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Carbon vaults on farmlands: Unveiling the carbon sequestration potential of trees for climate resilience

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Abstract

Farmlands are emerging as a crucial landscape for sequestering carbon, while trees acting as a natural carbon vault that capture and store atmospheric carbon dioxide in biomass and soil. Understanding the potential of trees in sequestering carbon is essential for assessing their role in climate resilience and sustainable management practices. This review evaluates the carbon storage capacity of various tree species, examining factors such as species allocation, carbon accumulation and sequestration rates. By exploring the existing research, it highlights how various agroforestry systems contribute to long term carbon storage, with sequestration rates ranging from 0.29 to 15.21 Mg C $ha^{-1} year^{-1}$ in aboveground biomass and 30 to 300 Mg C $ha^{-1} year^{-1}$ in soil. Short-rotation species have demonstrated rapid carbon uptake, while long-rotation species contribute to sustained sequestration over the decades. This review also highlights the challenges in precisely quantifying carbon stocks, emphasizing the need for advanced allometric models, remote sensing and standardized methodologies. Additionally, the potential for monetizing farmland carbon stocks through carbon credits and offset trading is explored, emphasizing the economic viability of tree based carbon sequestration. While policies support afforestation and tree farming implementation gaps need to be filled. In conclusion, trees in farmlands hold immense promise as carbon sink, reinforcing the need for research driven strategies, policy support and financial incentives to enhance their role in mitigating climate change and strengthening climate resilience.

Keywords

agroforestry; biomass; carbon; carbon sequestration; farmland; greenhouse gas

Introduction

There has been an increase in greenhouse gas concentrations in the atmosphere and annual anthropogenic Green House Gas (GHG) emissions which is a significant driver of global climate change, as highlighted in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (1). Anthropogenic GHG emissions, primarily from fossil fuel combustion, have reached record levels, intensified the greenhouse effect and contributed to global warming (2). Recent data indicate that global per capita GHG emissions rose by 0.4 % in 2022, culminating in an 8.3 % increase from 1990 levels.

Simultaneously, emissions intensity per unit of Gross Domestic Product (GDP) reached a 52-year low in 2022, reflecting a modest decoupling of emissions from economic growth. However, these achievements are insufficient to meet global climate targets (3).

Atmospheric gases like carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are trapped in the atmosphere of the Earth and because of this, the atmosphere amplifies the greenhouse effect, heating the Earth (4). CO_2 is the most important of the total GHG emissions and it comprises 81 % of this total (5). The highest level of atmospheric CO_2 in these recent years is 421 ppm in 2023, a record high, due to human activities such as fossil fuel combustion, deforestation and land use change of the natural carbon cycle (6). The Intergovernmental Panel on Climate Change (IPCC) reports that reaching global carbon neutrality by 2050 with carbon negativity by 2100 requires capturing 6 billion metric tons of CO_2 each year by 2050 and increasing this to 14 billion metric tons annually by 2100 to keep temperature rise below 1.5 °C (1). Carbon sequestration decreases the warming potential of greenhouse gases by capturing and storing atmospheric CO_2 (7). Trees cultivated on agricultural lands within agroforestry systems receive significant interest due to their dual capability of storing carbon in biomass and soil while delivering other ecosystem benefits (8). The IPCC Special Report on Climate (9) demonstrates how agroforestry can mitigate 0.08 to 5.7 Gt CO_2-eq annually across the world. Planting trees within agricultural systems helps capture carbon while advancing sustainable farming techniques and creating additional revenue streams for farmers alongside conserving biological diversity (10). Integrating trees into farmland enhances crop productivity and soil health by elevating soil fertility through nutrient cycling and microclimate regulation. This integration reduces the impact on food production unlike large-scale afforestation projects and provides environmental and rural livelihood benefits (11). Carbon sequestration capabilities in these systems differ according to tree species and management practices alongside climate conditions and socio-economic circumstances which require comprehensive understanding to maximize their impact on climate change mitigation (12). This review intends to provide a thorough examination of how trees on farmlands can capture carbon. This study will assess how different agroforestry systems perform while investigating implementation challenges and limitations and scrutinizing policy frameworks and incentives that support their adoption. Through synthesizing current knowledge this review aims to deliver practical insights for policymakers as well as researchers and practitioners who address climate change with nature-based strategies.

The carbon sequestration process in trees

Carbon sequestration is the phenomenon of extraction of atmospheric CO_2 and storing them in other carbon pools such as oceanic, pedologic, biotic and geological strata for longer period (Fig. 1). The main aim is to reduce the accumulation of excessive CO_2 in the atmosphere (13).

