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PRELIMINARY STUDY ON CARBON STOCK OF CACAO AGROFORESTRY IN SEMI ARID REGION OF EASTERN INDONESIA

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ABSTRAK

Penelitian mengenai biodiversitas vegetasi dan estimasi cadangan karbon menjadi semakin penting seiring meningkatnya perhatian global terhadap perubahan iklim dan kebutuhan akan pengelolaan pertanian berkelanjutan di kawasan tropis kering. Meskipun demikian, kajian tentang sistem agroforestri berbasis kakao di Indonesia bagian timur, khususnya yang berkaitan dengan struktur vegetasi dan potensi penyimpanan karbon, masih tergolong terbatas. Penelitian ini bertujuan untuk mengidentifikasi pola sebaran vegetasi serta mengestimasi cadangan karbon pada sistem agroforestri berbasis kakao di wilayah Indonesia timur. Metode yang digunakan adalah studi literatur dengan menelaah berbagai hasil penelitian mengenai karakteristik agroforestri kakao, terutama terkait komposisi vegetasi, struktur tegakan, dan total simpanan karbon. Analisis data dilakukan secara deskriptif kuantitatif menggunakan data sekunder berupa biomassa vegetasi dan karbon organik tanah. Hasil penelitian menunjukkan bahwa sistem agroforestri berbasis kakao dalam kajian ini memiliki total simpanan karbon sebesar 56,9 ton/ha. Sebaran vegetasi pada sistem agrisilvikultur mendominasi sebagian besar lokasi penelitian, yang tercermin dari tingginya nilai Indeks Nilai Penting (IVI) pada jenis *Swietenia mahagoni*. Dominasi tersebut terutama ditemukan pada tingkat tiang dan dipengaruhi oleh kondisi ekologis serta pola pengelolaan vegetasi di wilayah semi-kering. Temuan ini mengindikasikan bahwa pengaturan komposisi tanaman penaung memiliki peranan penting dalam meningkatkan fungsi ekologis sekaligus kapasitas penyimpanan karbon pada sistem agroforestri berbasis kakao.
Kata Kunci: *Biodiversitas, Simpanan Karbon, Perubahan Iklim, Indonesia Timur*

ABSTRACT

Studies on vegetation biodiversity and carbon stock estimation are becoming increasingly significant in response to global climate change concerns and the growing demand for sustainable agricultural management in tropical drylands. Nevertheless, research focusing on cocoa-based agroforestry systems in eastern Indonesia, particularly related to vegetation structure and carbon sequestration potential, is still relatively scarce. This study was conducted to examine vegetation distribution and estimate carbon stocks within cocoa-based agroforestry systems in eastern Indonesia. A literature review method was applied by analyzing previous studies concerning the characteristics of cocoa agroforestry, especially vegetation composition, stand structure, and total carbon storage. The analysis used a descriptive quantitative approach based on secondary data of vegetation biomass and soil organic carbon. The findings revealed that the cocoa-based agroforestry systems evaluated in this study stored approximately 56.9 tons ha^{-1} of carbon. Vegetation distribution in the agrisilvicultural system dominated most of the study sites, as reflected by the highest Important Value Index (IVI) recorded for *Swietenia mahagoni*. This dominance was primarily observed at the pole stage and was closely associated

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with ecological conditions and vegetation management practices in semi-arid environments. These results suggest that proper management of shade-tree composition plays a crucial role in improving ecological functions and increasing carbon storage capacity in cocoa-based agroforestry systems.
Keywords: *Biodiversitas, Carbon Stock, Climate Change, Eastern Indonesia*

INTRODUCTION

Cacao (*Theobroma cacao* L.) is native to the tropical regions of South America, especially the upper Amazon basin, which is considered the center of its early domestication (Jaimez et al., 2022). The species belongs to the genus *Theobroma* in the Malvaceae family (Abdullah et al., 2021). As an evergreen tree, cacao can grow between 6 and 12 meters in height and commonly develops as an understory plant in tropical forest ecosystems (Cook, 2024). Its cultivation is geographically restricted to areas within approximately 20° north and south of the equator, widely known as the "cocoa belt" (Cocoterra, 2024). According to Dillinger et al., cacao plantations are spread across equatorial regions covering more than 70,000 km² globally. This distribution pattern remains relevant today, with nearly 70% of world cocoa production originating from West Africa, while the rest is produced in Latin America and tropical Asia (ICCO, 2024; Goñas et al., 2025). Indonesia is among the leading cocoa-producing countries, contributing around 14.26% of global cocoa output (ICCO, 2024). Cocoa is extensively used in the manufacture of chocolate products, both solid and liquid, as well as in a wide range of food and beverage industries (Wiati et al., 2025).

