha observed under T_8 Coconut based AFS (Coconut + Turmeric) and the lowest carbon sequestration was found in T_4 Sandal based AFS (Sandal + Jackfruit) 3.14 t/ha. Shinde *et al*., 2020 [35]; Kumar (2019) [22] and Bhagya *et al*. (2017) [1], who observed that improved intercrop performance in coconut-based systems due to better light availability and nutrient cycling. Similar findings were also reported by Swamy *et al*. (2015); Ramesh *et al*. (2013) who reported maximum carbon sequestration by turmeric under agroforestry system. In contrast, the lowest total biomass (t/ha), carbon stock and carbon sequestration among all the intercrop has been reported in jackfruit (T_4 - Sandal based AFS) due to young age of jackfruit, dense tree canopies, root competition. Sandalwood, being semi-parasitic, competes with intercrops for nutrients and water. Tree age significantly impacts biomass growth and carbon accumulation (Kumar *et al.*, 2022) [23].

Total biomass, Carbon stock and Carbon sequestration by tree

Total tree biomass (TTB), the sum of above and below ground biomass, provides a complete estimate of tree carbon sequestration potential. The values for TTB across agroforestry systems are presented in Table 2. The maximum TTB was recorded in T_6 Mango based AFS with 247.01 t/ha, while the lowest TTB was recorded in T_2-Malabar neem based AFS 2.69 t/ha. The mean data of carbon stock (t/ha) of the tree component through different treatments is presented in Table 2, which revealed that there was considerable variation in the carbon stock under different agroforestry systems. The highest carbon stock was observed in T_6 - Mango based AFS (123.50 t/ha) and the lowest value was recorded in T_2 - Malabar based AFS (1.34 t/ha). Carbon sequestration can be defined as the removal of CO_2 from the atmosphere (source) into green plants (sink), where it can be stored indefinitely. The mean data showed variation in carbon sequestration by trees under different treatments, as presented in Table 2. A critical review of the data showed that carbon sequestration was influenced by the type of agroforestry system and tree species. The maximum carbon sequestration was recorded in T_6 - Mango based AFS (453.26 t/ha), while the minimum was observed in T_4 - Sandal based AFS 4.94 (t/ha). Overall carbon sequestration rate of AF farm unit for tree was calculated as 12.99 t/ha/year.

Among all treatments, the (T_6) recorded the highest biomass, carbon stock and corresponding carbon sequestration due to higher age of plantation. The findings align with and which was more than reported by Ganeshamurthy *et al.* (2019) [9]; Murali *et al.* (2022) [27]; Das *et al.* (2022) [5]; Salunkhe *et al.* (2021) [34]; Nimbalkar *et al.* (2017) [31], who highlighted the high carbon sequestration potential of mango-based systems in the Konkan and Deccan Plateau regions, respectively. In the present study, Malabar neem based AFS (T_2) recorded notably low biomass, carbon stock and sequestration despite Chandana *et al.* (2020) [2]; Gautam *et al.* (2025) [10], Deshmukh *et al.* (2025) [6] and Vasudev *et al.* (2021) [38] reporting higher carbon stocks under well-established *Melia dubia* systems.

Total Carbon stock and carbon sequestration by agroforestry systems

The data presented in Table 2 clearly indicate that carbon stock and carbon sequestration varied significantly among different agroforestry systems, reflecting the influence of tree species, intercrop type, and their interaction. A perusal of the data indicates that the total carbon stock across different agroforestry treatments ranged from 4.68 to 126.35 t/ha. The highest carbon stock was recorded in T_6 - Mango based AFS with 126.35 t/ha. The lowest carbon stock was observed in T_2 - Malabar neem based AFS, with only 4.68 t/ha. Similarly, the total carbon sequestration showed a wider variation, ranging from 17.17 to 280.00 t/ha, with the highest value also noted in T_6 - Mango based AFS. On the other hand, T_2 - Malabar neem based AFS recorded the lowest sequestration value of 17.17 t/ha. The mango based AFS (T_6) has recorded the highest carbon stock, sequestration and carbon credits, confirming its superior performance in biomass accumulation and carbon storage. This aligns with findings by Ganeshamurthy *et al.* (2019) [9] and Murali *et al.* (2022) [27], who emphasized the high carbon storage capacity of mango orchards, particularly in tropical and semi-arid conditions, due to their large canopy spread, extended lifespan, and substantial woody biomass. The present finding on carbon stock (t/ha) is found more than reported by Naik *et al.* (2019), Rathore *et al.* (2021), Rupa *et al.* (2022) and Kumar *et al.* (2023) and found less than reported by Patil *et al.* (2024). The present finding on carbon stock (t/ha) for Malabar neem-based systems (T_2) is found less than reported by Chandana *et al.* (2020) [2], Gautam *et al.* (2025) [10], Deshmukh (2024) [7]. Whereas more or less similar value (4.66 t/ha) is reported by Vasudev *et al.* (2021) [38] in 2-year-old plantation of *Melia dubia*.