The primary process of carbon sequestration in trees involves the conversion of atmospheric carbon dioxide into plant biomass through the process of photosynthesis (14), which is then followed by the conversion of biomass into persistent Soil Organic Carbon (SOC) facilitated by the formation of organo-mineral complexes. After the decomposition of plant biomass in soil, a portion of it contributes to the formation of Soil Inorganic Carbon (SIC) in the form of bicarbonates and carbonates (15).

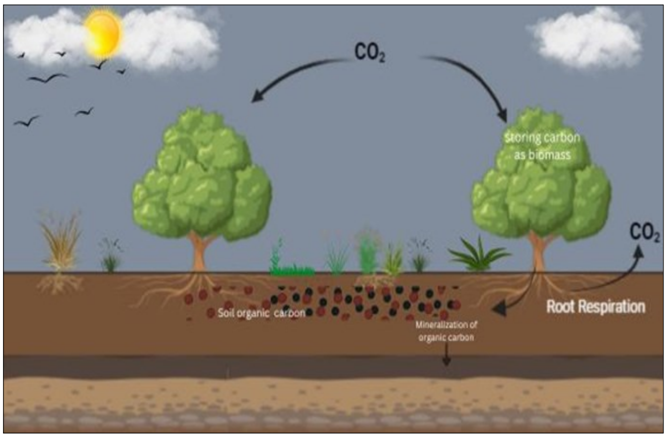

Fig.1. Carbon sequestration process.

Carbon allocation and partitioning

Once fixed, carbon is distributed among tree components through physiological mechanisms influenced by genetic and environmental factors (16).

Source-sink dynamics

All photosynthetic tissues are sources of carbon and all developing tissues and storage organs are sinks (17). The sink strength of developing meristems is an important factor in governing the movement of resources from sources towards sinks (18). Plant hormones such as auxins and cytokinins also regulate the allocation of carbon in response to dynamic environmental and developmental cues (19).

Biomass allocation patterns

Carbon allocation patterns differ considerably between tree species and are affected by factors such as age, nutrient availability and environmental stressors (20). Trade-offs occur between the distribution of biomass among leaves, stems and roots and these vary among plant species. The more limiting resource controls how much biomass a plant will allocate to the organ that is most critical in obtaining that resource (21). On average, plants allocate 46 % of their Biomass to aboveground parts of the plant (leaves, branches and stems), 21 % to coarse roots and 33 % to their fine roots (22).

Carbon pools in tree-based systems

Knowledge of how carbon is distributed in tree-based systems is necessary for optimizing tree-based system's role on carbon sequestration. These systems contribute to three primary carbon pools *viz.,* aboveground biomass, belowground biomass and SOC.

1. Aboveground Biomass : Often, aboveground biomass accounts for the largest share of carbon storage in trees (23). Carbon content varies among different tree components and species but is approximately 45-50 % of the dry biomass. The scale at which trees store carbon is determined by wood density, with denser woods storing more carbon per unit volume (24). Since modern remote sensing technologies, particularly LiDAR (Light Detection and Ranging), provide new opportunities for mapping aboveground biomass and carbon storage on large landscapes at high spatial resolution, there is interest and considerable need for developing algorithms that improve scaling these technologies (25).

2. Belowground biomass *:* Although extremely difficult to measure carbon sequestration accurately, root systems play a critical role in it. Tree biomass is about 20 to 47 % belowground (26) and is a function to a large degree of the age, species and environmental conditions (27). Under the conditions of nutrient poor soils or younger trees the proportion of biomass in root tends to increase to maximise nutrient uptake (26). Belowground biomass also helps to stable soils, retain water and improve the cycling of nutrients in agroforestry systems (28). These benefits contribute to the resilience and productivity of agricultural systems, making belowground biomass a critical focus in tree-based farming.

***3. Soil Organic Carbon* (SOC):** The large pool of organic carbon in terrestrial ecosystems is stored mostly in SOC, which is subject to vegetation inputs and soil processes and positively affects soil fertility for sustaining sustainable agricultural practices (29). Therefore SOC in trees is derived from root exudates, rooted turnover and aboveground litter deposition, which together determine the composition and stability of the soil organic matter (30). SOC dynamics are strongly influenced by roots, whereby the mineralization of soil carbon and the formation of organo-mineral complexes are promoted (31).

