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ICAR

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Foreword

Soil and vegetation constitute two of the most important terrestrial carbon reservoirs and play a pivotal role in regulating the global carbon cycle and mitigating climate change. The long-term accumulation and stabilization of carbon in soils, together with carbon sequestration in tree biomass in agroforestry systems, are essential for enhancing ecosystem resilience, improving soil health, sustaining land productivity, and supporting climate change mitigation. Understanding the temporal and spatial dynamics of these carbon pools is therefore crucial for developing effective land-use and climate-resilient management strategies.

The technical bulletin entitled "Long term build-up of carbon in soil and tree biomass in agroforestry systems" presents valuable insights into the process of carbon accumulation in soil and tree biomass over time and across spatial gradients. Long-term studies are particularly important because changes in soil organic carbon and perennial biomass occur gradually and are influenced by interactions among vegetation, soil properties, climate, topography, management practices, and land-use history. Such assessments provide a sound scientific basis for evaluating the carbon sequestration potential and sustainability of agroforestry systems.

The information presented in this bulletin enhances our understanding of carbon storage in both above- and below-ground pools and highlights the importance of integrating temporal and spatial perspectives to assess ecosystem carbon stocks and the effectiveness of sustainable land-management practices. The knowledge is highly relevant for promoting climate-resilient agriculture, agroforestry development, restoration of degraded lands, and national efforts toward climate action and carbon neutrality.

This technical bulletin will serve as a valuable reference for researchers, academicians, students, extension professionals, policymakers, planners, administrators, land managers, agroforestry practitioners, and farmers, The scientific findings and practical insights presented herein will encourage further long-term research and support the development of effective strategies for enhancing carbon sequestration while maintaining productive and resilient landscapes. I congratulate the authors for bringing out this important publication and hope that it will make a meaningful contribution to research, policy, and the wider adoption of sustainable agroforestry practices.

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Preface

Agroforestry has emerged as one of the most promising land-use systems for addressing the interconnected challenges of climate change, land degradation, biodiversity loss, and food security. By integrating trees with agricultural crops and/or livestock, agroforestry systems provide multiple ecological, economic, and social benefits while simultaneously enhancing the resilience and sustainability of farming landscapes. Among these advantages, the long-term carbon storage in soil and tree biomass has drawn a lot of attention because of its critical role in ecosystem restoration and climate change mitigation. Carbon sequestration in agroforestry system is a dynamic process that varies across temporal and spatial scales depending upon many biological and physical factors. These factors impart their effects over time from the establishment phase to mature agroforestry systems, and exhibit considerable spatial variability across agroecological regions, soil types, and land-use histories. Understanding these temporal and spatial patterns is therefore essential for accurately quantifying carbon stocks, assessing ecosystem services, and designing climate-smart land management strategies. Thus, it was felt essential to publish a technical document on "*Long term build-up of carbon in soil and tree biomass in agroforestry systems*" which would help to bridge that gap by compiling scientific knowledge on the accumulation of soil organic carbon and tree biomass carbon across a wide range of agroforestry systems, emphasizing their long-term behaviour over both temporal and spatial scales.

The document presents an in-depth analysis of carbon accumulation under diverse agroforestry systems. It synthesizes long-term experimental findings and sequential studies to illustrate how soil organic carbon and tree biomass carbon accumulated with the progression of the ages of the tree over time. It also highlights the influence of tree species composition and spatial heterogeneity on carbon sequestration efficiency. Comparative analyses among agri-silvicultural, agri-horticultural and other agroforestry systems at ICAR-CAFRI, Jhansi provide valuable insights into their relative carbon storage potential on a long term basis. The key points emerged from this compilation have been summarized in the "Epilogue" section.

This technical bulletin would serve as a comprehensive resource for researchers, students, academicians, agroforesters, agricultural professionals, policymakers, and land use practitioners. By integrating the data and information from multiple angles and synthesizing the findings across diverse agroforestry systems, the technical bulletin would surely provide both scientific understanding and practical guidance for enhancing carbon sequestration while promoting sustainable and resilient agroforestry systems for mitigating global climate change.

- Authors

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Chapter 1 Background

Agroforestry is an important land use practice that widely demonstrates its capacity for sequestering carbon and CO_2 from the atmosphere that secures carbon in both perennial woody biomass and deep soil layers, offering far greater permanence and depth than commonly used conventional standard cropland management. Agroforestry provides greater scope for storing carbon in biomass pool for longer duration in various ways through integrating long- and medium rotation timber trees as well as long-standing fruit trees. Besides, deep root system of trees can store biomass carbon in the deeper layer of the soil, which is subjected to minimum or no disturbance due to routine agricultural operations. The opportunities for building up soil organic carbon (SOC) are manifolds in agroforestry systems than sole crop or monocrop culture. Diversification of crops and practicing intercrop in the agroforestry system provide huge possibilities not only to increase the build-up of SOC, but also to increase the soil carbon storage, which improves soil health and quality in the long run. Despite having the known importance of SOC build-up in agroforestry system, there is very scanty or no much systematic data and information available ready to refer from a single documented source to substantiate the significance of such contribution of various agroforestry systems in temporal and spatial basis for long term gain. In this context, gathering information from the existing agroforestry systems to relate the status of carbon in different pools, mainly soil and tree biomass, would hold much significance for establishing the trend of carbon build-up for the long term duration as it could be observed from the comprehensive research using different model of agroforestry systems at the research farm of ICAR-Central Agroforestry Research Institute (erstwhile NRCAF), Jhansi since its inception.

The major thrust of the present compilation work was to relate the carbon status in different major pools (soil and biomass) with the progression of time, which would lead to determine the basis of long term carbon build-up in the system. For this, age of the agroforestry system was crucial determinant for understanding the trend in carbon accumulation. Systematic approach was necessary to document the contribution of tree biomass (aboveground and belowground) and the soil organic carbon in different agroforestry systems, which required extensive efforts to search various available documents. The collated data and information will be very instrumental to strengthen the scope of agroforestry systems for transformational research and development to enhance the wider utility and popularity among the various stakeholders and potential clients who forsee the agroforestry for better and remunerative land use system in the changing climate scenarios and demand for meeting the targets of sustainable development goals along with various national and global priorities.

Chapter 2

Rationale

The increasing concentration of atmospheric carbon dioxide (CO_2) and its associated impacts on global climate have intensified the need to identify sustainable land-use systems capable of sequestering and storing carbon over the long term. Agroforestry, through the deliberate integration of perennial woody vegetation with agricultural crops and/or livestock, offers considerable potential for climate-change mitigation by simultaneously accumulating carbon in tree biomass and enhancing soil organic carbon (SOC) stocks. In addition to carbon sequestration, the build-up of soil carbon contributes to improved soil structure, nutrient cycling, water-holding capacity, biological activity, and overall soil health, thereby strengthening the resilience and long-term productivity of agroecosystems. Unlike annual cropping systems, agroforestry systems continuously add organic carbon to the soil through litterfall, root turnover, rhizodeposition, pruning residues, and decomposition of below-ground biomass. At the same time, growing trees progressively accumulate carbon in their above- and below-ground biomass, creating a substantial and relatively persistent carbon pool. However, the magnitude and rate of carbon accumulation are not uniform and vary considerably with tree species, stand age, planting geometry, soil type, climate, management practices, and interactions between tree and crop components. Consequently, a comprehensive understanding of carbon sequestration under agroforestry requires assessment across both temporal and spatial scales.

The temporal dimension is particularly important because the carbon sequestration potential of agroforestry systems evolves as trees grow and the system matures. Long-term observations can reveal whether soil and biomass carbon stocks continue to increase, approach a steady state, or vary across different stages of system development. Such information is essential for quantifying the long-term carbon sequestration potential of agroforestry and determining the time required for measurable improvements in soil carbon stocks following the establishment of trees on agricultural land. Similarly, carbon distribution within an agroforestry system is spatially heterogeneous because of the localized influence of trees. Variations in litter deposition, root density and turnover, microclimate, soil moisture, nutrient availability, and rhizospheric processes may create distinct gradients in soil carbon with increasing distance from tree trunks or tree rows. Vertical variations across soil depths are equally important, as surface soil carbon may respond relatively rapidly to management, whereas deeper soil layers can represent a substantial and potentially more stable carbon reservoir. Understanding these horizontal and vertical patterns is therefore critical for accurate estimation of ecosystem carbon stocks and for developing robust sampling and carbon-accounting methodologies.

Despite the recognized potential of agroforestry for carbon sequestration, long-term information integrating changes in soil carbon and tree biomass carbon across temporal and spatial scales remains limited for many agroecological regions and production systems. Short-duration studies or assessments confined to surface soils may inadequately represent the actual carbon sequestration potential of mature agroforestry systems. There is a strong need to consolidate long-term observations and systematically evaluate the accumulation and spatial distribution of carbon in both soil and tree biomass pools. By examining carbon accumulation in relation to system age, soil depth, and spatial proximity to trees, the bulletin aims to provide a comprehensive understanding of how agroforestry influences ecosystem carbon storage over space and time. The information generated is expected to support researchers, land managers, policymakers, extension personnel, and other stakeholders in designing and promoting agroforestry interventions that maximize carbon sequestration, while simultaneously improving soil health, agricultural sustainability, and climate resilience.

Chapter 3

Outline of the Approach

Carbon build-up in various sinks is a very important phenomenon in the nature. Soil and tree biomass are among the most crucial components where terrestrial carbon are stored. In this context, agroforestry has huge potential of storing carbon in long term perspectives. Trees being integral component of agroforestry system, carbon are stored in the tree biomass in the aboveground and below ground part. Soil organic carbon (SOC) is the most abundant and important form of carbon which contributes to the soil health and quality. Build-up of SOC depends on many physical and biological factors including the soil type and its use for the purposes. Agroforestry contributes to increase SOC through many prominent ways depending upon the tree types and duration. Therefore, the purpose of the compilation of the present work was to document the carbon status in long term and spatial scale in agroforestry land use system to delineate the impact of agroforestry or the tree components for building up the carbon in different sinks *viz.* in form of tree biomass in aboveground and belowground simultaneously in the soil as well. Historical data on bulk density was used to compute SOC stocks. However, a global mean value of bulk density (1.33 g/cc) was used to compute SOC stocks wherever historical data of bulk density were not available. For this, revisiting of the historical data on the existed system in the past and the presently existing agroforestry systems were one of the major approaches to work out the carbon build-up in different prominent agroforestry systems at ICAR-CAFRI, Jhansi research farm with varying time and system scale till inception of the institute. Thus, it was one of the important steps adopted to relate the carbon accumulation with the age of the systems and the type of the tree species integrated for the long term basis.

