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Carbon sequestration potential of coconut-based intercropping systems under humid tropical conditions of Kerala, India

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ABSTRACT

In Kerala, India's humid tropics, coconut (*Cocos nucifera* L.) plantations dominate the land-use system; however, monocropping techniques frequently lead to inefficient use of biomass resources and land. Introducing perennial plantation crops within the coconut plantation led to enhance the carbon storage and farm sustainability. This study quantified and compared carbon sequestration potential in coconut monoculture and coconut-based intercropping systems with cocoa (*Theobroma cacao*) and nutmeg (*Myristica fragrans*) under humid tropical conditions in Kerala, India. The experiment was conducted at Kerala Agricultural University, Vellanikkara, from September 2024 to September 2025, with five treatments: coconut monocrop (WCT), hybrid monocrop (Dwarf × Tall), coconut-cocoa, coconut-nutmeg and a non-cropped control. Above ground biomass was estimated using species-specific allometric equations, while soil organic carbon (SOC) was measured at 0-15, 15-30 and 30-45 cm depths. Total carbon stock, obtained by combining above ground and soil carbon, varied significantly among systems. The coconut-cocoa system recorded the highest total carbon stock (156.79 t ha^{-1}), followed by coconut-nutmeg (110.95 t ha^{-1}), coconut monoculture (82.89 t ha^{-1}) and hybrid monoculture (72.48 t ha^{-1}), while in non-cropped control recorded only 13.91 t ha^{-1}. SOC declined with depth, with maximum values in the 0-15 cm layer. Intercropped systems also showed lower bulk density than the non-cropped control, indicating improved soil physical condition. The results underscore coconut-based intercropping, particularly with cocoa, as an effective plantation management strategy for enhancing carbon sequestration and promoting climate-resilient, sustainable coconut production.

Key words: Carbon sequestration, coconut-based intercropping, soil organic carbon, plantation cropping systems

INTRODUCTION

The global greenhouse effect has been strengthened by human-induced changes in land use and energy consumption, which have significantly raised atmospheric concentrations of greenhouse gases. Recent warming trends have been caused by emissions from the use of fossil fuels, industrial processes, land clearance and intensive fertilizer application. According to observations, the average global surface temperature has increased by roughly 1.1°C since pre-industrial times, primarily due to human activity (Davis *et al.,* 3). For controlling the atmospheric CO_2 level, carbon storage is the essential step in terrestrial ecosystem. As long-term carbon reservoirs, agroforestry and intensive land-use systems with perennial vegetation are crucial in this situation (Montagnini and Nair, 8).

Coconut (*Cocos nucifera* L.), a significant plantation crop in the humid tropics, due to its perennial growth habit and consistent biomass production and also has a strong capacity for storing carbon (Ranasinghe and Silva, 17). Maheswarappa *et al.* (6) found monocropping of coconuts to be economically and ecologically inefficient due to its limited use of available resources, only capturing 45–50% of incoming solar radiation, and taking up about 21% of the total land area. Also in recent years, growing cultivation costs and market price had a greater impact on coconut producers. Adding perennial intercrops within coconut plantations improve food security and income stability through more efficient use of available land and resources, along with increasing in carbon sequestration and provide a major contribution to broader sustainability objectives related to climate action and sustainable agricultural practices.

Since cocoa plants are long-lived and the leaves, root and branches, which act as organic residues continually get added to the soil, it has been stated that cocoa-based agroforestry systems store significant amounts of carbon (Raveendra *et al.,* 16). Also, nutmeg absorb atmospheric carbon dioxide during photosynthesis and storing it as biomass carbon, showed a greater potential in carbon sequestration.

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Although coconut-based intercropping systems are widely promoted for enhancing productivity and sustainability, quantitative assessments of their carbon sequestration potential, integrating both aboveground biomass and soil organic carbon pools under humid tropical plantation ecosystems, remain limited. Accordingly, the present study aimed to quantify and compare aboveground, soil, and total carbon stocks in coconut monocropping and coconut-based intercropping systems with cocoa and nutmeg in Kerala, India.