Carbon sequestration in agroforestry systems

Integrating trees on farms can improve agricultural productivity, increase carbon sequestration, prevent environmental degradation and support healthy soil and ecosystems (32). Through a meta-analysis Stefano and Jacobson (33), concluded that a shift in simplified land use system such as agricultural systems to a complex land use systems like agroforestry systems had increased the SOC stocks.

The potential for carbon sequestration within agroforestry systems varies according to the type of agroforestry system being implemented, the ecological region and the characteristics of the soil with levels ranging from 0.29 to 15.21 Mg ha^{-1} $year^{-1}$ above-ground and 30-300 Mg C ha^{-1} $year^{-1}$ in the soil up to 1 m depth (34). Trees can be incorporated into agricultural landscapes through various agroforestry systems, including alley cropping, silvipasture, windbreaks and shelterbelts and home gardens, each offering unique carbon sequestration potentials.

1. Alley cropping : Alley cropping system incorporates parallel rows of trees or shrubs alongside agricultural crops, has demonstrated considerable promise for carbon sequestration. This approach improves carbon retention in both above ground and below ground environments by integrating woody perennials into cultivated areas (35). Incorporation of agricultural crops and tree crops caused SOC stocks to rebound significantly (36). Research has shown that these systems can sequester 2-4 times more carbon than conventional agricultural practices (37). SOC levels also rise in alley cropping systems. The recurrent addition of organic matter from tree litter and crop residues, along with minimized soil disturbance, fosters SOC accumulation. In temperate regions alley cropping systems could increase SOC stocks by 0.24 to 0.72 Mg C ha^{-1} yr^{-1} compared to treeless croplands (38). The carbon sequestration potential of alley cropping varies depending on factors such as tree species, crop type, climate and management practices. Alley cropping systems implemented in Costa Rica exhibit a superior soil organic carbon reservoir and an elevated annual rate of SOC accumulation relative to southern Canada, primarily attributed to the increased contribution from tree prunings (35).

2. Silvipasture system : Silvipasture system combines trees and grazed pastures, while enhancing carbon sequestration, as well as the production of livestock (39). Studies conducted in various countries, including the USA, Brazil, Mexico and India, it is shown that the system is highly effective at sequestering carbon through biomass accumulation and deep root systems (40). A study conducted in Southern Mexico shows that the total carbon stock was 8 % higher in silvipasture with *Leucaena* trees (276.3 Mg C ha^{-1}) compared to open pasture (255.3 Mg C ha^{-1}) (41). Moreover, SOC stocks in grasslands converted to silvipastoral systems have been shown to increase significantly (42) by as much as 36.3 % to 60 % in relation to tree-only systems and as much as 27.1 % to 70.8 % in comparison to pasture systems (43). Total carbon stock sequestered in two silvipasture systems namely *Chrysopogon fulvus* and *Hardwickia binata* based system were around 55.18 t/ha in India during a period of five years (44). In addition silvipasture has also been shown to have broader indirect benefits (differential impact only) including improved soil composition, reduced erosion and biodiversity, all of which indirectly facilitate greater net carbon sequestration and climate change mitigation (39). Therefore, it underlines the superiority of silvipastoral systems as a better alternative for atmospheric carbon sequestration compared to systems based on trees as well as pastures.

3. Windbreaks and shelterbelts : Linear plantings of trees and shrubs, windbreaks and shelterbelts, have long been used to moderate wind velocity, change exchange of moisture and heat and retard pollutant diffusion (45). In addition, these practices not only increase agricultural productivity but also contribute to quality of the environment (46). Agroforestry systems in China, particularly shelterbelts, have been shown to effectively increase SOC stocks in both topsoil and subsoil, with soil type playing a crucial role (47). In Hungary doubling the extent of windbreak plantations established across a combined expanse of 14256 hectares would cumulatively sequester around of 913 kilotons of carbon (48).

4. Home garden systems : Home gardens are advanced agroforestry systems characterized by multi-layered canopy structures that maximize space utilization and carbon capture potential (49). Typically found in tropical regions, these gardens consist of tall trees, medium-sized fruit trees, shrubs, herbs and ground covers, fostering significant agrobiodiversity (50). The home gardens of Kerala on an average tend to possess 16 to 36 Mg ha^{-1} of aboveground carbon (51). Smaller gardens tend to have higher SOC concentrations (46.85 Mg ha^{-1}), while larger gardens show greater vegetative biomass carbon (60.38 Mg ha^{-1}) (52).