Various relevant information and required data were collected from the available published documents of ICAR-CAFRI, Jhansi (erstwhile NRCAF) *e.g.* annual reports, technical bulletins, newsletters, technology documents, research papers, success stories, popular articles and information from published documents in open media sources that are duly acknowledged. Therefore, the carbon status in the major carbon pools *i.e.* biomass and soil with progression of the age of the system and the nature of different contributing components of agroforestry have been duly considered to establish the build-up of carbon with long term and spatial basis. This is also noted that wherever required data were available, the CO_2 sequestration potential of the particular agroforestry systems have also been worked out for relevant information in the context of long term carbon build-up for multipurpose use following the IPCC guidelines for multiplying carbon with a factor of 3.67 to convert it to equivalent CO_2 sequestration following the widely used protocol.

Chapter 4 Agroforestry Systems

Largely in agroforestry, trees and crops are integrated for multiple purposes depending upon the land uses and geographical choices of the stakeholders. Broadly, the following types of existing agroforestry sytems in ICAR-CAFRI, Jhansi have been considered for documentating the long-term carbon build-up.

Agri-silviculture

Mostly seasonal crops (*kharif* and *rabi*) were grown in between the rows of multiple purposes tree species. Prominent tree species were safed siris (*Albizia procera*) , sisham (*Dalbergia sissoo*), anjan (*Hardwickia binata*), teak (*Tectona grandis*), babul (*Acacia nilotica*), kumath (*A. senegal*), eucalyptus (*Eucalyptus tereticornis*), bamboo (*Dendrocalamus* spp.).

Agri-horticulture

Seasonal crops were integrated among the fruit yielding trees. Major horticultural trees were aonla (*Emblica officinalis*), guava (*Psidium guajava*), ber (*Ziziphus mauritiana*), pomegranate (*Punica granatum*), mandarin orange (*Citrus reticulata*).

Silvi-pasture

Various prominent fodder grasses were integrated under many popular fodder trees namely safed siris (*Albizia procera*), siris (*Albizia lebeck*), *Ailanthus* spp., babul (*Acacia nilotica*), anjan (*Hardwickia binata*), Leucaena (*Leucaena leucocephala*) for establishing silvi-pasture experiments.

Block plantation

Eucalyptus (*Eucalyptus tereticornis*) was planted in block for relevant reference with agroforestry systems.

A. Agri-silviculture systems

1. *Albizia procera* based agroforestry system

Albizia procera (Roxb.) Benth., commonly known as white siris, is a fast-growing, nitrogen-fixing tree species widely integrated into agroforestry systems across tropical and subtropical regions (Fig. 1). Owing to its deep root system, rapid biomass production, and adaptability to diverse soils, it enhances soil fertility, improves organic carbon status, and supports crop productivity. The species provides valuable timber, fodder, fuelwood, and shade while contributing significantly to carbon sequestration, making it an important component of sustainable agroforestry and climate-resilient farming systems.

Fig. 1. Glance of experimental fields with understory crops under *Albizia procera* based agroforestry

In an experiment conducted on *Albizia procera b*ased agroforestry with a spacing 8×4 m, tree biomass, biomass carbon and carbon sequestration increased consistently from the fifth to the eighth year, demonstrating rapid stand growth and enhanced carbon storage with increasing plantation age (Table 1). Aboveground biomass increased from a minimum of 17.80 t ha^{-1} in the fifth year to a maximum of 47.02 t ha^{-1} in the eighth year, representing a 164.2% increase, while belowground biomass increased from 8.25 to 21.80 t ha^{-1} (164.2% increase). Consequently, total tree biomass increased from 26.05 to 68.82 t ha^{-1}, corresponding to a 164.2% enhancement over the study period. The greatest year-to-year increase in total biomass occurred between the seventh and eighth years (34.9%), followed by the sixth to seventh years (34.7%), indicating sustained and vigorous biomass accumulation (Newaj *et al*. 2012). Tree biomass carbon increased proportionally from 13.03 to 34.41 t ha^{-1}, while equivalent CO_2 sequestration increased from 47.80 to 126.28 t ha^{-1}, both recording an overall 164.2% increase. The annual CO_2 sequestration rate also exhibited a continuous upward trend, increasing from 9.56 t ha^{-1} y^{-1} in the fifth year to a maximum of 15.79 t ha^{-1} y^{-1} in the eighth year, reflecting a 65.2% increase in annual sequestration efficiency. Based on Table 2, *Albizia procera* based agroforestry system showed 0.54% and 0.43% mean SOC in the surface (0–15 cm) and sub-surface (15–30 cm) soil following eighth year of plantation, respectively (Newaj *et al*. 2012). Soil organic carbon stock (0-30 cm) increased gradually from 12.04 to 13.94 t ha^{-1} (15.8% increase), with the corresponding equivalent soil CO_2 sequestration increasing from 44.19 to 51.16 t ha^{-1} in fifth year and eighth year, respectively. In contrast, the annual soil CO_2 sequestration rate declined progressively from 8.84 to 6.39 t ha^{-1} y^{-1} (27.7% decrease), suggesting that although soil carbon continued to accumulate, the annual rate of soil carbon sequestration slowed with plantation maturity. Overall, both tree biomass and soil carbon contributed substantially to increasing ecosystem carbon stocks over time.

Table 1. Biomass carbon and soil organic C (SOC) stock at different age in *Albizia procera* based agroforestry system

Year (Age)	Tree biomass components ($t\ ha^{-1}$)		Tree bio-mass ($t\ ha^{-1}$) (c=a+b)	Tree bio-mass carbon ($t\ ha^{-1}$) (c*0.5)	Eq. CO_2 Seq. ($t\ ha^{-1}$)	CO_2 Seq. rate ($t\ ha^{-1}\ y^{-1}$)	SOC stock* ($t\ ha^{-1}$)	Eq. CO_2 Seq. ($t\ ha^{-1}$)	CO_2 Seq. rate ($t\ ha^{-1}\ y^{-1}$)
	Aboveground (a)	Belowground (b)							
5	17.80	8.25	26.05	13.03	47.80	9.56	12.04	44.19	8.84
6	25.85	12.00	37.85	18.93	69.45	11.58	12.73	46.72	7.79
7	34.80	16.20	51.00	25.5	93.59	13.37	13.43	49.29	7.04
8	47.02	21.80	68.82	34.41	126.28	15.79	13.94	51.16	6.39

*up to 0-30 cm [Eq: equivalent, Seq.: sequestration]

2. *Dalbergia sissoo* based agroforestry system

Dalbergia sissoo Roxb. (shisham) is an important multipurpose tree species widely integrated into agroforestry systems with a spacing 8×4 m for its ecological and economic benefits (Fig. 2). *Dalbergia sissoo*, a nitrogen-fixing leguminous tree, enhances soil fertility, improves organic carbon, and provides high-quality timber and fuelwood. Based on Table 2, a 14-year-old *Dalbergia sissoo*-based agroforestry system showed 0.53% and 0.35% mean SOC in the surface (0–15 cm) and sub-surface (15–30 cm) soil, respectively. The system recorded 55.77 $t\ ha^{-1}$ aboveground biomass, 13.94 $t\ ha^{-1}$ belowground biomass, and 34.86 $t\ ha^{-1}$ total tree biomass (Table 3). Tree biomass carbon of the system showed a value of 119.39 $t\ ha^{-1}$ with the equivalent CO_2 sequestration of 127.92 $t\ ha^{-1}$, and the annual CO_2 sequestration rate of 9.14 $t\ ha^{-1}\ y^{-1}$ (Newaj *et al*. 2012). Soil organic carbon stock under the system was 31.74 $t\ ha^{-1}$ with equivalent soil CO_2 sequestration of 116.49 $t\ ha^{-1}$, and the annual CO_2 sequestration rate of 8.32 $t\ ha^{-1}\ y^{-1}$ (Table 3).

3. *Hardwickia binata* based agroforestry system

Hardwickia binata Roxb. is also an important multipurpose tree species widely integrated into agroforestry systems with a spacing 5×5 m for their ecological benefits (Fig. 2). The species is a drought-tolerant well suited to dry and degraded lands, valued for its durable timber, fodder, and role in soil conservation. It is a nitrogen-fixing leguminous tree, which enhances soil fertility and improves soil organic carbon. Based on Table 2, a 17-year-old *Hardwickia binata* based agroforestry system showed 0.55% and 0.39% mean SOC in the surface (0–15 cm) and sub-surface (15–30 cm) soil, respectively (Newaj *et al*. 2012). The system recorded 62.50 $t\ ha^{-1}$ aboveground biomass, 16.62 $t\ ha^{-1}$ belowground biomass, and 78.12 $t\ ha^{-1}$ total tree biomass (Table 3). Tree biomass carbon of the system showed a value of 39.06 $t\ ha^{-1}$ with the equivalent CO_2 sequestration of 143.35 $t\ ha^{-1}$, and the annual CO_2 sequestration rate of 8.43 $t\ ha^{-1}\ y^{-1}$. Soil organic carbon stock under the system was 35.53 $t\ ha^{-1}$ with equivalent soil CO_2 sequestration of 130.40 $t\ ha^{-1}$, and the annual CO_2 sequestration rate of 7.67 $t\ ha^{-1}\ y^{-1}$ (Table 3).