In Indonesia, cocoa cultivation is generally practiced through monoculture and agroforestry systems. Since cacao is naturally shade-tolerant and adapted to grow beneath tropical rainforest canopies, agroforestry systems are considered more compatible with its ecological and physiological needs. Besides reducing excessive sunlight exposure, this cultivation system also enhances soil quality through interactions among plants, root systems, and soil microorganisms (Schmidt et al., 2022). Furthermore, cocoa-based agroforestry can increase biomass production and improve nutrient cycling, thereby supporting sustainable land productivity and long-term ecosystem stability (Addo-Danso et al., 2024).

In the face of climate change, cocoa-based agroforestry systems play an important role in carbon sequestration and storage, both in aboveground biomass and soil, thereby helping reduce carbon emissions (Goñas et al., 2022; Gnagbo et al., 2024). The capacity of these systems to store carbon is affected by several factors, including plant age, developmental stage, vegetation density, and the species of shade trees applied. Research conducted in Ghana revealed that 15-year-old *Theobroma cacao* plantations under agroforestry systems stored 52.6 Mg C ha^{-1}, whereas monoculture plantations stored only 5.73 Mg C ha^{-1} (Afele et al., 2021). Comparable findings were also reported in the Democratic Republic of Congo, where carbon stocks ranged between 23.8 and 56.6 Mg C ha^{-1} (Batsi et al., 2021). In the Ecuadorian Amazon, cacao plantations aged three years sequestered 1.2–3.6 Mg C ha^{-1} in agroforestry systems, exceeding monoculture systems that accumulated only 1.1 Mg C ha^{-1} (Tinoco-Jaramillo et al., 2024). Likewise, cocoa agroforestry systems in the Peruvian Amazon aged 8–15 years and 30–40 years stored 13.6 and 24.9 Mg C ha^{-1}, respectively (Goñas et al., 2022). Overall, these studies consistently demonstrate that agroforestry systems possess greater carbon storage potential than monoculture cultivation systems.

Despite the growing number of studies on carbon stocks in cocoa-based agroforestry systems worldwide, related research in Indonesia, especially in East Nusa Tenggara, is still relatively scarce. This region possesses unique agroecosystem conditions, including lower

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rainfall intensity and land that is more susceptible to degradation. In addition, differences in the composition of shade tree species within agroforestry systems may affect carbon storage capacity, yet information regarding this factor remains limited. These conditions highlight an important research gap that requires further investigation within the local context.

Based on the aforementioned background, this research seeks to estimate carbon stocks in cocoa-based agroforestry systems in Sikka Regency, East Nusa Tenggara Province, Indonesia, by taking into account the variation of shade tree species used within the systems. Variations in shade tree composition are presumed to affect the capacity of ecosystems to store carbon, both in aboveground biomass and other ecological components. Accordingly, this study not only quantifies carbon stocks but also evaluates the contribution of vegetation composition to strengthening the ecological functions of agroforestry systems. The findings are expected to provide scientific insight for the sustainable management of agroforestry practices, particularly in determining suitable shade tree species. Furthermore, the study is anticipated to support climate change mitigation strategies through enhanced carbon sequestration and storage in agricultural landscapes.

RESEARCH METHODOLOGY

This study applied a literature review method by examining a range of previous studies concerning the contribution of agroforestry systems and the factors affecting their successful implementation. The research relied on secondary data obtained from relevant scientific journal articles. Data collection was conducted through searches in journal databases, followed by a screening process based on the relevance of article titles, abstracts, and full contents to the research objectives. The selected articles were subsequently analyzed to gather information on vegetation characteristics and carbon stocks in cocoa-based agroforestry systems.

Secondary data were used in this research because of limitations in collecting primary data directly from the study site. The selection of these data was based on their high relevance and similarity to the characteristics of the research area. The analyzed information included vegetation composition and structure in cocoa agroforestry systems from West Nusa Tenggara, along with soil organic carbon data from Ende Regency, East Nusa Tenggara Province. These datasets were employed to support carbon stock estimation in cocoa-based agroforestry systems. Data analysis was conducted using a quantitative descriptive approach by estimating soil carbon stocks from available secondary data parameters, including bulk density, soil sampling depth, and soil organic carbon content. The calculation of soil carbon stocks was carried out using these variables, while the formula applied in this study is shown in Table 1.