MATERIALS AND METHODS

The study was conducted during September 2024 to September 2025 at selected farms of Kerala Agricultural University, Kerala, India. Coconut–cocoa intercropping was studied at the Instructional Farm, Vellanikkara; coconut–nutmeg intercropping and coconut monocropping with West Coast Tall (WCT) at the Plantation Farm, Vellanikkara; and coconut hybrid (Dwarf × Tall) monocropping at the Krishi Vigyan Kendra (KVK), Thrissur (Fig. 1). During the study period, the mean maximum temperature was 32.7 °C, the minimum temperature was 24.1 °C, mean relative humidity was 76%, and the total annual rainfall received was 3674.6 mm. The study comprised five treatments representing different coconut-based cropping systems Coconut monocropping with West Coast Tall (WCT), Coconut hybrid monocropping (Dwarf × Tall), Coconut (WCT)–cocoa intercropping, Coconut (WCT) nutmeg intercropping, Non-cropped control.

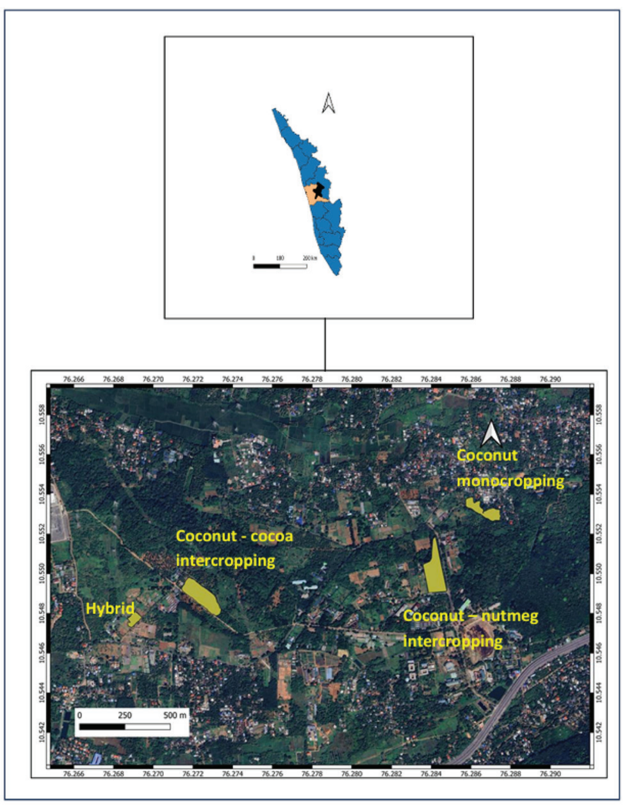

Fig. 1. Study area of coconut-based cropping systems.

These treatments were evaluated to analyse the variations in aboveground biomass, soil organic carbon and total carbon stocks under different plantation systems. A comparative field study was conducted across existing coconut-based cropping systems. For aboveground biomass estimation, five trees per species were randomly selected from each plot and considered as subsamples, while soil samples were collected in triplicate at each depth to capture within-plot spatial variability. Coconut palms in monocropping and hybrid systems were spaced at 7.5 × 7.5 m, corresponding to a population of 175 palms ha^{-1}. Cocoa and nutmeg were established as intercrops at densities of 500 and 156 plants ha^{-1}, respectively.

The age of the trees selected for observation is presented in Table 1. Coconut palms (West Coast Tall and hybrid Dwarf × Tall) were 33 years old, while cocoa (*Theobroma cacao*) and nutmeg (*Myristica fragrans*) trees were 20 years old. The plants were observed from 2024 September to 2025 September.

Aboveground biomass of coconut was estimated using a non-destructive method by measuring stem girth and height. At 1.5 m height from the base, the girth was measured and height was taken up to the base of the crown (Naresh *et al., 11*). For calculating the above ground biomass equation used as follows.

$$\text{Stem dry weight (kg)} = \text{Length (m)} \times [\text{Girth (m)}]^2 \times 41.14142$$

This non-destructive allometric equation has been widely used for estimating aboveground biomass of coconut palms under plantation conditions. Aboveground biomass of cocoa and nutmeg was estimated by measuring stem diameter of 50 cm height and applying the allometric equation proposed by Ketterings *et al.* (5).

$$W = 0.11 \times \rho \times D^{2.62}$$

W is the dry biomass (kg per tree)

D is the stem diameter in centimetres

Table 1: Age of trees chosen for observation.