4. *Tectona grandis* based agroforestry system

Tectona grandis L.f. (teak) is an important multipurpose tree species widely integrated into agroforestry systems with a spacing 4×4 m for their ecological and economic benefits (Fig. 2). It is one of the world's most valuable timber species, characterized by rapid biomass accumulation, high carbon sequestration potential, and adaptability to diverse environments. Overall, the species improves farm productivity, diversify income, conserve natural resources, and contribute significantly to long-term carbon storage and climate-resilient agroforestry systems. A 28-year-old *Tectona grandis*-based agroforestry system recorded the highest values for all biomass-related parameters, with 189.50 t ha^{-1} aboveground biomass, 49.27 t ha^{-1} belowground biomass, and 238.77 t ha^{-1} total tree biomass (Table 3) (Alam *et al*. 2026). Tree biomass carbon followed the same trend, reaching a maximum of 119.39 t ha^{-1}, and consequently, the equivalent CO_2 sequestration was highest at 438.15 t ha^{-1}, and the annual CO_2 sequestration rate from the system was 15.65 t ha^{-1} y^{-1} (Table 3). Soil organic carbon stock under the system was again highest as compared to other systems as 41.77 t ha^{-1} with equivalent soil CO_2 sequestration of 153.30 t ha^{-1}, and the annual CO_2 sequestration rate of 5.47 t ha^{-1} y^{-1} (Table 3).

Table 2. Status of soil organic carbon (SOC) at different agroforestry systems

Year (Age)	Agroforestry system	Soil organic carbon (%)					
		0-15 cm			15-30 cm		
		Min.	Max.	Mean	Min.	Max.	Mean
Agri-silviculture							
14	*Dalbergia sissoo*	0.50	0.58	0.53	0.31	0.38	0.35
8	*Albizia procera*	0.49	0.60	0.54	0.38	0.50	0.43
17	*Hardwickia binata*	0.50	0.63	0.55	0.30	0.45	0.39
12	*Emblica officinalis*	0.30	0.35	0.32	0.26	0.30	0.28

Fig. 2. Glance of experimental fields with understory crop under different agri-silviculture based agroforestry [A. *Dalbergia sissoo*, B. *Hardwickia binata*, and C. *Tectona grandis*] systems

Table 3. Build-up of biomass carbon and soil organic carbon (SOC) stock at different agri-silviculture based agroforestry systems

Year (Age)	Agroforestry System	Tree biomass components (t ha^{-1})		Tree bio-mass (t ha^{-1}) (c=a+b)	Tree bio-mass carbon (t ha^{-1}) (c*0.5)	Eq. CO_2 Seq. (t ha^{-1})	CO_2 Seq. rate (t ha^{-1} y^{-1})	SOC stock* (t ha^{-1})	Eq. CO_2 Seq. (t ha^{-1})	CO_2 Seq. rate (t ha^{-1} y^{-1})
		Aboveground (a)	Belowground (b)							
14	*Dalbergia sissoo*	55.77	13.94	69.71	34.86	127.92	9.14	31.74	116.49	8.32
17	*Hardwickia binata*	62.50	15.62	78.12	39.06	143.35	8.43	35.53	130.40	7.67
28	*Tectona grandis*	189.50	49.27	238.77	119.39	438.15	15.65	41.77	153.30	5.47

*up to 0-30 cm [Eq: equivalent, Seq.: sequestration]

5. *Acacia senegal* based agroforestry system

Acacia senegal (L.) Willd., commonly known as gum arabic tree, is a drought-tolerant, multipurpose leguminous species widely used in rainfed agroforestry systems of arid and semi-arid regions (Fig. 3). It improves soil fertility through biological nitrogen fixation, enhances soil organic matter, and helps control land degradation. The species provides gum arabic, fuelwood, fodder, and small timber while supporting crop production under low-input conditions. Its ability to accumulate biomass and sequester carbon makes it an important component of sustainable agroforestry systems.

An experiment was laid out with *Acacia senegal* based agroforestry system on a temporal and spatial scales under rainfed conditions. The experiment was conducted up to seven years with three distinct spacing *viz.* 5×5, 10×5, and 10×10 m. Results showed that tree biomass production and carbon sequestration increased markedly with plantation age across all planting densities, with the 5×5 m spacing consistently outperforming the wider spacing (10×5 and 10×10 m). At the third year, total tree biomass ranged from 1.26 t ha^{-1} (10×10 m) to 4.48 t ha^{-1} (5×5 m), while by the seventh year it increased to 7.00, 7.35 and 20.76 t ha^{-1} under 10×10, 10×5 and 5×5 m spacing, respectively (Table 4). Over the study period, total biomass increased by 455.6% under 10×10 m, 412.9% under 10×5 m and 363.4% under 5×5 m spacing. Aboveground biomass increased from 1.00 to 5.56 t ha^{-1} (10×10 m), 1.13 to 5.83 t ha^{-1} (10×5 m) and 3.55 to 16.48 t ha^{-1} (5×5 m), whereas belowground biomass increased from 0.26 to 1.45, 0.29 to 1.52 and 0.92 to 4.28 t ha^{-1}, respectively (Prasad *et al.* 2020). Tree biomass carbon followed a similar pattern, reaching the highest value of 9.86 t ha^{-1}

Fig. 3. Glance of experimental fields under *Acacia senegal* based agroforestry

Table 4. Tree biomass, biomass carbon, and soil organic carbon (SOC) stock at different years in *A. senegal* based agroforestry systems under rainfed conditions

Year (Age)	Spacing	Tree biomass components ($t\ ha^{-1}$)		Tree bio-mass ($t\ ha^{-1}$) (c=a+b)	Tree bio-mass carbon ($t\ ha^{-1}$) (c*0.475)	Eq. CO_2 Seq. ($t\ ha^{-1}$)	CO_2 Seq. rate ($t\ ha^{-1}\ y^{-1}$)	SOC stock* ($t\ ha^{-1}$)	Eq. CO_2 Seq. ($t\ ha^{-1}$)	CO_2 Seq. rate ($t\ ha^{-1}\ y^{-1}$)
		Above ground (a)	Below ground (b)							
3	10×10	1.00	0.26	1.26	0.60	2.20	0.73	N.A.		
	10×5	1.13	0.29	1.43	0.68	2.48	0.83	N.A.		
	5×5	3.55	0.92	4.48	2.13	7.80	2.60	N.A.		
4	10×10	1.62	0.42	2.05	0.97	3.56	0.89	N.A.		
	10×5	2.64	0.69	3.32	1.58	5.79	1.45	N.A.		
	5×5	5.74	1.49	7.23	3.43	12.60	3.15	N.A.		
5	10×10	2.58	0.67	3.26	1.55	5.68	1.14	23.14	84.93	16.99
	10×5	2.42	0.63	3.05	1.45	5.31	1.06	24.34	89.32	17.86
	5×5	8.20	2.13	10.33	4.91	18.01	3.60	25.94	95.18	19.04
6	10×10	3.78	0.98	4.77	2.26	8.31	1.38	N.A.		
	10×5	5.00	1.30	6.30	2.99	10.98	1.83	N.A.		
	5×5	11.85	3.08	14.93	7.09	26.02	4.34	N.A.		
7	10×10	5.56	1.45	7.00	3.33	12.21	1.74	25.94	95.18	13.60
	10×5	5.83	1.52	7.35	3.49	12.81	1.83	31.12	114.22	16.32
	5×5	16.48	4.28	20.76	9.86	36.19	5.17	36.71	134.72	19.25

*up to 0-30 cm; N.A.-data not available [Eq: equivalent, Seq.: sequestration] under the 5×5 m spacing in the seventh year, compared with 3.33 and 3.49 t ha^{-1} under the 10×10 and 10×5 m spacing, respectively. Equivalent CO_2 sequestration also increased steadily with age, attaining a maximum of 36.19 t ha^{-1} under the 5×5 m spacing, nearly three times greater than the wider spacing. The highest annual CO_2 sequestration rate (5.17 t ha^{-1} y^{-1}) and SOC stock (36.71 t ha^{-1}, equivalent to 134.72 t CO_2 ha^{-1} and 19.25 t CO_2 ha^{-1} y^{-1}) were likewise recorded under the 5×5 m spacing in the seventh year. These findings demonstrate that closer spacing substantially enhanced biomass accumulation, carbon storage and CO_2 sequestration throughout plantation development.

6. *Acacia nilotica* based agroforestry system

Acacia nilotica (L.) Delile, commonly known as babul or Egyptian thorn, is a multipurpose, nitrogen-fixing tree widely incorporated into rainfed agroforestry systems in tropical and subtropical regions (Fig. 4). The species is valued for its adaptability to diverse soil and climatic conditions, rapid growth, and ability to improve soil fertility and organic carbon status. It provides timber, fuelwood, fodder, and medicinal products while enhancing biodiversity and carbon sequestration, making it an important species for sustainable agroforestry and land restoration programs.