Table 1. Soil Carbon Calculation Formula

Calculation Stage	Formula	Symbol	Description
Soil carbon calculation (g/cm^2)	Cs = Bd × Sd × %C-organic	Cs	Soil carbon (g/cm^2)
		Bd	Bulk density (g/cm^3)
		Sd	Soil sampling depth (cm)

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		%C-organic	Soil organic carbon content (%)
Conversion to soil carbon stock (ton/ha)	Csoil = Cs × 100	Csoil	Soil carbon stock (ton/ha)
		Cs	Soil carbon (g/cm²)

Source: Yulnafatmawita & Yasin (2018); Suich et al. (2017)

RESULT AND DISCUSSION

Result

The provinces of West Nusa Tenggara (NTB) and East Nusa Tenggara (NTT) encompass approximately 6.6 million hectares, with around 95% of the area categorized as drylands characterized by annual rainfall below 2,000 mm and prolonged dry seasons lasting 5–8 months. This study was conducted to identify the biophysical characteristics and determine the main challenges of dryland agricultural development in both provinces. Biophysical land assessments were carried out, and soil samples were analyzed to evaluate their physical and chemical properties.

Overall, soil fertility in these regions was considered relatively good, as reflected by neutral to alkaline soil pH, moderate to high levels of total phosphorus (P) and potassium (K), high cation concentrations, elevated cation exchange capacity, and high to very high base saturation. Nevertheless, several areas in Southwest Sumba and West Sumba showed acidic soil conditions caused by andesitic lava parent material and rainfall exceeding 2,000 mm per year, which increased leaching intensity. Soil texture also played a significant role in determining water availability, since soils with higher sand content tended to have lower capacities to retain water and nutrients. Although the general fertility status was favorable, the soils contained low organic carbon levels, indicating the need for improved soil quality management. Therefore, dryland management in upland areas should emphasize surface water availability and the application of conservation agriculture practices (Suriadi et al., 2021).

These biophysical characteristics underline the importance of suitable vegetation management approaches, especially through agroforestry systems, to enhance soil quality, improve water retention, and sustain ecosystem stability. In this regard, understanding species composition and dominance is essential for evaluating the ecological structure and functions of agroforestry systems. The Important Value Index (IVI) is commonly used as an ecological indicator to determine species dominance and ecological significance within plant communities. This parameter is particularly relevant for assessing the contribution of shade trees in cocoa-based agroforestry systems. In the present study, the data presented in Tables 1, 2, and 3 were utilized to examine the ecological position of cocoa within three agroforestry systems: agrisilviculture, silvopastoral, and silvofishery. Analyzing vegetation composition and species dominance in cocoa agroforestry systems is crucial for understanding ecological structure, shade-tree diversity, and ecosystem functions that support the sustainability of cocoa-based agroforestry practices (Zequeira-Larios et al., 2021).

Based on the analysis of the Important Value Index (IVI), the agrisilvicultural system demonstrated relatively high species diversity with different levels of dominance among species. *Swietenia mahagoni* recorded the highest IVI value within this system. The dominance of mahogany at the pole stage can be explained by ecological and economic considerations. As

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a valuable timber species commonly integrated into agrisilvicultural practices, mahogany growth is highly dependent on nutrient availability. Consequently, farmers in semi-arid areas tend to maintain mahogany as a dominant component because of its significant economic benefits.

In the same agrisilvicultural system, cocoa (*Theobroma cacao* L.) showed a density of 22.22 trees ha^{-1} with an IVI value of 15.82%, which was lower than that of mahogany (45.59%) and coconut (52.45%). The lower dominance of cocoa reflects the typical characteristics of agrisilvicultural systems, where forestry species and food crops are generally prioritized as the primary components. Agroforestry systems with high shade-tree diversity usually possess more complex vegetation structures and are dominated by species that provide both economic value and household needs.