Common name	Scientific name	Age (yr)
Coconut var. WCT	*Cocos nucifera L.*	33
Cocoa	*Theobroma cacao*	20
Nutmeg	*Myristica fragrans*	20
Hybrid (D×T)	*Cocos nucifera L. 'Dwarf' × 'Tall'*	33

Diameter is measured at 50 cm height from the base of crop

ρ is the wood density (g cm^{-3})

Global wood density values were utilized from the Global Wood Density Database (Chave *et al.*, 2; Zanne *et al.*, 22), based on these literature values, cocoa and nutmeg wood density were taken as 0.60 g cm^{-3} and 0.42 g cm^{-3}. The aboveground carbon stocks were calculated considering carbon as 50% of the measured dry biomass, consistent with established approaches used in tropical agroforestry research (Pearson *et al.*, 15). Carbon stocks were quantified for per hectare basis. The amount of CO_2 sequestered was estimated by multiplying the carbon stock by a conversion factor of 3.67.

Soil samples were collected from the basin area of the plantation trees using standard procedures. The soil's organic carbon (OC) content was estimated by adopting the Walkey and Black (21) method for three different depths *i.e.* 0 – 15 cm, 15 – 30 cm and 30 – 45 cm. Additionally, bulk density was determined using a core sampler at three different depths. Soil carbon stock was estimated by following standard formula Srinivasan *et al.* (19).

Soil carbon stock (Mg ha^{-1}) = C concentration layer (kg Mg^{-1}) × Bulk density layer (Mg m^{-3}) ×Depth (m)×10^{-3} Mg kg^{-1}×10^{4} (m^2 ha^{-1})

Below ground biomass and root carbon were not included due to practical limitations. Total carbon sequestration in coconut and coconut based intercropping system was calculated by adding the above ground carbon sequestration and soil carbon sequestration.

Statistical analyses were performed using GRAPES statistical software. Data obtained from different coconut-based cropping systems were subjected to analysis of variance (ANOVA). Differences among treatment means were compared using the least significant difference (LSD) test at the 5% level of significance ($P \leq 0.05$).

RESULTS AND DISCUSSION

The average plant height and girth of hybrid (D×T) variety of coconut in coconut monocropping was 6.86m and 0.72m (Table 2). Average height and girth of coconut WCT variety of coconut in coconut monocropping was 10.32m and 0.76m, also the coconut WCT in coconut - cocoa and coconut - nutmeg based intercropping system was 14.19m and 0.95m and 13.91m and 0.80m respectively. Among the all the coconut in different cropping system the coconut hybrid (D×T) showed the lowest carbon sequestration *i.e.* 46.40 t ha^{-1} because of less biomass accumulation than coconut WCT variety this result coincides with the study by Ghavale *et al.* (4).

The average diameter of cocoa and nutmeg was 19.83cm and 16.73cm and the above ground carbon sequestration of cocoa and nutmeg was 112.84 t ha^{-1} and 31.93 t ha^{-1} (Table 3).

Monocropping systems, both WCT and hybrid coconut, showed relatively low carbon stocks, with values of 21.90 t ha^{-1} and 12.71 t ha^{-1}, respectively. In contrast, intercropping systems, such as coconut - cocoa and coconut - nutmeg, significantly increased carbon stock, mainly due to the additional contribution from the intercrop species. The coconut-cocoa

Table 2: Above ground carbon sequestration in coconut at different cropping systems.

Coconut in different cropping system	Plant height (m)	Plant girth (m)	AGB (kg $plant^{-1}$)	Carbon stock (kg $plant^{-1}$)	Carbon stock (t ha^{-1})	CO_2 sequestrated (t ha^{-1})
Coconut monocropping	10.32	0.76	250.24	125.12	21.90	79.92
coconut hybrid monocropping	6.86	0.72	145.30	72.65	12.71	46.40
Coconut in coconut - cocoa intercropping system	14.19	0.95	530.79	265.40	46.44	169.52
Coconut in coconut - nutmeg intercropping system	13.91	0.80	368.99	184.49	32.29	117.85

*AGB: Above ground biomass

Table 3: Above ground carbon sequestration in cocoa and nutmeg.