5. Industrial agroforestry : Industrial agroforestry systems focus on cultivating fast-growing tree species such as *Populus deltoides*, *Eucalyptus tereticornis*, *Melia dubia* and *Casuarina equisetifolia*. In these systems, capturing carbon and supplying industrial wood are dual advantages (53). Industrial agroforestry has become popular in India since the enforcement of Forest Conservation Act of 1980 and National Forest Policy of 1988, when wood-based industries were required to obtain their own raw materials (54). These systems combine structured arrangements of woody perennials to improve the above and below ground pools of carbon storage. Moreover, there are species including *Leucaena leucocephala* and *Dalbergia sissoo* that further enhance soil fertility through nitrogen fixation and enhance long term carbon storage (55).

Carbon sequestration potential of different tree species

1. *Short rotation crops :* Fast-growing species are trees that grow quickly and accumulate biomass at a fast rate and can achieve a mean annual increment of at least 10 m^3 per hectare under favourable conditions, provided proper techniques are used for site preparation, planting and management (56). Short rotation forestry represents a silvicultural approach that employs fast growing species planted at higher densities, accompanied by more intensive management practices compared to conventional forestry, with harvesting cycles ranging from 2 to 25 years (57). Block and boundary plantations are known for their incredibly high carbon sequestration potential. In poplar-based agroforestry systems, block plantations have been shown to sequester 5.45 t ha^{-1} yr^{-1} and boundary plantations sequester 1.84 t ha^{-1} yr^{-1} and thus represent a means of reducing fossil fuel-based carbon emissions (58). In Coromandel coasts of India, the plantations of *Casuarina equisetifolia* (12 years old) are known to store 2.792 tonnes of total carbon (59). Meanwhile in Gujarat the *Casuarina equisetifolia* plantations sequestered 1609.91 kg of CO_2 per tree by a total of 767.97 t ha^{-1} in six years which can be witnessed in Fig. 2 (60). In semi-arid region of Northwestern India, *Eucalyptus tereticornis* plantations stored between 114.1 and 118.8 Mg C ha^{-1} (61). This effectiveness in capturing the atmospheric carbon while supplying sustainable wood and bioenergy products, makes it attractive to farmers.

Leucaena based farm forestry systems in Andhra Pradesh stored 62 t $ha^{-1}$and Eucalyptus stored 34 t ha^{-1} for four years with the highest rate of carbon accumulation in the third year (62). Particularly, fast growing species can be used as alternatives to fossil fuels and are very valuable for short term carbon storage (63).

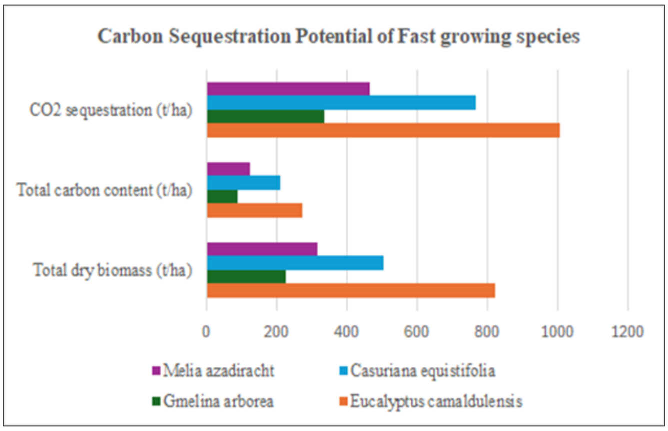

Fig. 2. Carbon sequestration potential of fast-growing species.

2. Long rotation species : Long-lived species grow more slowly than fast growing species, however they store more carbon in larger amounts through longer periods of time (64) (Table 1). These trees play a critical role in both biomass and soil carbon storage, especially when they are grown for extended rotations (69). Studies shows that increasing the rotation period of long-lived species increases carbon storage. Extension of the rotation period from 120 to 150 years resulted in a 12 % increase in the average carbon stock of the forest ecosystem, encompassing both tree biomass and soil carbon (70). Long-duration rotational systems, including agroforestry, homegardens and boundary plantings, possess the capacity to sequester substantial amounts of carbon within both plant biomass and durable wood products (71).

Traditional agroforestry systems in Timor-Leste store an average of 156 Mg C ha^{-1}, up to 210 Mg C ha^{-1} in forest gardens, comparable to old growth tropical forest (72). As a potential long-term carbon sinks, long lived species of trees are indispensable in the climate change mitigation strategies, as they can store carbon for decades and even centuries (73).