Like *Acacia senegal*, another experiment was laid out with *Acacia nilotica* based agroforestry system on a temporal and spatial scales under rainfed conditions, and conducted up to seven years with three distinct spacing *viz.* 5×5 m , 10×5 m, and 10×10 m. Tree biomass production, carbon storage and CO_2 sequestration increased substantially with plantation age across all planting densities, with the 5×5 m spacing

Fig. 4. Glance of experimental fields with understory crops under *Acacia nilotica* based agroforestry

consistently recording the highest values, followed by the 10×5 m and 10×10 m spacing (Table 5). Total tree biomass increased from 1.48, 2.82 and 8.18 t ha^{-1} in the 3rd year to 6.59, 10.18 and 24.77 t ha^{-1}, respectively, in the seventh year, corresponding to increases of 345.3% (10×10 m), 261.0% (10×5 m) and 202.8% (5×5 m). Aboveground biomass increased from 1.18 to 5.23 t ha^{-1}, 2.23 to 8.08 t ha^{-1}, and 6.49 to 19.66 t ha^{-1}, while belowground biomass increased from 0.31 to 1.36 t ha^{-1}, 0.58 to 2.10 t ha^{-1}, and 1.69 to 5.11 t ha^{-1} under the respective spacing. Tree biomass carbon followed a similar trend, attaining maximum values of 3.13, 4.84, and 11.76 t ha^{-1} under the 10×10, 10×5 and 5×5 m spacing, respectively (Prasad *et al.* 2020). Equivalent CO_2 sequestration increased steadily with stand age, reaching 11.49, 17.75 and 43.18 t ha^{-1} in the seventh year. The annual CO_2 sequestration rate was consistently highest under the 5×5 m spacing, peaking at 6.21 t ha^{-1} y^{-1} in the fourth year before declining slightly to 6.17 t ha^{-1} y^{-1} in the

Table 5. Tree biomass, biomass carbon, and soil organic carbon (SOC) stock at different years in *A. nilotica* based agroforestry systems under rainfed conditions

Year (Age)	Spacing	Tree biomass components (t ha^{-1})		Tree bio-mass (t ha^{-1}) (c=a+b)	Tree bio-mass carbon (t ha^{-1}) (c*0.475)	Eq. CO_2 Seq. (t ha^{-1})	CO_2 Seq. rate (t ha^{-1} y^{-1})	SOC stock* (t ha^{-1})	Eq. CO_2 Seq. (t ha^{-1})	CO_2 Seq. rate (t ha^{-1} y^{-1})
		Above ground (a)	Below ground (b)							
3	10×10	1.18	0.31	1.48	0.70	2.59	0.86	N.A.		
	10×5	2.23	0.58	2.82	1.34	4.91	1.64	N.A.		
	5×5	6.49	1.69	8.18	3.89	14.26	4.75	N.A.		
4	10×10	1.64	0.43	2.07	0.98	3.61	0.90	N.A.		
	10×5	3.83	1.00	4.83	2.29	8.41	2.10	N.A.		
	5×5	11.30	2.94	14.24	6.77	24.83	6.21	N.A.		
5	10×10	2.69	0.70	3.39	1.61	5.91	1.18	24.74	90.79	18.16
	10×5	3.91	1.02	4.92	2.34	8.58	1.72	27.53	101.04	20.21
	5×5	11.85	3.08	14.93	7.09	26.02	5.20	29.93	109.82	21.96
6	10×10	4.97	1.29	6.26	2.97	10.92	1.82	N.A.		
	10×5	6.72	1.75	8.47	4.02	14.77	2.46	N.A.		
	5×5	16.37	4.26	20.63	9.80	35.96	5.99	N.A.		
7	10×10	5.23	1.36	6.59	3.13	11.49	1.64	26.73	98.11	14.02
	10×5	8.08	2.10	10.18	4.84	17.75	2.54	32.72	120.08	17.15
	5×5	19.66	5.11	24.77	11.76	43.18	6.17	35.51	130.33	18.62

*up to 0-30 cm; N.A. -data not available [Eq: equivalent, Seq.: sequestration] seventh year. Similarly, SOC stock increased with age and closer spacing, with the highest value (35.51 t ha^{-1}) recorded under the 5×5 m spacing in the seventh year, equivalent to 130.33 t CO_2 ha^{-1} and a sequestration rate of 18.62 t CO_2 ha^{-1} y^{-1}. Overall, closer spacing markedly enhanced biomass accumulation, carbon storage and CO_2 sequestration throughout plantation development.

7. *Acacia senegal* based agroforestry system

Apart from rainfed conditions, another experiment was laid out with *Acacia senegal* based agroforestry system on a temporal scale under irrigated conditions (Fig. 5). The experiment was set-up in 2009 with a spacing 20×10 m and still continuing. However, the data presented in this bulletin is from the sixth year up to seventeenth year of observations only. Results showed that tree biomass and carbon sequestration increased markedly with plantation age, demonstrating continuous stand development and progressive carbon accumulation over a 17-year period (Table 6). Aboveground biomass increased from a minimum of 26.10 q ha^{-1} in the sixth year to a maximum of 94.16 q ha^{-1} in the seventeenth year, while belowground biomass increased from 6.79 to 24.48 q ha^{-1}. Consequently, total tree biomass increased from 32.89 q ha^{-1} in the sixth year to 118.65 q ha^{-1} in the seventeenth year, with tree biomass carbon increasing proportionally from 15.62 to 56.36 q ha^{-1}. Equivalent CO_2 sequestration followed a similar trend, increasing steadily from only 57.33 q ha^{-1} in the sixth year to a maximum of 206.83 q ha^{-1} in the seventeenth year. The annual CO_2 sequestration rate also increased from 9.55 q $ha^{-1}y^{-1}$ in the sixth year to 12.71 q $ha^{-1}y^{-1}$ in the ninth year, after which it fluctuated between 10.69 and 12.30 q $ha^{-1}y^{-1}$, reaching 12.30 q $ha^{-1}y^{-1}$ in the sixteenth year before declining slightly to 12.17 q $ha^{-1}y^{-1}$ in the seventeenth year. Soil organic carbon (SOC) stock also increased with stand age, from 21.95 t ha^{-1} in the ninth year to 35.91 t ha^{-1} in the twelfth year, corresponding to an increase in equivalent SOC-derived CO_2 sequestration from 80.54 to 131.79 t ha^{-1} and sequestration rate from 8.95 to 10.98 t CO_2 ha^{-1} y^{-1}, highlighting the increasing contribution of mature plantations to long-term carbon storage.

Fig. 5. Glance of experimental fields with understory crops under *Acacia senegal* based agroforestry

Table 6. Tree biomass, biomass carbon, and soil organic carbon (SOC) stock at different years in *A. senegal* based agroforestry systems under irrigated conditions

Year (Age)	Tree biomass components ($q\ ha^{-1}$)		Tree bio-mass ($q\ ha^{-1}$) (c=a+b)	Tree bio-mass carbon ($q\ ha^{-1}$) (c*0.5)	Eq. CO_2 Seq. ($q\ ha^{-1}$)	CO_2 Seq. rate ($q\ ha^{-1}\ y^{-1}$)	SOC stock* ($t\ ha^{-1}$)	Eq. CO_2 Seq. ($t\ ha^{-1}$)	CO_2 Seq. rate ($t\ ha^{-1}\ y^{-1}$)
	Aboveground (a)	Belowground (b)							
6	26.10	6.79	32.89	15.62	57.33	9.55		N.A.	
7	31.25	8.12	39.37	18.70	68.63	9.80		N.A.	
8	45.60	11.86	57.46	27.29	100.16	12.52		N.A.	
9	52.08	13.54	65.62	31.17	114.40	12.71	21.95	80.54	8.95
10	54.73	14.23	68.96	32.76	120.21	12.02		N.A.	
11	57.19	14.87	72.05	34.23	125.61	11.42		N.A.	
12	58.68	15.26	73.94	35.12	128.89	10.74	35.91	131.79	10.98
13	63.27	16.45	79.72	37.87	138.97	10.69		N.A.	
14	72.61	18.88	91.49	43.46	159.49	11.39		N.A.	
15	75.10	19.53	94.63	44.95	164.96	11.00		N.A.	
16	89.60	23.30	112.90	53.63	196.80	12.30		N.A.	
17	94.16	24.48	118.65	56.36	206.83	12.17		N.A.	

*up to 0-30 cm; N.A.-data not available [Eq: equivalent, Seq.: sequestration]

8. Bamboo based agroforestry systems

Bamboo (*Dendrocalamus* sp; *Bambusa* sp.) is a fast-growing perennial grass widely integrated into agroforestry systems due to its high biomass productivity, extensive root network, and adaptability to diverse environmental conditions (Fig. 6). It plays a significant role in soil and water conservation, carbon sequestration, and land restoration. Bamboo provides valuable products such as poles, timber substitutes,

Fig. 6. Glance of experimental fields with understory crops under Bamboo based agroforestry

fodder, handicraft materials, and bioenergy feedstock. Its rapid growth, economic value, and environmental benefits make it an important component of sustainable and climate-resilient agroforestry systems.

An experiment was laid out with bamboo based agroforestry system on a temporal and spatial scales. The experiment was conducted up to seven years with two distinct spacing *viz*. 10×10 and 12×10 m. Based on Table 7, soil organic carbon (SOC) stock and equivalent CO_2 sequestration in the 0–15 cm soil layer increased markedly from the initial condition to the seventh year under both spacing treatments (Dev *et al*. 2020). The initial SOC stock was 7.82 t ha^{-1}, with an equivalent CO_2 sequestration of 28.70 t ha^{-1}. At the seventh year, the 10×10 m spacing recorded the highest SOC stock of 12.43 t ha^{-1}, which represented a 58.9% increase over the initial SOC. This treatment also produced the maximum equivalent CO_2 sequestration of 45.61 t ha^{-1}, corresponding to the same 58.9% enhancement compared with the initial value. The annual CO_2 sequestration rate under 10×10 m spacing was 6.52 t ha^{-1} y^{-1}, the highest among the seventh-year observations. Under 12×10 m spacing, SOC increased to 11.63 t ha^{-1}, representing a 48.7% increase over the initial value. Equivalent CO_2 sequestration also increased to 42.69 t ha^{-1}, indicating a 48.7% enhancement compared with the initial condition. The corresponding annual CO_2 sequestration rate was 6.10 t ha^{-1} y^{-1}. The minimum SOC and equivalent CO_2 sequestration values were observed initially (7.82 and 28.70 t ha^{-1}, respectively), while the maximum values were recorded under 10×10 m spacing at the seventh year. Compared with the 12×10 m spacing, the 10×10 m spacing showed a 6.9% higher SOC stocks, 6.8% higher equivalent CO_2 sequestration, and a 6.9% higher annual CO_2 sequestration rate. Overall, the results indicate that SOC stocks and carbon sequestration improved substantially on a temporal scale, with the 10×10 m spacing exhibiting the greatest enhancement.