Scientific name	Diameter (cm)	Stem dry weight (Kg $plant^{-1}$)	Carbon stock (kg $plant^{-1}$)	Carbon stock (t ha^{-1})	CO_2 sequestrated (t ha^{-1})
Theobroma cacao	19.83	123.66	61.83	30.91	112.84
Myristica fragrans	16.73	124.63	56.08	8.75	31.93

system demonstrated the highest total above ground carbon stock (77.35 t ha^{-1}), combining 46.44 t ha^{-1} from coconut and 30.91 t ha^{-1} from cocoa. Similarly, the coconut-nutmeg system achieved a combined carbon stock of 41.04 t ha^{-1}, with 32.29 t ha^{-1} from coconut and 8.75 t ha^{-1} from nutmeg based on Fig 2. The presence of cocoa and nutmeg in coconut cropping system led to extra biomass accumulation with efficient utilisation of vertical and horizontal space. Similar Increase in carbon stock under coconut-based intercropping systems have been reported earlier in tropical plantation ecosystems (Raveendra *et al.*, 16; Naveen Kumar and Maheswarappa., 12), confirming the ecological advantage of diversified coconut production systems.

At all depths (0-15 cm, 15-30 cm and 30-45 cm), the non-cropped area had significantly higher bulk density (Fig. 3), suggesting that the lack of continuous plant cover had increased soil compaction. Conversely, there were no significant variations in bulk density across all cultivated plots, including hybrid systems, coconut monocropping, coconut-cocoa and coconut-nutmeg intercropping. The absence of significant differences in bulk density among cropped treatments suggests that perennial plantation systems effectively maintain favourable soil physical conditions. These findings are consistent with earlier studies demonstrating reduced soil compaction under tree-based and intercropping systems due to improved aggregation and porosity (Tesfahunegn and Gebru, 20; Ozturkmen *et al.*, 14).

Across all depths (0-15 cm, 15-30 cm and 30-45 cm), the coconut–cocoa intercropping system exhibited the highest soil organic carbon (SOC), followed by coconut–nutmeg intercropping. Coconut monocropping and hybrid systems recorded lower SOC, while the non-cropped control showed the lowest values, significantly different from all cropping systems (Fig. 4). The higher SOC level in intercropping systems is mainly due to its greater litter fall and root

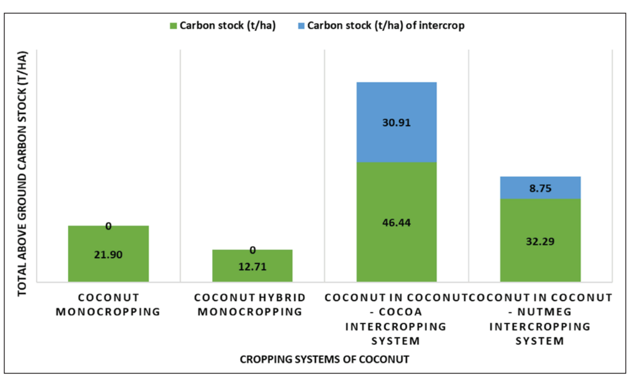

Fig. 2. Total above ground carbon stock in different cropping systems.