In contrast, the silvopastoral system displayed a substantially higher IVI value for cocoa (85.67%), indicating stronger dominance compared to species such as mahogany (55.53%) and *Gmelina arborea* (52.67%). This strong cocoa dominance suggests a simpler vegetation structure that may enhance production efficiency but potentially decrease ecological complexity. Similarly, the silvofishery system showed a very simple vegetation composition, consisting only of cocoa and *Toona sureni*, both having the same IVI value (150%). Such uniform dominance and low species diversity may weaken ecosystem resilience, especially under dryland conditions (Fisher-Ortíz et al., 2025). These findings further emphasize the differences in vegetation structure and species dominance among the agroforestry systems observed in this study. A more detailed presentation of the vegetation composition, density, frequency, dominance, and Importance Value Index (IVI) at the pole level across the observed agroforestry systems is presented in Table 2.

Tabel 2. Vegetation Analysis On Pole Level

No	Local name	Scientific name	Density		Frequency		Dominance		IVI (%)
			D (stem/ha)	DR (%)	F	FR (%)	D (m^2/ha)	DR (%)	
		Agrisilviculture							
1	Aren	*Arenga pinnata*	7.41	2.38	0.04	2.17	0.09	6.72	11.28
2	Bajur	*Pterospermum javanicum*	3.7	1.19	0.04	2.17	0.11	8.06	11.43
3	Banten	*Lannea coromandelica*	3.7	1.19	0.04	2.17	0.07	5.38	8.74
4	Dao	*Dracontomelon dao*	3.7	1.19	0.04	2.17	0.07	5.38	8.74
5	Jambu Batu	*Psidium guajava*	3.7	1.19	0.04	2.17	0.07	5.38	8.74
6	Jambu Mete	*Anacardium occidentale*	33.33	10.71	0.11	6.52	0.07	5.38	22.61
7	Jati Putih	*Gmelina arborea*	14.81	4.76	0.07	4.35	0.09	6.72	15.83
8	Kakao	Theobroma cacao L	22.22	7.14	0.11	6.52	0.03	2.15	15.82
9	Kelanjuh	*Albizia procera Benth*	3.7	1.19	0.04	2.17	0.11	8.06	11.43
10	Kelapa	*Cocos nucifera*	70.37	22.62	0.41	23.91	0.08	5.91	52.45

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No	Local name	Scientific name	Density		Frequency		Dominance		IVI (%)
			D (stem/ha)	DR (%)	F	FR (%)	D (m^2/ha)	DR (%)	
11	Ketapang	*Terminalia catappa L.*	11.11	3.57	0.11	6.52	0.07	5.38	15.47
12	Mahoni	*Swietenia mahagoni*	77.78	25	0.26	15.22	0.07	5.38	45.59
13	Mangga	*Mangifera indica*	7.41	2.38	0.07	4.35	0.07	5.38	12.11
14	Nyamplung	*Calophylum inophyllum*	3.7	1.19	0.04	2.17	0.04	2.69	6.05
15	Piling	*Adenather apavonina L.*	3.7	1.19	0.04	2.17	0.04	2.69	6.05
16	Sengon	*Albizia chinensis*	18.52	5.95	0.07	4.35	0.07	5.38	15.68
17	Sentul	*Sandoricum koetjape*	3.7	1.19	0.04	2.17	0.07	5.38	8.74
18	Sonokeling	*Dalberga latifolia*	11.11	3.57	0.07	4.35	0.06	4.57	12.49
19	Sropan	*Caesalpinia sappan*	7.41	2.38	0.07	4.35	0.06	4.03	10.76
		Total	311.11	100	1.7	100	1.38	100	300
Silvopastoral									
1	Aren	*Arenga pinnata*	14.29	4.55	0.14	11.11	0.43	25.21	40.87
2	Jambu Mete	*Anacardium occidentale*	14.29	4.55	0.14	11.11	0.14	8.4	24.06
3	Jati Putih	*Gmelina arborea*	42.86	13.64	0.29	22.22	0.29	16.81	52.67
4	Kakao	*Theobroma cacao L.*	157.14	50	0.29	22.22	0.23	13.45	85.67
5	Kelapa	*Cocos nucifera*	28.57	9.09	0.14	11.11	0.36	21.01	41.21
6	Mahoni	*Swietenia mahagoni*	57.14	18.18	0.29	22.22	0.26	15.13	55.53
		Total	314.29	100	1.29	100	1.7	100	300
Silvofishery									
1	Kakao	Theobroma cacao L.	33.33	50	0.33	50	0.67	50	150
2	Surren	*Toona sureni*	33.33	50	0.33	50	0.67	50	150
		Total	66.67	100	0.67	100	1.33	100	300