Table 7. Buildup of soil organic carbon (SOC) stock in bamboo based agroforestry systems

Year (Age)	Spacing (m) (t ha^{-1})	SOC stock (t ha^{-1})	Eq. CO_2 seq. (t ha^{-1} y^{-1})	CO_2 Seq. rate
Initial	Baseline	7.82	28.70	-
7	10×10	12.43	45.61	6.52
7	12×10	11.63	42.69	6.10

[Eq: equivalent, Seq.: sequestration]

9. *Eucalyptus tereticornis* based agroforestry system

Eucalyptus tereticornis, commonly known as forest red gum, is a fast-growing multipurpose tree widely adopted in agroforestry systems for its high biomass production and adaptability to a range of soil and climatic conditions (Fig. 7). It is

Fig. 7. ***Eucalyptus tereticornis based*** **agroforestry with understory crops**

valued for timber, pulpwood, fuelwood, and carbon sequestration potential. The species contributes to farm income, provides protective shelter, and supports sustainable land use. Its rapid growth and substantial carbon storage capacity make it an important component of agroforestry-based climate change mitigation strategies.

Based on Table 8, a 5-year-old block plantation (3×3 m) recorded substantially higher biomass production and carbon sequestration than the agri-silviculture system (10×2 m). Aboveground biomass was 146.36 t ha^{-1} under block plantation compared with 65.86 t ha^{-1} under agri-silviculture, representing a 122.2% increase (Tiwari *et al*. 2013). Similarly, belowground biomass increased from 16.47 t ha^{-1} in agri-silviculture to 36.59 t ha^{-1} in block plantation, accounting for a 122.2% enhancement. Consequently, total tree biomass nearly doubled under block plantation, increasing from 82.33 t ha^{-1} in agri-silviculture to 182.96 t ha^{-1}, which corresponds to a 122.2% increase. Tree biomass carbon followed the same trend, with block plantation recording 91.48 t ha^{-1} compared with 41.17 t ha^{-1} under agri-silviculture, reflecting a 122.2% increase. Equivalent CO_2 sequestration was also markedly higher under block plantation, reaching a maximum of 335.72 t ha^{-1}, whereas agri-silviculture recorded 151.08 t ha^{-1}. This represents an overall 122.2% increase in CO_2 sequestration under block plantation. The annual CO_2 sequestration rate was highest in block plantation at 67.14 t $ha^{-1}y^{-1}$, compared with 30.22 t $ha^{-1}y^{-1}$ in agri-silviculture, indicating a 122.2% higher sequestration rate.

Overall, the results demonstrate that block plantation had the maximum values for all biomass and carbon sequestration parameters, while agri-silviculture recorded the minimum values. The consistent increase across all parameters highlights the superior potential of block plantation for biomass accumulation and carbon storage at the fifth year.

Table 8. Biomass and biomass carbon at different method of *E. tereticornis* plantation in agroforestry system

Year (Age)	Agroforestry system	Spacing (m)	Tree biomass components ($t\ ha^{-1}$)		Tree biomass ($t\ ha^{-1}$)	Tree biomass carbon ($t\ ha^{-1}$)	Eq. CO_2 Seq. ($t\ ha^{-1}$)	CO_2 Seq. rate ($t\ ha^{-1}\ y^{-1}$)
			Above ground (a)	Below ground (b)	(c=a+b)	(c*0.5)		
5	Agri-silviculture	10×2	65.86	16.47	82.33	41.17	151.08	30.22
5	Block plantation	3×3	146.36	36.59	182.96	91.48	335.72	67.14

[Eq: equivalent, Seq.: sequestration]

B. Agri-horticulture systems

1. *Emblica officinalis* based agroforestry systems

Emblica officinalis Gaertn. (synonymous *Phyllanthus emblica* L.), commonly known as Indian gooseberry or aonla, is a multipurpose fruit tree widely cultivated in agroforestry systems (Fig. 8). It is well adapted to arid and semi-arid regions and improves land productivity through efficient resource utilization and soil conservation. The species provides nutrient-rich fruits of high medicinal and economic value while enhancing soil organic carbon and supporting carbon sequestration. Its resilience, low management requirements, and compatibility with intercrops make it an important component of sustainable agroforestry systems.

Fig. 8. Glance of experimental fields with understory crops under *Emblica officinalis* based agroforestry

The data presented in Table 2 revealed that a 12-year-old *Emblica officinalis* based agroforestry system, with a spacing 8×8 m, showed the mean SOC in the surface (0–15 cm) and sub-surface (15–30 cm) soil layer as 0.32 and 0.28%, respectively. Based on Table 9, tree biomass, biomass carbon, CO_2 sequestration, and soil organic carbon stock increased markedly with plantation age. The 27-year-old stand recorded the highest values for all parameters, whereas the 12-year-old stand showed the minimum values. Aboveground biomass increased from 9.91 t ha^{-1} at twelve years to 23.80 t ha^{-1} at twenty-seventh years, representing a 140.2% increase (Newaj *et al*. 2012; Alam *et al*. 2026). Similarly, belowground biomass increased from 2.48 to 7.04 t ha^{-1}, corresponding to a 183.9% increase. Consequently, total tree biomass increased from 12.39 to 30.84 t ha^{-1}, recording an overall 148.9% enhancement. Tree biomass carbon followed the same trend, increasing from 6.20 to 15.42 t ha^{-1}, which represents a 148.7% increase. Equivalent CO_2 sequestration also increased substantially from 22.74 t ha^{-1} in the twelfth year to 56.60 t ha^{-1} in the twenty-seventh year, accounting for a 148.9% increase. The annual CO_2 sequestration rate from tree biomass increased slightly from 1.89 to 2.10 t ha^{-1} y^{-1}, indicating an 11.1% increase with age. Soil carbon showed the most pronounced improvement, increasing from 5.89 to 33.73 t ha^{-1}, which represents a 472.5% increase. Likewise, equivalent soil CO_2 sequestration increased from 21.62 to 123.79 t ha^{-1}, and the soil CO_2 sequestration rate increased from 1.80 to 4.58 t ha^{-1} y^{-1}, corresponding to a 154.4% increase. Overall, the results indicate that older plantations accumulated substantially greater biomass and carbon stocks than younger plantations.

Table 9. Biomass carbon and soil organic carbon (SOC) stock at different age in *Emblica officinalis* based agroforestry system

Year (Age)	Tree biomass components (t ha^{-1})		Tree biomass (t ha^{-1}) (c=a+b)	Tree biomass carbon (t ha^{-1}) (c*0.5)	Eq. CO_2 Seq. (t ha^{-1})	CO_2 Seq. rate (t ha^{-1} y^{-1})	SOC stock* (t ha^{-1})	Eq. CO_2 Seq. (t ha^{-1})	CO_2 Seq. rate (t ha^{-1} y^{-1})
	Aboveground (a)	Belowground (b)							
12	9.91	2.48	12.39	6.20	22.74	1.89	5.89	21.62	1.80
27	23.80	7.04	30.84	15.42	56.60	2.10	33.73	123.79	4.58

*up to 0-30 cm [Eq: equivalent, Seq.: sequestration]

2. *Psidium guajava* based agroforestry systems

Psidium guajava L., commonly known as guava, is a widely cultivated fruit tree integrated into agroforestry systems due to its high economic value, adaptability, and compatibility with intercrops (Fig. 9). It thrives under diverse agro-climatic conditions and contributes to soil conservation, organic matter accumulation, and carbon sequestration. The species produces nutrient-rich fruits with high market demand while providing additional farm income. Its efficient resource utilization and sustainable production make guava an important component of diversified agroforestry systems.

Fig. 9. Glance of *Psidium guajava* based agroforestry in experimental field

An experiment was laid out with *Psidium guajava* based agroforestry system on a temporal scale. The experiment was conducted up to eight years with a spacing 10×10 m. The tree biomass components exhibited a marked increase with plantation age, indicating progressive biomass accumulation and enhanced carbon sequestration potential (Table 10). Aboveground biomass increased steadily from a minimum of 1.73 t ha^{-1} in the third year to a maximum of 3.72 t ha^{-1} in the eighth year, reflecting a 115.0% increase. Likewise, belowground biomass nearly doubled from 0.58 to 1.24 t ha^{-1}, representing a 113.8% increase. Consequently, total tree biomass increased consistently from 2.30 t ha^{-1} in the third year to 4.96 t ha^{-1} in the eighth year, accounting for a 115.7% increase (NRCAF Annual Report 1995-96). The largest year-to-year increase in total biomass was observed between the sixth and seventh year (30.3%), followed by the transition from the third to fourth year (34.3%), whereas only a marginal increase (1.2%) occurred between the seventh and eighth year, indicating that biomass accumulation slowed as the trees approached maturity. Tree biomass carbon followed a similar trend, increasing from 1.15 to 2.48 t ha^{-1} (115.7% increase). Equivalent CO_2 sequestration also increased continuously from 4.22 to 9.09 t ha^{-1}, corresponding to a 115.4% enhancement, with the maximum value recorded in the eighth year and the minimum in the third year. In contrast, the annual CO_2 sequestration rate varied only slightly, ranging from 1.14 to 1.42 t ha^{-1} y^{-1}. The highest sequestration rate was observed during the fourth year (1.42 t $ha^{-1}y^{-1}$), followed closely by the third year (1.41 t ha^{-1} y^{-1}), while the lowest occurred in the eighth year (1.14 t ha^{-1} y^{-1}), suggesting that although cumulative biomass and carbon stocks continued to increase with age, the annual rate of carbon sequestration gradually declined in the mature stage.