Quantification of carbon sequestration

The measurement of carbon storage in trees helps us understand their impact on climate change mitigation. Different methods and models are utilized for quantifying the carbon sequestration task with its distinct benefits and drawbacks. The simplest approach requires multiplying tree biomass with the average carbon content in dry biomass which generally falls between 47 % and 50 % (74). This basic method delivers rapid assessments even though it fails to provide accurate results when applied to extensive projects (75).

Scientists use allometric equations as a precise approach because these equations link tree growth parameters to carbon storage amounts (76). Tree height and Diameter at Breast Height (DBH) data from a two-parameter equation can be reduced to one-parameter data just utilizing only DBH. This enables the assessment of carbon storage levels without felling the tree by measuring its basal area alone (77). Allometric models serve as essential tools for site-specific and

Table 1. Carbon sequestration potential of long rotation trees in farmlands

Tree Species	Biomass carbon storage (t ha^{-1})	Rotation age (Years)	Methodology	Reference
Teak (*Tectona grandis*)	330.00	20-30	Non-destructive method	(65)
Mahogany (*Swietenia macrophylla*)	150.17	15-20	Non-destructive method	(66)
Rosewood (*Dalbergia latifolia*)	42.95	40-50	Destructive Sampling and regression modelling	(67)
Sandalwood (*Santalum album*)	21.05	30-40	Non-destructive method	(68)

species-specific assessments which makes them broadly useful in forestry research (78).

Remote sensing technologies including LiDAR and multi-spectral aerial imagery represent advanced methods to assess tree coverage, structural attributes and species classification. Experts utilize these methods to evaluate carbon storage and sequestration potential across large geographical areas (79). Studies conducted across urban areas in the U.S. showed that urban forests maintain 7.69 kg C m^{-2} of carbon storage while capturing 0.28 kg C m^{-2} every year (80).

However, different models often yield varying estimates. A study conducted in Bolzano, Italy, showed that the Urban Forest Effects Model produced conservative carbon storage numbers while CUFR Tree Carbon Calculator (CTCC) generated more positive sequestration estimates (81). The US Forest Service's Center for Urban Forest Research's CTCC model generated increased sequestration estimates than satellite-based methods for the North Little Rock, Arkansas region (82). The variation between different methodologies demonstrates why researchers should choose methods that fit their study scale and available resources while meeting precision needs (83). Future carbon accounting will see revolutionary changes through emerging technologies such as machine learning, artificial intelligence and blockchain along with traditional techniques (84, 85).

Monetization of carbon stocks

The monetization of carbon stocks in farmland trees presents significant opportunities for financial incentives, especially for farmers engaging in sustainable practices. This process involves mechanisms such as carbon credit trading and participation in carbon markets, where the quantified sequestered carbon in agroforestry systems can be converted into tradable carbon credits (Fig. 3). These credits, representing sequestered carbon in both trees and soil, are increasingly sought in voluntary and compliance markets (86).

Carbon offset trading

Agroforestry provides opportunities to the farmers in yielding economic benefits through carbon offset trading mechanism. The programs like Chicago Climate Exchange (CCX) allowed industries to offset their emissions by balancing them through investing in carbon reduction activities. This activity not only opened marketplace for sustainable practices but also supports climate change mitigation (87). Additionally, the

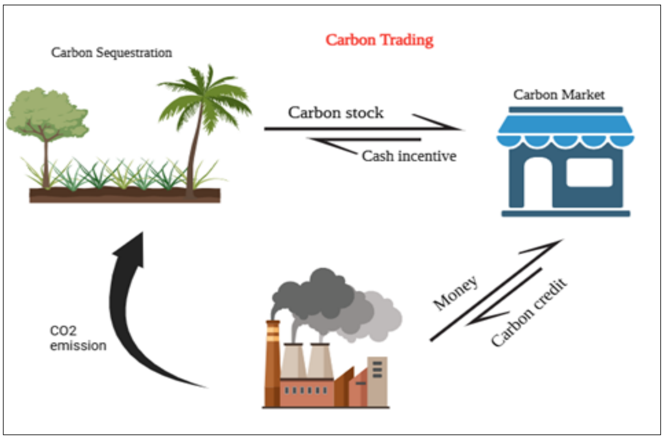

Fig. 3. Carbon trading.