At the sapling stage within the agrisilvicultural system, cocoa showed a density of 59.26 trees ha^{-1} with an IVI value of 37.89%, which was lower than that of the saga tree (*Adenanthera pavonina*) with an IVI of 44.73%. This condition suggests intense competition for light and growing space that may restrict cocoa development. Such findings highlight the importance of managing species composition in agroforestry systems. Although diversified organic cocoa agroforestry systems contribute significantly to biodiversity conservation, the dominance of highly competitive species can diminish both ecological functions and production performance. Therefore, species such as *Adenanthera pavonina* should be carefully managed to prevent

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excessive dominance, since the composition and characteristics of shade trees strongly affect light competition, nutrient availability, productivity, and the sustainability of cocoa agroforestry ecosystems (Asitoakor et al., 2022). In the silvopastoral system, cocoa exhibited clear dominance with a density of 228.57 trees ha^{-1} and an IVI of 69.70%, reflecting strong regeneration capacity. This density aligns with multistrata agroforestry systems, which can support more than 1,000 trees per hectare, indicating that vegetation density is highly influenced by the agroforestry model applied (Santhyami et al., 2020).

A notable pattern was observed in the silvofishery system at the sapling stage, where Arabica coffee (Coffea arabica) became the dominant species with an IVI of 138.1%, whereas cocoa reached only 61.9%. This shift in dominance demonstrates that coffee functions as a strong competitor within agroforestry and secondary forest environments. Coffee-based agroforestry systems are recognized for their high adaptability under shaded conditions and their capacity to alter vegetation structure and composition through competition for light, space, and soil resources (Koutouleas et al., 2022). These findings are consistent with the vegetation analysis results presented in Table 3, which further illustrate the dominance pattern of Arabica coffee compared to cocoa within the observed silvofishery system. In addition, the data in Table 3 indicate that Arabica coffee exhibited higher relative density, relative frequency, and relative dominance values than cocoa, reinforcing its ecological advantage at the sapling level within the silvofishery ecosystem.

Tabel 3. Vegetation Analysis On Sapling Level

No	Local name	Scientific name	Density		Frequency		IVI (%)
			D (stem/ha)	DR (%)	F	FR (%)	
		Agrisilviculture					
1	Jambu Batu	*Psidium guajava*	14.81	3.7	0.04	7.69	11.4
2	Jati Putih	*Anacardium occidentale*	74.07	18.52	0.04	7.69	26.21
3	Kakao	*Theobroma cacao* L.	59.26	14.81	0.11	23.08	37.89
4	Ketapang	*Terminalia catappa L.*	14.81	3.7	0.04	7.69	11.4
5	Nangka	*Atrocarpus heterophyllus*	14.81	3.7	0.04	7.69	11.4
6	Nyamplung	*Calophylum inophyllum*	14.81	3.7	0.04	7.69	11.4
7	Piling (Saga Pohon)	*Adenathera pavonina* L.	148.15	37.04	0.04	7.69	44.73
8	Sengon	*Albizia chinensis*	14.81	3.7	0.04	7.69	11.4
9	Sirsak	*Annona muricata L.*	14.81	3.7	0.04	7.69	11.4
10	Sonokeling	*Dalberga latifolia*	14.81	3.7	0.04	7.69	11.4
11	Sropan	*Caesalpinia sappan*	14.81	3.7	0.04	7.69	11.4
		Total	400	100	0.48	100	200
		Silvopastoral					
1	Jambu Air	*Syzygium aqueum*	57.14	9.09	0.14	16.67	25.76
2	Kakao	*Theobroma cacao* L.	228.57	36.36	0.29	33.33	69.7

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No	Local name	Scientific name	Density		Frequency		IVI (%)
			D (stem/ha)	DR (%)	F	FR (%)	
3	Lamtoro	*Leucaena leucocephala*	171.43	27.27	0.14	16.67	43.94
4	Mahoni	*Swietenia mahagoni*	57.14	9.09	0.14	16.67	25.76
5	Nangka	*Atrocarpus heterophyllus*	114.29	18.18	0.14	16.67	34.85
		Total	628.57	100	0.86	100	200
Silvofishery							
1	Kakao	*Theoroma cacao* L.	266.67	28.57	0.33	33.33	61.9
2	Kopi	*Coffea arabica*	666.67	71.43	0.67	66.67	138.1
		Total	933.33	100	1	100	200