Table 10. Tree biomass and biomass carbon at different years in *Psidium guajava* based agroforestry system

Year (Age)	Tree biomass components ($t\ ha^{-1}$)		Total tree biomass ($t\ ha^{-1}$)	Tree biomass carbon ($t\ ha^{-1}$)	Eq. CO_2 Seq. ($t\ ha^{-1}$)	CO_2 Seq. rate ($t\ ha^{-1}\ y^{-1}$)
	Aboveground (a)	Belowground (b)	(c=a+b)	(c*0.5)		
3	1.73	0.58	2.31	1.15	4.22	1.41
4	2.32	0.77	3.09	1.55	5.68	1.42
5	2.41	0.80	3.21	1.61	5.89	1.18
6	2.82	0.94	3.76	1.88	6.89	1.15
7	3.68	1.23	4.91	2.45	8.99	1.28
8	3.72	1.24	4.96	2.48	9.09	1.14

[Eq: equivalent, Seq.: sequestration]

3. *Ziziphus jujube* based agroforestry systems

Ziziphus jujube Lam., commonly known as Indian jujube or ber, is a hardy, drought-tolerant fruit tree widely grown in agroforestry systems of arid and semi-arid regions (Fig. 10). It is valued for its adaptability to marginal soils, low water requirement, and compatibility with intercrops. The species provides nutritious fruits, fodder, and fuelwood while improving soil fertility, reducing erosion, and enhancing carbon sequestration, particularly in arid and semiarid conditions. Its resilience and economic importance make it an ideal component of sustainable agroforestry systems.

Fig. 10. Glance of experimental fields with understory crops under *Ziziphus jujube* based agroforestry

An experiment was laid out with *Ziziphus jujube*-based agroforestry system on a temporal scale. The experiment was conducted up to eight years with a spacing 10 × 10 m. Tree biomass components increased consistently with plantation age, demonstrating continuous biomass production and carbon storage throughout the study period (Table 11). Aboveground biomass increased from the lowest value of 1.62 t ha^{-1} in the third year to the highest value of 3.78 t ha^{-1} in the eighth year, representing a 133.3% increase (NRCAF Annual Report 1995-96). Similarly, belowground biomass increased from 0.29 to 0.67 t ha^{-1}, recording a 131.0% increase. As a result, total tree biomass exhibited a substantial increase from 1.90 t ha^{-1} in the third year to 4.45 t ha^{-1} in the eighth year, corresponding to a 134.2% enhancement. The greatest year-to-year increase in total biomass occurred between the fourth and fifth year (39.5%), indicating the most vigorous growth phase, whereas the increase slowed markedly after the fifth year, with only a 3.1% increase between the fifth and sixth years and 4.2% between the seventh and eighth year, suggesting the onset of biomass stabilization. Tree biomass carbon followed a similar trend, increasing from 0.95 to 2.23 t ha^{-1} (134.7% increase), while equivalent CO_2 sequestration increased steadily from 3.49 to 8.17 t ha^{-1}, representing a 134.1% increase over the study period. In contrast, the annual CO_2 sequestration rate showed relatively small fluctuations, ranging from 1.02 to 1.31 t ha^{-1} y^{-1}. The highest sequestration rate was recorded in the fifth year (1.31 t ha^{-1} y^{-1}), followed by the fourth year (1.17 t ha^{-1}y^{-1}), whereas the lowest value was observed in the eighth year (1.02 t ha^{-1}y^{-1}). These findings indicate that although cumulative biomass and carbon stocks continued to increase with tree age, the annual rate of carbon sequestration gradually declined as the plantation matured.

Table 11. Tree biomass and biomass carbon at different years in *Ziziphus jujube* based agroforestry system

Year (Age)	Tree biomass components (t ha^{-1})		Total tree biomass (t ha^{-1})	Tree biomass carbon (t ha^{-1})	Eq. CO_2 Seq. (t ha^{-1})	CO_2 Seq. rate (t ha^{-1} y^{-1})
	Aboveground (a)	Belowground (b)	(c=a+b)	(c*0.5)		
3	1.62	0.29	1.90	0.95	3.49	1.16
4	2.18	0.38	2.56	1.28	4.70	1.17
5	3.03	0.54	3.57	1.79	6.55	1.31
6	3.13	0.55	3.68	1.84	6.75	1.12
7	3.63	0.64	4.27	2.14	7.84	1.12
8	3.78	0.67	4.45	2.23	8.17	1.02

[Eq: equivalent, Seq.: sequestration]

4. *Punica granatum* based agroforestry system

Punica granatum L., commonly known as pomegranate, is a high-value fruit tree widely incorporated into agroforestry systems due to its drought tolerance, adaptability, and economic importance (Fig. 11). It performs well under semi-arid and subtropical conditions and is compatible with a wide range of intercrops. The species contributes to soil conservation, carbon sequestration, and efficient land use while producing antioxidant-rich fruits with high market demand. Its productivity and resilience make it a valuable component of sustainable agroforestry systems.

Fig. 11. Glance of experimental fields with understory crops under *Punica granatum* based agroforestry.

An experiment was laid out with *Punica granatum* based agroforestry system on a temporal scale. The experiment was conducted up to eight years with a spacing 10×10 m. Tree biomass components increased progressively with plantation age, indicating continuous biomass accumulation and enhanced carbon sequestration potential throughout the study period (Table 12). Aboveground biomass exhibited a steady rise from 1.84 to 3.87 t ha^{-1}, corresponding to a 110.3% increase. Similarly, belowground biomass increased from a minimum of 0.46 t ha^{-1} in the third year to a maximum of 0.97 t ha^{-1} in the eighth year, representing a 110.9% increase (NRCAF Annual Report 1995-96). As a result, total tree biomass increased from 2.30 t ha^{-1} in the third year to 4.84 t ha^{-1} in the eighth year, accounting for an overall 110.4% increase. The most pronounced year-to-year increase in total biomass occurred between the fourth and eighth year (38.3%), followed by gradual increments of 15.1%, 13.4%, 8.7%, and 7.3% during subsequent years, indicating rapid early growth followed by a progressive decline in biomass accumulation as the stand matured. Tree biomass carbon increased proportionally from 1.15 to 2.42 t ha^{-1}, reflecting a 110.4% increase, while equivalent CO_2 sequestration rose steadily from 4.22 to 8.88 t ha^{-1}, also representing a 110.4% enhancement over the study period. In contrast, the annual CO_2 sequestration rate showed a declining trend with increasing age, decreasing from a peak of 1.46 t ha^{-1} y^{-1} in the fourth year to the lowest value of 1.11 t ha^{-1} y^{-1} in the eighth year. Although cumulative biomass and carbon stocks continued to increase with age, the gradual decline in annual CO_2 sequestration rate suggests reduced annual carbon fixation efficiency in the later stages of plantation development.

Table 12. Tree biomass and biomass carbon at different years in *Punica granatum* based agroforestry system

Year (Age)	Tree biomass components (t ha^{-1})		Total tree biomass (t ha^{-1})	Tree biomass carbon (t ha^{-1})	Eq. CO_2 Seq. (t ha^{-1})	CO_2 Seq. rate (t ha^{-1} y^{-1})
	Aboveground (a)	Belowground (b)	(c=a+b)	(c*0.5)		
3	1.84	0.46	2.30	1.15	4.22	1.41
4	2.54	0.64	3.18	1.59	5.84	1.46
5	2.93	0.73	3.66	1.83	6.72	1.34
6	3.32	0.83	4.15	2.07	7.61	1.27
7	3.61	0.90	4.51	2.26	8.28	1.18
8	3.87	0.97	4.84	2.42	8.88	1.11

[Eq: equivalent, Seq.: sequestration]

Another experiment was laid out again with *Punica granatum* based agroforestry system on a temporal scale. In contrast to the previous setup, this experiment was conducted up to five years with a spacing 5×3 m. Based on Table 13, tree biomass components and carbon sequestration increased progressively from the third to the fifth year, indicating continuous growth and enhanced carbon storage with plantation age. Aboveground biomass increased from 3.46 t ha^{-1} in the third year to 6.39 t ha^{-1} in the fifth year, representing an 84.7% increase. Similarly, belowground biomass increased from 0.69 to 1.28 t ha^{-1}, recording an 85.5% increase. Consequently, total tree biomass increased from a minimum of 4.15 t ha^{-1} in the third year to a maximum of 7.67 t ha^{-1} in the fifth year, corresponding to an overall 84.8% increase. Tree biomass carbon followed the same trend, increasing from 2.08 to 3.83 t ha^{-1}, which represents an 84.1% increase. Equivalent CO_2 sequestration also increased steadily from 7.62 t ha^{-1} in the third year to 14.07 t ha^{-1} in the fifth year, reflecting an 84.6% enhancement over the study period. The annual CO_2 sequestration rate from tree biomass increased from 2.54 t ha^{-1} y^{-1} in the third year to 2.82 t ha^{-1} y^{-1} in the fourth year, followed by a slight decline to 2.81 t ha^{-1} y^{-1} in the fifth year. Soil organic carbon (SOC, 0–30 cm) stock also increased consistently from 20.0 to 25.9 t ha^{-1}, corresponding to a 29.5% increase. The equivalent SOC-derived CO_2 sequestration increased from 73.2 to 95.2 t ha^{-1}, while CO_2 sequestration rate in soil declined from 24.41 to 19.04 t ha^{-1} y^{-1}, indicating a gradual reduction in annual soil carbon sequestration rate with increasing plantation age.

Table 13. Biomass carbon and soil organic carbon (SOC) stock at different age in *Punica granatum* based agroforestry system

Year (Age)	Tree biomass components (t ha^{-1})		Tree bio-mass (t ha^{-1}) (c=a+b)	Tree bio-mass carbon (t ha^{-1}) (c*0.5)	Eq. CO_2 Seq. (t ha^{-1})	CO_2 Seq. rate (t ha^{-1} y^{-1})	SOC stock* (t ha^{-1})	Eq. CO_2 Seq. (t ha^{-1})	CO_2 Seq. rate (t ha^{-1} y^{-1})
	Aboveground (a)	Belowground (b)							
3	3.46	0.69	4.15	2.08	7.62	2.54	20.0	73.2	24.41
4	5.13	1.03	6.16	3.08	11.30	2.82	22.7	83.5	20.87
5	6.39	1.28	7.67	3.83	14.07	2.81	25.9	95.2	19.04

*up to 0-30 cm [Eq: equivalent, Seq.: sequestration]

5. *Citrus reticulata* based agroforestry systems

Citrus reticulata Blanco, commonly known as mandarin orange, is an economically important fruit tree widely cultivated in agroforestry systems of tropical and subtropical regions. It is valued for its high-quality fruits, adaptability, and compatibility with intercrops. The species contributes to soil conservation, improves land-use efficiency, and enhances carbon sequestration through perennial biomass accumulation. Its high economic returns, nutritional value, and suitability for diversified farming systems make it an important component of sustainable agroforestry practices.