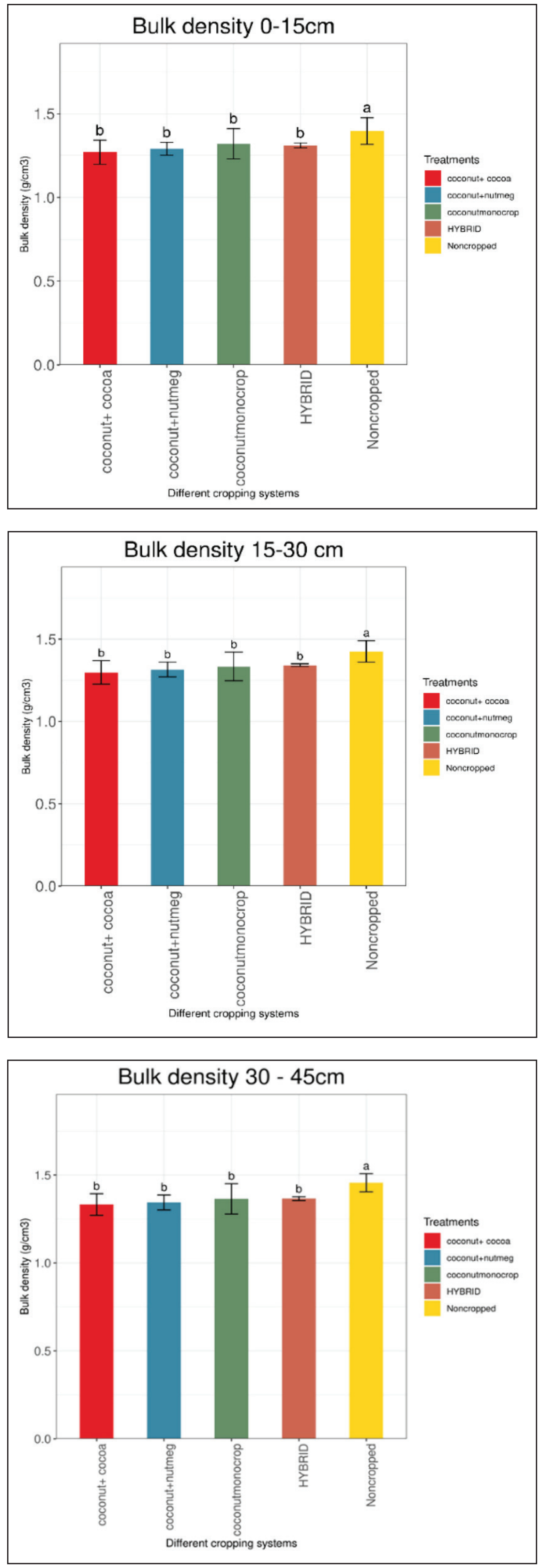

Fig. 3. Bulk density at different cropping system at different depths.

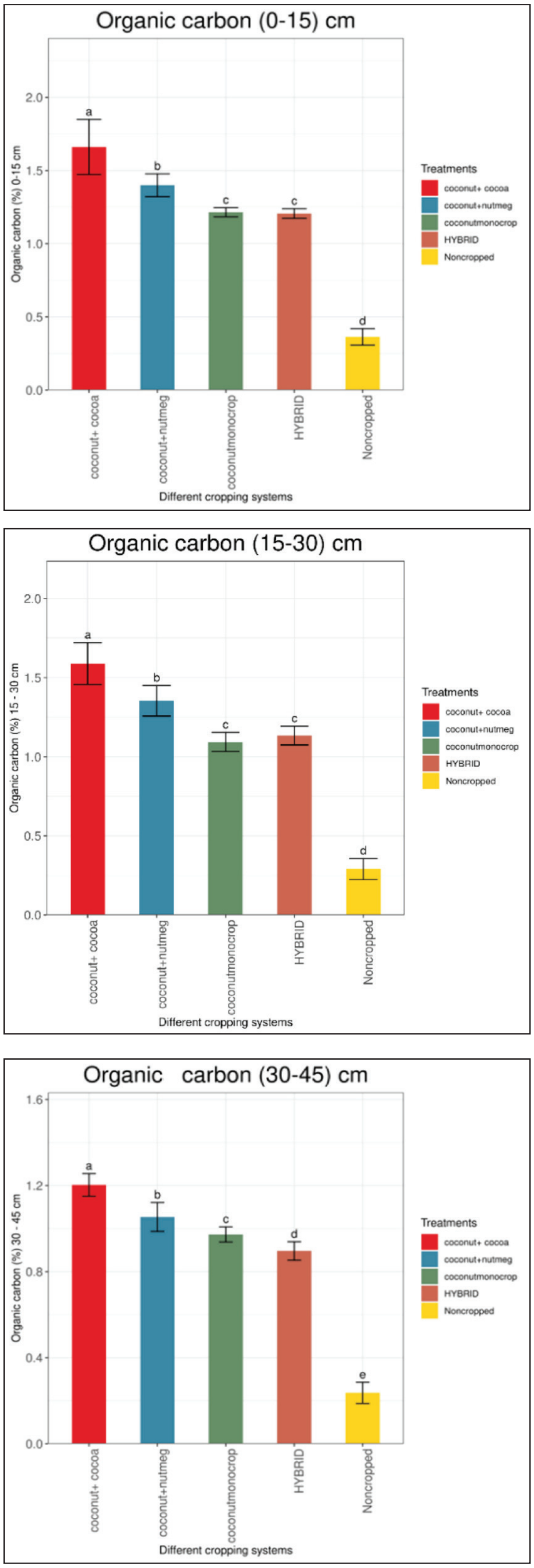

Fig. 4. Soil organic carbon in different cropping system at different depths.