At the seedling stage in the agrisilvicultural system, cocoa had a density of only 185.19 trees/ha with an IVI of 5.49%, representing the lowest value among all species. This is a serious indicator of the long-term sustainability of cocoa populations. The density and height of shade trees strongly influence cocoa growth, particularly through competition for nutrients and light. Species such as mahogany and leucaena, which regenerate rapidly, are suspected to inhibit cocoa seedling growth. In the silvopastoral system, cocoa had a density of 714.29 trees/ha with an IVI of 20.95%. However, leucaena (Leucaena leucocephala) showed extremely strong dominance with a density of 7,857.14 trees/ha and an IVI of 116.19%. This extreme dominance requires attention because leucaena may inhibit light penetration to the soil surface and has the potential to become an invasive species in various regions worldwide. Such conditions need to be anticipated to prevent long-term disruption of cocoa regeneration, as presented in Table 4 below.

Tabel 4. Vegetation Analysis On Seedling Level

No	Local name	Scientific name	Density		Frequency		IVI (%)
			D (stem/ha)	DR (%)	F	FR (%)	
Agrisilviculture							
1	Agel	*Corypha utan*	92.59	0.96	0.04	3.57	4.53
2	Alpukat	*Persea americana*	92.59	0.96	0.04	3.57	4.53
3	Brora	Kleinhovia hospita L.	92.59	0.96	0.04	3.57	4.53
4	Jambu Batu	*Psidium guajava*	277.78	2.88	0.04	3.57	6.46
5	Jambu Mete	*Anacardium occidentale*	925.93	9.62	0.11	10.71	20.33
6	Jati	*Tectona grandis*	462.96	4.81	0.04	3.57	8.38
7	Jati Putih	*Gmelina arborea*	2037.04	21.15	0.11	10.71	31.87
8	Kakao	*Theobroma cacao* L.	185.19	1.92	0.04	3.57	5.49
9	Kapuk	*Gossampinus malabarica*	92.59	0.96	0.04	3.57	4.53
10	Kopi	*Coffea arabica*	92.59	0.96	0.04	3.57	4.53
11	Lamtoro	*Leucaena leucocephala*	1296.3	13.46	0.19	17.86	31.32

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No	Local name	Scientific name	Density		Frequency		IVI (%)
			D (stem/ha)	DR (%)	F	FR (%)	
12	Mahoni	*Swietenia mahagoni*	2037.04	21.15	0.15	14.29	35.44
13	Piling (Saga Pohon)	*Adenanthera pavonina L.*	1666.67	17.31	0.07	7.14	24.45
14	Putat	*Planchonia valida*	92.59	0.96	0.04	3.57	4.53
15	Sonokeling	*Dalberga latifolia*	185.19	1.92	0.07	7.14	9.07
		Total	9629.63	100	1.04	100	200
		Silvopostural					
1	Durian	*Durio zibenthinus Murr.*	714.29	6.67	0.14	14.29	20.95
2	Kakao	*Theobroma cacao* L.	714.29	6.67	0.14	14.29	20.95
3	Kesambi	*Schleichera oleosa*	357.14	3.33	0.14	14.29	17.62
4	Lamtoro	*Leucaena leucocephala*	7857.14	73.33	0.43	42.86	116.19
5	Sonokeling	*Dalberga latifolia*	1071.43	10	0.14	14.29	24.29
		Total	10714.29	100	1	100	200

The cocoa-based agroforestry system in this study has a total carbon stock of 56.9 tons.ha-1, which is lower than the others cocoa agroforestry systems (Fig.1). The value of carbon stock varies for each agroforestry system implemented, for example, cocoa agroforestry in South Sulawesi's Pinrang region found that monoculture cocoa plantations had a total carbon of 21.51 tons.ha-1, while multi strata cocoa-based agroforestry had an average of 26.34 tons.ha-1. The multistrata cocoa agroforestry system has a higher carbon stock of 37.68 ton.ha-1 when compared to the 27.09 ton.ha-1 monoculture cocoa grown in Bantaeng, South Sulawesi (Supriadi et al., 2022).