An experiment was laid out with *Citrus reticulata* based agroforestry system on a temporal scale. The experiment was conducted up to eight years with a spacing 10×10 m (Fig. 12). Tree biomass components exhibited a continuous increase with plantation age, indicating sustained tree growth and progressive carbon accumulation throughout the study period (Table 14). Aboveground biomass increased steadily from 1.58 to 3.71 t ha^{-1}, recording a 134.8% increase. Likewise, belowground biomass increased from the minimum value of 0.53 t ha^{-1} in the third year to the maximum value of 1.24 t ha^{-1} in the eighth year, representing a 134.0% increase (NRCAF Annual Report 1995-96). Consequently, total tree biomass increased from 2.10 t ha^{-1} in the third year to 4.94 t ha^{-1} in the eighth year, corresponding to an overall 135.2% increase. The most substantial year-to-year increase in total biomass occurred between the third and fourth years (67.1%), indicating the most vigorous growth phase during the early establishment period. Thereafter, biomass accumulation slowed, with successive increases of 5.7%, 12.7%, 12.7%, and 4.9% from the fourth to eighth years, suggesting gradual stabilization as the plantation matured. Tree biomass carbon followed the same pattern, increasing from 1.05 to 2.47 t ha^{-1}, representing a 135.2% increase. Similarly, equivalent CO_2 sequestration increased steadily from 3.85 to 9.07 t ha^{-1}, reflecting a 135.6% enhancement, with the highest value recorded in the eighth year and the lowest in the third year. In contrast, the annual CO_2 sequestration rate showed a declining trend after the initial growth phase. The maximum sequestration rate (1.61 t ha^{-1} y^{-1}) was observed during the fourth year, whereas the minimum (1.13 t ha^{-1} y^{-1}) occurred in the eighth year, indicating that although cumulative biomass and carbon stocks continued to increase, the annual carbon sequestration efficiency gradually decreased with advancing plantation age.

Fig. 12. Glance of experimental field of *Citrus reticulata* based agroforestry

Table 14. Tree biomass and biomass carbon at different years in *Citrus reticulata* based agroforestry system

Year (Age)	Tree biomass components ($t\ ha^{-1}$)		Total tree biomass ($t\ ha^{-1}$)	Tree biomass carbon ($t\ ha^{-1}$)	Eq. CO_2 Seq. ($t\ ha^{-1}$)	CO_2 Seq. rate ($t\ ha^{-1}\ y^{-1}$)
	Aboveground (a)	Belowground (b)	(c=a+b)	(c*0.5)		
3	1.58	0.53	2.10	1.05	3.85	1.28
4	2.63	0.88	3.51	1.76	6.44	1.61
5	2.78	0.93	3.71	1.86	6.81	1.36
6	3.14	1.05	4.18	2.09	7.68	1.28
7	3.53	1.18	4.71	2.35	8.63	1.23
8	3.71	1.24	4.94	2.47	9.07	1.13

[Eq: equivalent, Seq.: sequestration]

C. Silvi-pasture systems

Silvi-pasture is an important agroforestry system that integrates trees, forage grasses, and livestock on the same land to enhance productivity, sustainability, and environmental quality. This land-use system improves the efficient utilization of natural resources by combining woody perennials with pasture species, thereby increasing biomass production, soil fertility, and livestock carrying capacity. Tree species such as *Dalbergia sissoo*, *Albizia procera*, *Hardwickia binata*, *Acacia nilotica*, and *Eucalyptus tereticornis etc.* provide timber, fuelwood, fodder, shade, and litter, while perennial grasses (*Cenchrus ciliaris or Stylosanthes hamata*) and legumes supply nutritious forage for livestock (Rai *et al*. 1995). Silvi-pasture systems also reduce soil erosion, improve soil organic carbon, enhance biodiversity, and sequester significant amounts of atmospheric carbon (Fig. 13). Their resilience to drought and climate variability makes them particularly suitable for degraded lands and rainfed regions, offering a sustainable approach to increasing farm income, restoring ecosystem services, and supporting climate-smart agriculture.

Based on Table 15, substantial variation was observed among the tree species in terms of biomass production, carbon storage, and CO_2 sequestration potential. Among all the species, *Leucaena leucocephala* recorded the maximum values for aboveground biomass (6.93 t ha^{-1}), belowground biomass (1.80 t ha^{-1}), total tree biomass (8.74 t ha^{-1}), tree biomass carbon (4.37 t ha^{-1}), equivalent CO_2 sequestration (16.03 t ha^{-1}), and CO_2 sequestration rate (3.21 t ha^{-1} y^{-1}). In contrast, *Eucalyptus tereticornis* exhibited the minimum values, with aboveground biomass of 0.49 t ha^{-1}, belowground biomass of 0.13 t ha^{-1}, total biomass of 0.62 t ha^{-1}, biomass carbon of 0.31 t ha^{-1}, equivalent CO_2 sequestration of 1.13 t ha^{-1}, and CO_2 sequestration rate of 0.23 t ha^{-1} y^{-1}.

Among the remaining species, *Dalbergia sissoo* ranked second, producing 5.75 t ha^{-1} total biomass and 10.55 t ha^{-1} equivalent CO_2 sequestration, followed by *Melia azedarach* (4.60 t ha^{-1} biomass and 8.44 t ha^{-1} CO_2 sequestration) and *Albizia procera* (4.34 t ha^{-1} biomass and 7.96 t ha^{-1} CO_2 sequestration). Compared with *Eucalyptus tereticornis*, *Leucaena leucocephala* produced approximately 1309.7% greater total biomass and 1318.6% higher CO_2 sequestration, highlighting its superior productivity. Similarly, *Dalbergia sissoo* accumulated 85.4% more total biomass and 32.4% more CO_2 sequestration than *Melia azedarach*. Overall, the results demonstrate a consistent positive relationship between biomass accumulation, carbon stock, and CO_2 sequestration across species, with *Leucaena leucocephala*, *Dalbergia sissoo*, and *Albizia procera* emerging as the most efficient species for biomass production and climate change mitigation in silvi-pasture based agroforestry systems.

Fig. 13. A glance of *Albizia procera* and *Tectona grandis* based slivi-pasture system

Soil organic carbon under the silvi-pasture systems

Soil organic carbon (SOC) is a key indicator of soil health, fertility, and ecosystem sustainability in silvi-pasture systems. The integration of trees with pasture grasses (*Chrysopogon fulvus*; *Stylosanthes hamata*; *S. scabra*) enhances SOC accumulation through continuous inputs of leaf litter, root biomass, and organic residues, while reducing soil erosion and improving nutrient cycling. Tree species such as *Dalbergia sissoo*, *Albizia procera*, *Leucaena leucocephala*, and *Hardwickia binata etc.* (Rai *et al*. 2009). contribute significantly to carbon storage by increasing belowground biomass and microbial activity. Variations in SOC among different silvi-pasture systems are influenced by tree

Table 15. Tree biomass and biomass carbon at 5-year-age under different silvi-pasture system

Species with spacing	Tree biomass components ($t\ ha^{-1}$)		Total tree biomass ($t\ ha^{-1}$)	Tree biomass carbon ($t\ ha^{-1}$)	Eq. CO_2 Seq. ($t\ ha^{-1}$)	CO_2 Seq. rate ($t\ ha^{-1}\ y^{-1}$)
	Aboveground (a)	Belowground (b)	(c=a+b)	(c*0.5)		
D. cinerea	2.54	0.66	3.20	1.60	5.86	1.17
M. azedarach	3.65	0.95	4.60	2.30	8.44	1.69
L. leucocephala	6.93	1.80	8.74	4.37	16.03	3.21
A. nilotica subsp. *cupressiformis*	2.75	0.72	3.47	1.73	6.36	1.27
E. officinalis	1.57	0.41	1.97	0.99	3.62	0.72
A. amara	1.42	0.37	1.79	0.89	3.28	0.66
A. nilotica subsp. *indica*	2.39	0.62	3.01	1.50	5.52	1.10
H. binata	0.71	0.18	0.89	0.44	1.63	0.33
A. procera	3.44	0.89	4.34	2.17	7.96	1.59
D. sissoo	4.56	1.19	5.75	2.88	10.55	2.11
E. tereticornis	0.49	0.13	0.62	0.31	1.13	0.23
A. indica	1.22	0.32	1.54	0.77	2.83	0.57
T. arjuna	1.47	0.38	1.85	0.93	3.40	0.68
A. pendula	0.58	0.15	0.74	0.37	1.35	0.27

[Eq: equivalent, Seq.: sequestration]

species, litter quality, root turnover, pasture composition, and management practices. Higher SOC not only improves soil physical, chemical, and biological properties but also enhances carbon sequestration, mitigates greenhouse gas emissions, and supports sustainable livestock production. Therefore, evaluating SOC under different silvi-pasture systems is essential for assessing their long-term productivity, environmental benefits, and role in climate-smart land-use management.

Based on Table 16, SOC, equivalent CO_2 sequestration, and annual CO_2 sequestration rate increased substantially after 10 years under the studied silvi-pasture systems compared with the initial condition. The initial SOC in the 0–30 cm soil depth was 15.56 $t\ ha^{-1}$, corresponding to an equivalent CO_2 sequestration of 57.11 $t\ ha^{-1}$.

Among the silvi-pasture systems, *Dalbergia sissoo* recorded the highest SOC stock (33.32 t ha^{-1}), representing a 114.1% increase over the initial value. This was followed by *Acacia nilotica* (28.93 t ha^{-1}; 85.9% increase), *Hardwickia binata* (26.73 t ha^{-1}; 71.8% increase), and the control (pasture without tree) (25.14 t ha^{-1}; 61.6% increase). A similar trend was observed for equivalent CO_2 sequestration, where *Dalbergia sissoo* recorded the maximum value of 122.27 t ha^{-1}, followed by *Acacia nilotica* (106.16 t ha^{-1}), *Hardwickia binata* (98.11 t ha^{-1}), and the control (92.25 t ha^{-1}). Compared with the initial value, equivalent CO_2 sequestration increased by 114.1%, 85.9%, 71.8%, and 61.5%, respectively.