Table 2: Total biomass, Carbon stock and Carbon sequestration by intercrop and tree under different agroforestry systems

Treatments	Biomass (t/ha)		Carbon stock (t/ha)			Carbon sequestration (t/ha)		
	Intercrop	Tree	Intercrop	Tree	Total	Intercrop	Tree	Total
T_1-Asana based AFS (Asana + Elephant foot yam)	7.62	129.56	3.79	64.78	68.57	13.92	244.87	258.79
T_2-Malabar neem based AFS (Malabar neem +Turmeric)	6.80	2.69	3.33	1.35	4.68	12.23	4.94	17.17
T_3-Bamboo based AFS (Bamboo + Turmeric)	5.64	97.82	2.78	45.11	47.90	10.21	179.50	189.71
T_4-Sandal based AFS (Sandal + Jackfruit)	1.69	8.04	0.86	88.12	4.88	3.14	14.75	17.90
T_5-Malabar neem based AFS (Malabar neem + Shivan)	4.31	176.24	2.20	4.02	90.32	8.08	323.39	331.47
T_6-Mango based AFS (Mango + Turmeric)	5.68	247.01	2.85	123.50	126.35	10.45	453.26	463.70
T_7-Cashew based AFS (Cashew + Turmeric)	7.38	68.56	3.74	34.28	38.02	13.73	125.81	139.54
T_8-oconut based AFS (Coconut + Turmeric)	7.98	144.34	4.12	72.17	76.29	15.13	264.86	280.00
Mean	5.89	109.28	2.96	54.17	57.13	10.86	201.42	212.29
SE±	0.53	9.28	0.31	5.03	5.03	1.14	17.10	17.15
CD.at 5%	1.62	28.15	0.95	15.26	15.26	3.47	51.88	52.04
CV%	15.70	14.71	18.23	16.08	15.25	18.23	14.71	14.00

Carbon credits accrued under agroforestry systems

In this study, however, carbon stock was already converted to CO_2 equivalent (t/ha), so the CO_2 values were directly interpreted as carbon credits. The carbon credit potential varied significantly among the agroforestry systems (AFS) evaluated (Table 3). The highest carbon credits per hectare were observed in the T_6 - Mango based AFS with 463.70 carbon credits/ha, and lowest was observed in T_2 - Malabar neem based AFS (17.17 credits/ha).The corresponding financial value of carbon credits also followed the same trend, with the highest monetary return recorded in T_6 - Mango based AFS (₹810825.82/ha), The lowest values were seen in T_2 - Malabar neem based AFS (₹30023.46/ha).

Table 3: Carbon credits accrued under agroforestry systems

Treatment	Total CO_2 (t/ha)	Carbon credits/ha	Value (US$/ha)	Value (₹/ha)
T_1-Asana based AFS (Asana + Elephant foot yam)	258.79	258.79	5175.80	452520.19
T_2-Malabar neem based AFS (Malabar neem +Turmeric)	17.17	17.17	343.40	30023.46
T_3-Bamboo based AFS (Bamboo + Turmeric)	189.71	189.71	3794.20	331726.91
T_4-Sandal based AFS (Sandal + Jackfruit)	17.90	17.90	358.00	31299.94
T_5-Malabar neem based AFS (Malabar neem + Shivan)	331.47	331.47	6629.40	579608.44
T_6-Mango based AFS (Mango + Turmeric)	463.70	463.70	9274.00	810825.82
T_7-Cashew based AFS (Cashew + Turmeric)	139.54	139.54	2790.80	243999.64
T_8-Coconut based AFS (Coconut + Turmeric)	280.00	280.00	5600.00	489608.00

Conclusion

The study demonstrates that agroforestry systems possess strong potential for carbon sequestration, driven by factors such as species selection, plantation age, canopy structure, rooting pattern, tree density, and intercrop compatibility. Among the evaluated systems, Mango-based AFS (T_6) showed the highest carbon stock, sequestration rate, and carbon credit generation, while Coconut (T_8) and Asana (T_1) also contributed substantially through intercrop performance and belowground biomass. Bamboo-based AFS (T_3) supported both turmeric yield and carbon capture, whereas the comparatively lower performance of younger Malabar neem plantations (T_2) highlighted the critical role of plantation maturity, with older Melia-based systems (T_5) exhibiting improved biomass accumulation. Turmeric performed consistently well as an intercrop across systems, indicating its suitability for the Konkan region. The results further confirm that carbon sequestration increases with tree age, diameter, and optimal spacing. Overall, the study underscores that well-planned agroforestry, supported by appropriate species combinations and site-specific management, can significantly contribute to India's INDC targets while providing considerable financial returns through carbon trading and enhancing long-term sustainability in land-use systems.

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