biomass accumulation, which improves organic matter in soil. Conversely, the absence of continuous vegetation cover in the non-cropped area likely promoted carbon losses through erosion and surface exposure, as also reported by Shinde and Nandgude (18). Organic carbon decreased with depth, with the topsoil (0-15 cm) showed the highest values due to litter addition and root turnover, consistent with Manzeke-Kangara *et al.* (7). The superior performance of the intercropping system of the coconut–cocoa system confirms earlier observations by Namitha *et al.* (10).

The coconut–cocoa intercropping system recorded the highest soil organic carbon stock, with about 28.51 t ha^{-1} in the topsoil (0-15 cm), 27.92 t ha^{-1} at 15-30 cm, and 23 t ha^{-1} at 30–45 cm depth. Coconut–nutmeg intercropping exhibited stocks around 25.06 t ha^{-1} in the topsoil, 24.63 t ha^{-1} at mid-depth, and 20.22 t ha^{-1} in deeper soil. Coconut and hybrid monocultures demonstrated intermediate values, i.e. 22 t ha^{-1}, 21.70 t ha^{-1} (0-15 cm), 20.15 t ha^{-1}, 20.71 t ha^{-1} (15-30 cm) and 18.59 t ha^{-1}, 17.35 t ha^{-1} (30-45 cm) respectively. The non-cropped area consistently displayed the lowest stocks approximately 5 t ha^{-1} across all the depth (Fig. 5).

The coconut–cocoa intercropping system achieved the highest total soil organic carbon stock, about 79.43 t ha^{-1}, followed by coconut–nutmeg intercropping with around 69.91 t ha^{-1}. Coconut monoculture and hybrid monoculture both recorded 61 t ha^{-1} and 59.77 respectively while the non-cropped area showed the lowest value, only about 13.91 t ha^{-1} (Fig. 6). These results demonstrated that intercropping systems, particularly coconut–cocoa, substantially increased total soil organic carbon compared to monocropping and non-cropped plots. The superior performance of the intercropping system confirms earlier observations by Nuwarapaksha *et al.* (13).

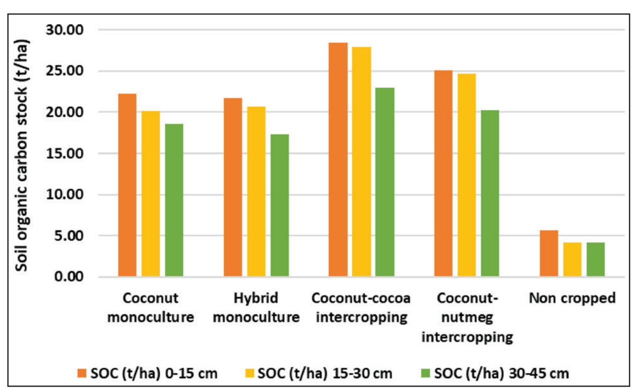

Fig. 5. Soil carbon stock in different cropping system at different depth.

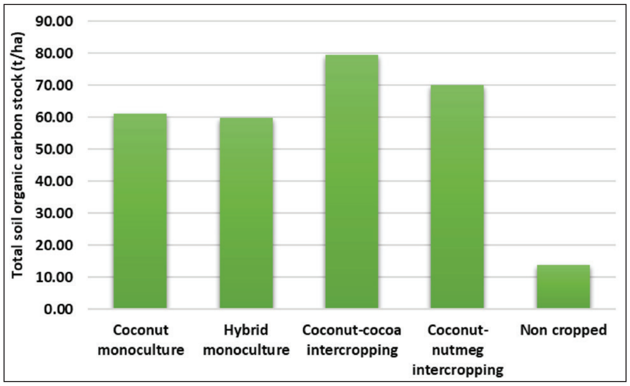

Fig. 6. Total soil organic carbon stock in different cropping system.

