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ESTIMATION OF SOIL ORGANIC CARBON AND ABOVE GROUND BIOMASS IN PLANTATION SITES AND AGROFORESTRY SYSTEMS IN SEMI-ARID REGION OF CHITTORGARH DISTRICT RAJASTHAN INDIA

Mushrif Ahmed Khan, Deepak Mishra* and Khushi Ram Choudhary

Department of Forestry, Faculty of Agriculture & Veterinary Sciences, Mewar University, Gangrar, Chittorgarh, Rajasthan, 301406, India

*Corresponding author E-Mail: mishra.deepak78@gmail.com

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ABSTRACT

This research investigates the Soil Organic Carbon dynamics, Above Ground Biomass, and vegetation carbon stock of pure plantation units (T_1), boundary plantation areas (T_2), and scattered agroforestry systems (T_3) in the semi-arid region of Chittorgarh district of Rajasthan from February 2026 to May 2026 by collecting data from several field sites. The parameters of the trees and the soil characteristics (for the soil depth of 0-15 cm and 15–30 cm) were taken for examining the structural effect of the plantation on the carbon capture potential. Structural configurations affected the growth of trees as well as their structures. Maximum vertical growth was observed in pure plantations (T_1) that reached up to 16.0 m with *Tectona grandis* species having a stand basal area of 44.86 m². On the contrary, scattered trees (T_3) offered larger girth growth of trunks with the largest girth of 230.0 cm attained in *Mangifera indica* species.

The amount of biomass and carbon stored was substantially different among the different densities and types of trees. The densest species (T_1) had the highest mean AGB (1.22 Mg ha⁻¹) and functioned as the largest carbon sink, absorbing 548 Mg of carbon per hectare at most, while *T. grandis* managed to absorb as much as 1121 Mg of carbon per hectare. The carbon absorption in boundary rows (T_2) and scattered systems (T_3) amounts to 229 and 239.0 Mg of carbon, respectively. The analysis of the soil showed that its volume density was 1.04 g cm⁻³ under scattered trees, the acidity of the soil was neutral (7.26), and the level of salinity was 0.420 dSm⁻¹. The organic carbon content in the soil was also different on different levels of soil: at the depth of 0 to 15 cm it was higher (1.44%) than at 15 to 30 cm (1.18%). Thus, the total SOC was as follows: T_1 (264.37 Mg ha⁻¹) > T_2 (253.86 Mg ha⁻¹) > T_3 (225.01 Mg ha⁻¹). This evidence shows that plantation geometry and the principles of agroforestry are vital for improving biomass production and long-term carbon storage in soil in semi-arid climatic conditions.

Key word: Soil Organic Carbon, Agroforestry, Carbon Sequestration, Biomass

Introduction

Climate change mitigation through carbon sequestration has emerged as a critical global challenge, with agroforestry systems playing a pivotal role in atmospheric carbon dioxide (CO₂) reduction. Increasing the atmospheric CO₂ concentrations in the atmosphere due to fossil fuel burning, industrialization, expansion of urbanization, deforestation and agriculture waste burning such as Parali burning of rice, wheat and other crops is major cause of hiking the CO₂ (O'Connor, 2020).

The Agroforestry systems have emerged as a promising solution for climate change mitigation through many type of AF systems, for example silvipasture model in which the trees used as carbon pool and agrisilviculture, hortisilviculture these models are hold carbon for long period with the potential to sequester up to 2.2 Pg C over 50 years through above- and below-ground carbon storage (Lorenz, 2014).

Plantations and agroforestry systems significantly contribute to carbon sequestration through biomass

accumulation and soil carbon enhancement (Lal, 2004; IPCC, 2019).

The soil organic carbon pool represents a particularly valuable terrestrial carbon reservoir, capable of storing carbon for millennia when managed through appropriate agroforestry practices (Lorenz, 2014).

Carbon is stored in Soil while atmospheric carbon dioxide is increasing through human influences that are noted as being responsible for climate change leading to global warming (Prentice, 2001).

India's diverse agroforestry landscape lies approximately 28.42 million hectares, with significant concentrations in states including Rajasthan (1.6 million ha), which ranks third nationally in agroforestry coverage. These systems range from simple monoculture block plantations to complex multi-species arrangements like home gardens, each exhibiting distinct biomass production and carbon sequestration characteristics. The carbon storage potential varies considerably across agro-climatic zones, with western and central India, including Rajasthan's arid regions, typically recording lower total biomass (<50 Mg ha⁻¹) compared to humid tropical regions (Panwar, 2022).

Soil Organic Carbon (SOC) constitutes approximately 58% of soil organic matter and is a key indicator of soil health, fertility, and climate mitigation potential (Walkley & Black, 1934; Lal, 2004). Above Ground Biomass (AGB) represents the largest carbon pool in forested systems and is commonly estimated using species-specific or generalized allometric equations (Brown, 1997; Chave, 2014).

Material and Method

Research was done between February and May 2026 across various locations in the district of Chittorgarh in Rajasthan. These locations included Gangrar, Bassi, Lambiya, Det, Ordi, Hamirgarh, Gurjaniya, Soniyana and

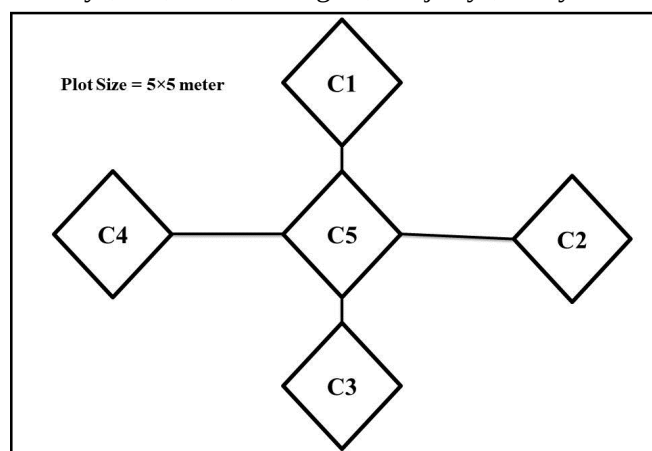


Fig. 1: Cluster Sampling Protocol.