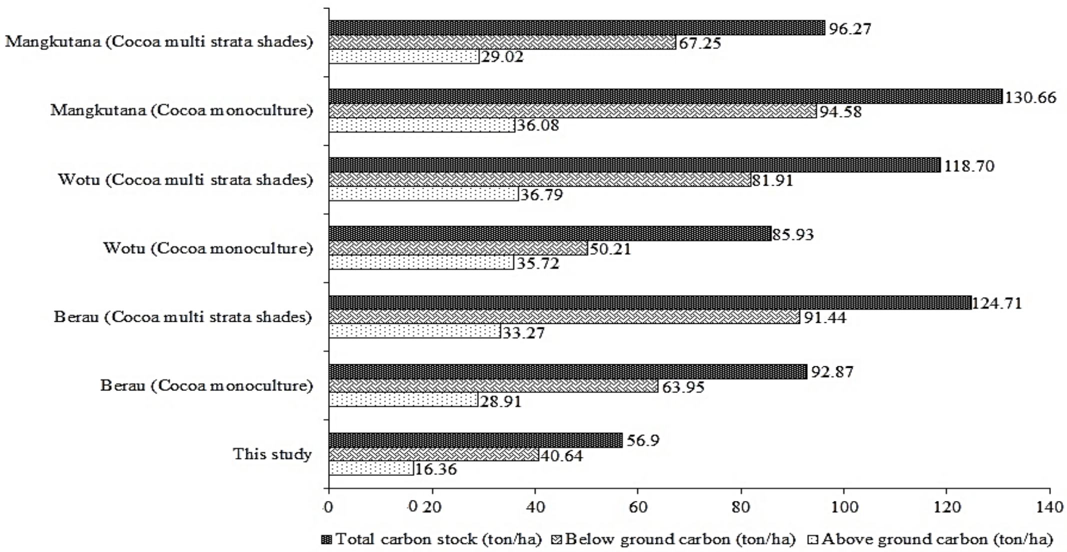

Figure 1. Carbon Stock In Cocoa Agroforestry Systems

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Discussion

Overall, the silvopastoral system provided the strongest support for the ecological position of cocoa across all growth stages. This result is in line with previous studies that identify cocoa-based agroforestry and silvopastoral systems as important sinks for atmospheric CO_2, where carbon sequestration and storage in biomass are influenced by vegetation structure, climatic conditions, and the age of the agroforestry system. Nevertheless, the low IVI values of cocoa at the seedling stage in all systems, particularly in the agrisilvicultural system (IVI 5.49%), indicate a potential concern for long-term sustainability. IVI patterns in cocoa agroforestry systems suggest that species with the highest economic value are generally those deliberately introduced by farmers rather than species that regenerate naturally, showing that farmers' economic priorities strongly shape agroforestry diversification. Therefore, to maintain sustainable cocoa populations, especially in the semi-arid areas of East Nusa Tenggara, active enrichment planting of cocoa seedlings is strongly recommended, particularly in agrisilvicultural systems (Goñas et al., 2022).

Comprehensive carbon stock estimation, covering aboveground biomass, belowground biomass, and soil organic carbon, enables the demonstration of agroforestry systems' contribution to climate change mitigation while also strengthening the environmental credibility of projects submitted for certification (Vervuurt et al., 2022). Furthermore, carbon stock assessments can be used to establish baseline conditions for measuring net increases in carbon sequestration during the project period (Kumah et al., 2024). The findings of this study provide insight into the effectiveness of cocoa-based agroforestry systems in lowering greenhouse gas emissions and rehabilitating degraded landscapes (Tracey et al., 2025). Well-managed agroforestry systems are capable of storing approximately 100–200 t C ha^{-1}, equivalent to up to 700 t CO_2e ha^{-1}, depending on shade-tree density and species diversity (Kouadio et al., 2024). These outcomes support the implementation of environmental certification schemes such as Rainforest Alliance, Fairtrade, and ISO 14064, while also creating opportunities for participation in voluntary carbon markets that can provide incentives for farmers adopting sustainable land management practices (Maathuis & Borrell, 2022).

The substantial carbon storage potential of agroforestry systems is determined not only by aboveground vegetation biomass but also by the dynamics of soil organic carbon. In agroforestry ecosystems, the diversity of plant species increases the variety of organic matter inputs originating from litter and root biomass, which in turn promotes humification processes and the formation of more stable humus in the soil. Root-derived carbon inputs are recognized to possess greater humification potential compared to aboveground biomass (Krause et al., 2025). In addition, soil organic carbon is composed of both labile and stable fractions that perform different functions in carbon sequestration. The labile fraction contributes mainly to short-term nutrient cycling, whereas the stable fraction, which is associated with soil minerals, is capable of retaining carbon for much longer periods due to the physical and chemical protection provided by mineral particles (Georgiou et al., 2022). Soil microbial activity and physicochemical interactions between organic matter and soil minerals also play an important role in stabilizing soil organic carbon (Krause et al., 2025). Consequently, the complexity of vegetation in cocoa-based agroforestry systems is essential for increasing carbon inputs into the soil and maintaining soil organic carbon stability through improvements in organic matter content and overall soil quality in tropical ecosystems (Sari et al., 2025).