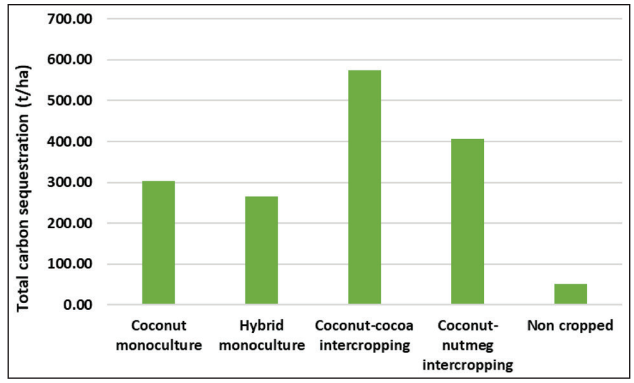

Fig. 8. Total CO_2 sequestrated in different cropping system.

Total carbon stock, combining aboveground and soil carbon pools, varied significantly among the cropping systems (Fig. 7). Coconut–cocoa intercropping recorded the highest total carbon stock, followed by coconut–nutmeg intercropping, while coconut monocropping and hybrid monocropping systems showed lower total carbon accumulation. The non-cropped control exhibited minimal carbon storage, emphasizing the importance of continuous vegetation cover for ecosystem carbon sequestration.

The enhanced total carbon stock in coconut-based intercropping systems highlights the combine contribution of aboveground biomass and soil organic carbon pools. Integration of perennial intercrops within coconut plantations improves overall carbon sequestration efficiency by maximizing biomass production and improving soil carbon retention.

The coconut–cocoa intercropping system achieved the maximum total carbon sequestration of 575.42 t ha^{-1}, followed by coconut–nutmeg intercropping at around 407.17 t ha^{-1}. Coconut monoculture and hybrid monoculture recorded about 304.22 t ha^{-1} and 266.01 t ha^{-1}, respectively, while the non-cropped area had the lowest value, of 51.06 t ha^{-1} (Fig. 8). The superior performance of carbon sequestration in intercropping system was observed earlier observations by Bhagya *et al*. (1). These findings strongly support the adoption of coconut-based intercropping systems as climate-resilient plantation management practices capable of enhancing ecosystem carbon stocks while sustaining productivity.

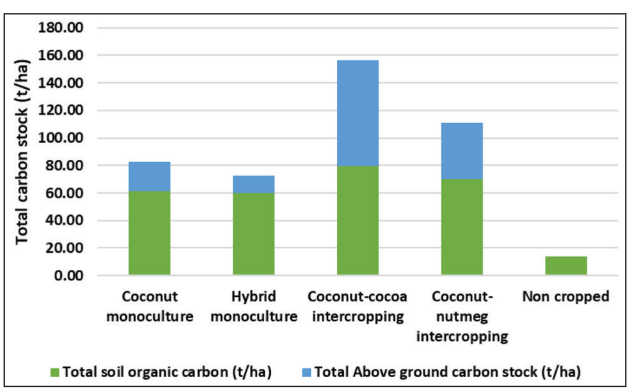

Fig. 7. Total carbon stock at different cropping system.

Coconut-based intercropping systems, especially those integrating perennial crops like cocoa and nutmeg were found to enhance carbon sequestration and ecosystem health compared to monoculture and non-cropped conditions. These diversified agroforestry practices not only support soil and aboveground carbon buildup but also contribute to climate change mitigation and improved farm sustainability. Further study is required to investigate the influence of weather and soil characteristics in carbon sequestration of coconut and coconut based intercropping systems.

AUTHOR'S CONTRIBUTION

Conceptualization, field investigation, data analysis, manuscript preparation (SN)., Supervision, methodology, manuscript review and editing (PLD), Experimental design and technical guidance (BAK), Field assistance and data collection (BVI), Data interpretation and statistical support (SVM).

DECLARATION

The authors declare that they have no conflict of interest.

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DATA AVAILABILITY

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

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