REDD+ (Reducing Emissions from Deforestation and Forest Degradation) program, managed by United Nations provides financial assistance to promote agroforestry practices that mitigate greenhouse gas emissions. These programs are well suited for tropical regions where agroforestry is a vital force for sustaining development (88).

Carbon credits trading

Carbon credits are a tradable permit within a market-based framework and the holder has the right to emit one metric tonne of carbon dioxide equivalent (89). So that organizations that emit less than their cap can sell the unused credits. This creates a monetary value for sustainable practices, including agroforestry (90). This gives a monetary price upon sustainable practices like agroforestry. Carbon credits are generated and traded by means of global mechanisms such as the Clean Development Mechanism (CDM) and the Verified Carbon Standard (VCS) (91). These projects are rewarded in the market through credits available from converting these reductions of greenhouse gas emissions, including agroforestry initiatives, which actively reduce carbon. There are 27 cap-and-trade programs in the world, but only a few include forest-based carbon offsets. This indicates an untapped potential for agroforestry systems to expand their role in climate mitigation through carbon credit markets (92).

Policy implications and incentives

Tree-based systems and agroforestry for carbon sequestration have gained global governmental acceptance. The Kyoto Protocol under Article 3.3 (93) supports afforestation and reforestation initiatives as well as wood product utilization to reduce climate change effects (94). Since 1986 Costa Rica has become a leader in reforestation while its payment for environmental services program established in 1996 offers financial rewards for planting native trees to demonstrate the effectiveness of government-backed incentives in carbon sequestration projects (95). The Conservation Reserve Program (CRP) in the United States functions as an essential tool for advancing both conservation initiatives and carbon sequestration practices. The CRP program works to get farmers to convert their cropland into grasslands or forestlands to capture carbon and lower greenhouse gas emissions (96). In the southern high plains region, the program produced yearly soil organic carbon gains of 69.82 kg C ha^{-1} in the top 10 cm and 132.87 kg C ha^{-1} in the top 30 cm (97).

The National Forest Policy in India sets the target of growing forest coverage from 23 % to 33 % across all land areas. Silvipasture along with agri-silviculture and agri-horticulture practices within agroforestry systems function as key elements to reach this target especially for both rain fed and irrigated lands. The ICAR works to promote agroforestry systems so the nation can better sequester carbon (98).

Several countries have incorporated agroforestry into their climate strategies, but additional targeted approaches are necessary for others. Specific provisions for agroforestry initiatives could be included in the US Farm Bill (99). Unlocking more opportunities for agroforestry to aid in climate change mitigation can be achieved through the simplification of forestry carbon project regulations combined with the examination of voluntary carbon markets and REDD+ programs. Agroforestry stands out as a powerful solution for

Table 2. Carbon sequestration potential of agroforestry tree species

SI. No	Potential agroforestry tree species	Carbon sequestration rate (kg tree^{-1} yr^{-1})
1	*Neolamarckia cadamba*	14.84
2	*Melia dubia*	6.85
3	*Toona ciliata*	2.64
4	*Tectona grandis*	4.48
5	*Lagerstroemia lanceolata*	6.11
6	*Swietenia macrophylla*	5.22
7	*Dalbergia latifolia*	3.54
8	*Psidium guajava*	1.08
9	*Syzygium cumini*	1.61
10	*Moringa oleifera*	1.65

carbon capture (100) (Table 2). To fully tap into the potential benefits of agroforestry and create lasting impacts on global climate goals we need improved policy support along with simplified procedures and financial incentives.

Conclusion

Trees planted in farmlands serve as essential elements for carbon sequestration while helping reduce climate impact and supporting practices for sustainable land management. The ability of tree species to capture carbon varies since short-rotation trees allow quick carbon capture while long-lived trees maintain carbon storage for extended periods. These trees enhance soil fertility along with biodiversity and improve farmers' livelihoods aside from their ability to store carbon. Accurate measurements of carbon stocks remain problematic because of the uneven distribution of biomass and changing soil dynamics. The accuracy of carbon stock measurement is improving because of the advancements in the field of remote sensing and machine learning which leads to increased economic benefits through carbon credits and encourage farmer participation. The implementation of robust policies combined with research funding and the integration of agroforestry practices into climate strategies will improve its effectiveness in global carbon reduction initiatives.

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Authors' contributions

VGYS and SR involved in collecting the articles relevant to the topic and framing the overall outline. AB, KTP and MS, BS, CNH participated in enhancing manuscript scientifically and grammatically. SNK, RAR, MM, helped in creating pictorial representation. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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