Estimating carbon stocks in cocoa-based agroforestry systems is also a critical component in implementing the REDD+ (Reducing Emissions from Deforestation and Forest

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Degradation) mechanism. By integrating agricultural production with tree conservation, cocoa agroforestry systems contribute simultaneously to reducing deforestation and enhancing carbon storage within agroecosystems. Therefore, these systems provide a sustainable strategy for restoring degraded landscapes while also improving farmers' livelihoods (Somarriba et al., 2021). Accurate measurement of carbon stored in biomass and soil enables the quantification of emission reductions and supports the Measurement, Reporting, and Verification (MRV) framework required under the United Nations Framework Convention on Climate Change, as well as international certification schemes such as the Verified Carbon Standard (VCS) and Gold Standard (Grajales & Toukpo, 2024). Moreover, locally based carbon stock estimations enhance the reliability of national greenhouse gas inventories and encourage the economic valuation of sequestered carbon through Payment for Environmental Services (PES) programs and carbon credit mechanisms (Dugasseh & Zandersen, 2025).

Furthermore, carbon quantification in agroforestry systems enables more effective identification of areas with high carbon sequestration potential, supports the development of national policies for forest restoration, and encourages the incorporation of agroforestry into regional climate change strategies. In Indonesia, where deforestation associated with cocoa cultivation continues to be a significant issue, acknowledging the contribution of agroforestry to carbon sequestration offers a practical opportunity to support the goals of the National REDD+ Strategy (Grajales & Toukpo, 2024). In addition, scientific estimation of carbon stocks represents a crucial stage in the carbon certification process, as it provides evidence of the actual amount of carbon captured or emissions reduced by a production system. Within cocoa-based agroforestry systems, these estimations generate the necessary data to translate ecological performance into measurable economic values in the form of carbon credits. Such credits correspond to one ton of carbon dioxide equivalent (t CO_2e) that is either sequestered or prevented from entering the atmosphere (Tracey et al., 2025).

In addition, these estimations support national sustainability policies, including the National Sustainable Cocoa Strategy 2023–2030, which incorporates carbon monitoring as an indicator of compliance with climate commitments and environmental traceability requirements for European markets (Vervuurt et al., 2022). Therefore, carbon stock measurement is not only a scientific indicator but also an important environmental and economic governance tool for aligning the cocoa sector with carbon neutrality targets and deforestation-free production goals (Kumah et al., 2024).

CONCLUSSION

This study reveals that vegetation structure and shade-tree composition vary among cocoa-based agroforestry systems in Sikka Regency, East Nusa Tenggara. Such differences affect both the ecological position of cocoa and the carbon storage potential of the agroforestry systems. Variations in vegetation composition also indicate differences in ecosystem complexity and species interactions that contribute to supporting ecological functions within the landscape. The total carbon stock recorded in this study was 56.9 tons ha^{-1}, suggesting that cocoa agroforestry systems possess considerable potential for supporting ecological functions and mitigating climate change, although the value is still lower than that reported in several other cocoa agroforestry systems. These results highlight the importance of vegetation management and appropriate shade-tree selection in increasing carbon storage capacity within cocoa-based agroforestry systems.

The low IVI value of cocoa at the seedling stage, especially in the agrisilvicultural system (IVI 5.49%), indicates limited natural regeneration of cocoa and may threaten the long-

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term sustainability of the system. This condition suggests that competition among plant species, particularly from certain shade trees, can suppress cocoa growth and regeneration during the early developmental stages. If this situation continues, the sustainability of cocoa populations in agroforestry systems could decline over time. Therefore, sustainable management efforts are needed through enrichment planting, proper regulation of shade-tree composition, and active involvement of local communities to improve vegetation regeneration and support the conservation of dryland ecosystems. Besides enhancing cocoa regeneration, these strategies are also essential for maintaining ecosystem stability and ensuring the continuity of ecological functions in agroforestry systems located in semi-arid environments.

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