The annual CO_2 sequestration rate also varied among species, with the maximum value recorded under *Dalbergia sissoo* (12.23 t ha^{-1} y^{-1}), followed by *Acacia nilotica* (10.62 t ha^{-1} y^{-1}), *Hardwickia binata* (9.81 t ha^{-1} y^{-1}), and the control (9.23 t ha^{-1} y^{-1}). Overall, the results demonstrate that silvi-pasture systems significantly enhanced soil carbon storage and CO_2 sequestration compared with the control, with *Dalbergia sissoo* exhibiting the greatest potential for long-term carbon accumulation and climate change mitigation.

Table 16. Soil organic carbon (SOC) stock (0-30 cm) of multi-purpose tree species at 10-year-age under different silvi-pasture systems

Year (Age)	Species	SOC stock (t ha^{-1})	Eq. CO_2 seq. (t ha^{-1})	CO_2 Seq. rate (t ha^{-1} y^{-1})
1	Baseline	15.56	57.11	-
10	Control (pasture without tree)	25.14	92.25	9.23
10	*A. nilotica*	28.93	106.16	10.62
10	*D. sissoo*	33.32	122.27	12.23
10	*H. binata*	26.73	98.11	9.81

[Eq: equivalent, Seq.: sequestration]

Allometric equations used for biomass estimation

Table 17 presents the allometric equations used for estimating tree biomass on a kg $tree^{-1}$ basis for different agroforestry species. The equations use tree dimensions such as diameter at breast height (DBH), collar diameter (CD), or age as predictor variables to estimate total biomass (T_1), aboveground biomass (T_3), and belowground biomass (T_2). For *Dalbergia sissoo*, total biomass is estimated as $0.904(DBH)^{1.760}$, and belowground biomass as $0.198(DBH)^{1.760}$; aboveground biomass is calculated as $T_3 = T_1 - T_2$. Similar equations are used for *Hardwickia binata* and *Albizia procera*, with species-specific coefficients and exponents. Among these, *Albizia procera* shows a higher DBH exponent (2.494) than *Dalbergia sissoo* and *Hardwickia binata*, indicating a stronger increase in biomass with increasing stem diameter. For *Acacia senegal*, *Tectona grandis*, and *Acacia* *nilotica*, aboveground biomass is estimated first, while belowground biomass is assumed to be 26% of aboveground biomass. Total biomass is then calculated as $T_1 = T_2 + T_3$. Among all species, *Tectona grandis* has the highest DBH exponent (2.6135), suggesting a rapid increase in biomass with diameter growth. For *Emblica officinalis*, biomass estimation is based on collar diameter (CD), with total biomass estimated as $2.994(CD)^{1.285}$ and belowground biomass as $0.622(CD)^{1.313}$; aboveground biomass is obtained by subtracting belowground biomass from the total biomass. Fruit tree species such as *Psidium guajava* and *Punica granatum* use CD-based equations for aboveground biomass, while *Citrus reticulata* uses an age-based equation [$y = 0.395(AGE)^{2.12}$].

Overall, Table 17 highlights species-specific biomass estimation approaches that account for differences in growth form, stem architecture, and root-to-shoot relationships, thereby improving the accuracy of biomass and carbon stock assessments.

Table 17. Allometric equations for biomass estimation of different tree species

Tree	Tree component (kg/tree)	Allometric equation	References
Dalbergia sissoo	Total biomass (T_1)	$0.904(DBH)^{1.760}$	Newaj *et al.* 2012
	Belowground biomass (T_2)	$0.198(DBH)^{1.760}$	
	Aboveground biomass (T_3)	$T_3=T_1-T_2$	
Hardwickia binata	Total biomass (T_1)	$0.158(DBH)^{2.338}$	Newaj *et al.* 2012
	Belowground biomass (T_2)	$0.036(DBH)^{2.337}$	
	Aboveground biomass (T_3)	$T_3=T_1-T_2$	
Albizia procera	Total biomass (T_1)	$0.102(DBH)^{2.494}$	Newaj *et al.* 2012
	Belowground biomass (T_2)	$0.031(DBH)^{2.494}$	
	Aboveground biomass (T_3)	$T_3=T_1-T_2$	
Acacia senegal	Aboveground biomass (T_3)	$0.904(DBH)^{1.760}$	Newaj *et al.* 2012, 2014
	Belowground biomass (T_2)	0.26x Aboveground biomass	
	Total biomass (T_1)	$T_1=T_2 + T_3$	
Tectona grandis	Aboveground biomass (T_3)	$0.0758(DBH)^{2.6135}$	Negi et al. 1995; Ravindranath and Ostwald 2008
	Belowground biomass (T_2)	0.26x Aboveground biomass	
	Total biomass (T_1)	$T_1=T_2 + T_3$	
Emblica officinalis	Total biomass (T_1)	$2.994(CD)^{1.285}$	Newaj *et al.* 2016
	Belowground biomass (T_2)	$0.622(CD)^{1.313}$	
	Aboveground biomass (T_3)	$T_3=T_1 - T_2$	

Acacia nilotica	Aboveground biomass (T_3)	$0.904(DBH)^{1.760}$	Newaj *et al.* 2012, 2014; Prasad *et al.* 2020
	Belowground biomass (T_2)	0.26x Aboveground biomass	
	Total biomass (T_1)	$T_1=T_2+T_3$	
Psidium guajava	Aboveground biomass (y)	$y=3.264(CD)^{1.012}$	Naik *et al.* 2021
Punica granatum	Aboveground biomass (y)	$y=0.215(CD)^{1.998}$	Arkalgud *et al.* 2023
Citrus reticulata	Aboveground biomass (y)	$y=0.395(AGE)^{2.12}$	Ledo *et al.* 2018

Chapter 5 Epilogue

The technical bulletin has details about the status of the carbon pool in different agroforestry systems prevailing at the research farm of CAFRI, Jhansi located in semi-arid climatic conditions of Bundelkhand region of Central India. Highlights were the observed dynamics of build-up of carbon in soil and in tree biomass components (aboveground and belowground) in various category of major agroforestry systems namely agri-silviculture, agri-horticulture, silvipusture and block plantation involving prominent multipurpose tree species of agroforestry importance. Based on the available data and information, highest soil organic carbon (SOC) was noted in teak based agroforestry system with the corresponding time scale of 28 years of age. On the other hand, relatively higher biomass carbon was also noted in teak based systems with the corresponding time scale. Overall, agri-silviculture exhibited relatively higher potential for carbon capturing in both soil and biomass component.

The long term presence of trees in the systems clearly indicated how the roots that bind the soil, the canopies that shield the land surface and the agroforestry systems that sustain ecosystem functions over the years. Further, data in this compilation demonstrate that the accumulation of biomass above ground and the stabilization of deep-soil carbon belowground are the main components, which supports the agroforestry for its potential for long term carbon storage. These properties of agroforestry systems vividly indicate that tree-based solutions *i.e.* agroforestry are having enormous capacity of buffering environmental deterioration due to climate change, ecosystems balance through upholding soil health against climate vulnerability while securing food, fodder and timber security.

The bulletin has emphasized the tree species involved in the agroforestry practices to depict the long term build-up of soil organic carbon and tree biomass carbon. There are clear trends of increasing carbon in different carbon pools throughout the course of the stand duration depending upon the types of agroforestry system and or the tree species selection. Besides, carbon storage, CO_2 sequestration potential is also another important derived tangible benefit from agroforestry systems that also needs to be brought into the focus for upscaling the agroforestry adoption among all the stakeholders including marginal farmers in the context of changing climate scenarios in the days ahead.

6 Future Perspectives

This document is aligned with the profound commitment to secure the future of various sectors through national missions namely National Mission for a Green India, National Mission for Sustainable Agriculture, National Mission on Strategic Knowledge for Climate Change, National Action Plan for Climate Change (NAPCC), National Food Security Mission and National Bamboo Mission . Similarly, it has been envisaged in line with the mission mode approach to fulfil many of the enlisted Sustainable Development Goals (SDGs) and Nationally Determined Contribution (NDC) in reducing carbon emission through alternate land-use planning like increasing tree cover through agroforestry. This document with the collective information on agroforestry systems, carbon stock and the potential of CO_2 sequestration of the agroforestry systems would facilitate to achieve many of the SDGs prominently SDG-1 (no poverty); SDG-2 (no hunger); SDG-8 (good jobs and economic growth); SDG-13 (climate action) and SDG-15 (life on land) through judicial use of agroforestry by the stakeholders. The data and information in this document would also augment the prospects of India's commitments which are aligned with vision of 'Viksit Bharat@2047' and 'Net-Zero by 2070' for wider perspectives through the scope of implementing agroforestry in mission mode. Efforts towards transforming agricultural landscapes into resilient carbon sinks, agroforestry deserves high priority in terms of both scientific validation and fullest support for required policy level implementation. It also requires an alignment of policy incentives, equitable carbon markets, local ecological perception, and smooth facilitation for end users' prospects. The long-term permanence of sequestered carbon is essentially fixed to the permanence of the livelihoods that are supported through agroforestry practices. The output of scientific research to establish the agroforestry systems as wonderful sinks for carbon are well proven. However, there is greater challenge to transform the research output to remarkable outcome for the wider benefits of all the stakeholders including the farmers. For the immediate future, the emphasis would be to increase awareness and popularity of agroforestry practices among the framers and other potential stakeholders of their choices providing the information for adopting suitable agroforestry with knowhow to manage and to sustain in the competitive environment. In this direction, contribution from research on enhancing higher carbon storage in agroforestry and equally emphasized policy level support for all the stakeholders including the farmers need to be strengthened simultaneously for inculcating a legacy of soil health and fertility, climate stability and resilience for the future-ready agroforestry.

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