Chogawadi. In addition to these sites, the average rainfall is 852 millimetres and Chittorgarh is positioned at coordinates of 24.8887 degrees north latitude and 74.6269 degrees east longitude. The climate lies under semi-arid condition. The study carried out in different plantation sites and agroforestry systems. In plantation sites pure plantation was taken for study and we adapted cluster sampling method for sample collection and in agroforestry systems, we took boundary plantation and scattered trees in AF systems, in both treatment boundary and scattered we took soil sample under half of tree canopy and five meters apart from canopy. The soil sampling was carried out in 0-15 cm and 15-30 cm soil depth.

In tree parameters we considered tree height using tree clinometer, and girth at breast height of 3.14 meter from ground level and total ABC, total Carbon in trees and Crown expansion and Basal Area was determined by mathematical equations. After those field collections we tested the samples in laboratory, the Bulk Density, pH, EC and SOC % ranges were extracted from samples. The calculations based on these formulas:

Parameter	Formula
Girth to Diameter	$\frac{G}{3.14}$
AGB (kg) in Trees	$0.181494261 \times D^2 \times 2.058650773$
Total Carbon in Trees (C)	Biomass $\times 0.4477$
Tree Basal Area	$0.005454 \times D^2$
Soil Bulk Density	Bulk Density (BD) = $\frac{\text{mass of oven - dry soil}}{\text{total volume of core}}$
Soil pH	Potentiometric method (1:2: soil: water suspension)
Soil EC	solubridge (dSm-1) at 25°C
Soil SOC %	$\text{SOC \%} = 10 \times \frac{B - S}{B} \times \frac{0.003}{1} \times 100$
Soil SOC (ton/ha.)	$\text{SOC (ton/ha)} = \frac{\text{SOC \%}}{100} \times 0.3 \times \text{BD} \times 10000$

For the data interpretation the best model for prediction of each biomass fraction was selected based on the highest value of the coefficient of determination (R²) among different curves.

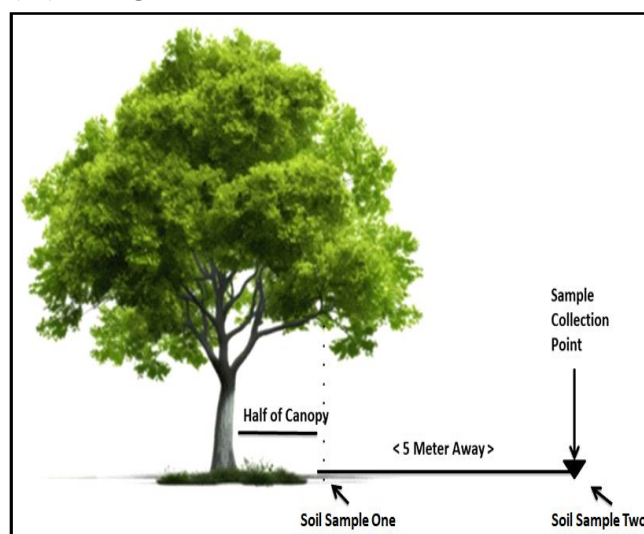


Fig. 2: Soil Sample Protocol.

Table 1: Tree Growth parameters of all treatments and their replications.

T/R	Tahsil	Tree Species	Year of Planting	Tree Height (m)	Tree Girth (cm)	Tree crown (m)	Basal Area (m ²)
T ₁ /R ₁	Gangrar	<i>T. grandis</i>	2012	12	49.41	3.58	59.34
T ₁ /R ₂	Chittorgarh	<i>T. grandis</i>	2009	12.5	60.26	6.16	90.75
T ₁ /R ₃	Gangrar	<i>T. grandis</i>	2011	16	58.44	4.53	50.73
T ₁ /R ₄	Gangrar	<i>Eucalyptus spp.</i>	2024	4	13.41	1.53	5.13
T ₁ /R ₅	Chittorgarh	<i>Eucalyptus spp.</i>	2023	12.5	17.64	0.95	18.36
T ₂ /R ₁	Gangrar	<i>Eucalyptus spp.</i>	2019	13	47	9.45	12.97
T ₂ /R ₂	Chittorgarh	<i>Eucalyptus spp.</i>	2018	14	55.28	11.60	17.56
T ₂ /R ₃	Gangrar	<i>T. grandis</i>	2018	14.5	47.87	9.79	14.70
T ₂ /R ₄	Gangrar	<i>A. indica</i>	2016	7.5	60.11	15.81	28.03
T ₂ /R ₅	Chittorgarh	<i>L. leucocephala</i>	2020	13	56.42	13.54	19.86
T ₃ /R ₁	Gangrar	<i>M. indica</i>	1995	14.5	175	11.56	24.38
T ₃ /R ₂	Chittorgarh	<i>M. indica</i>	1990	7	230	9.45	42.12
T ₃ /R ₃	Hamirgarh	<i>V. nilotica</i>	2000	14	143	14.35	16.28
T ₃ /R ₄	Gangrar	<i>D. sissoo</i>	2006	9	105	8.95	8.78
T ₃ /R ₅	Chittorgarh	<i>B. monosperma</i>	1998	10	137	13.23	14.94

Result and Discussion

Tree Growth & Architectural Parameters

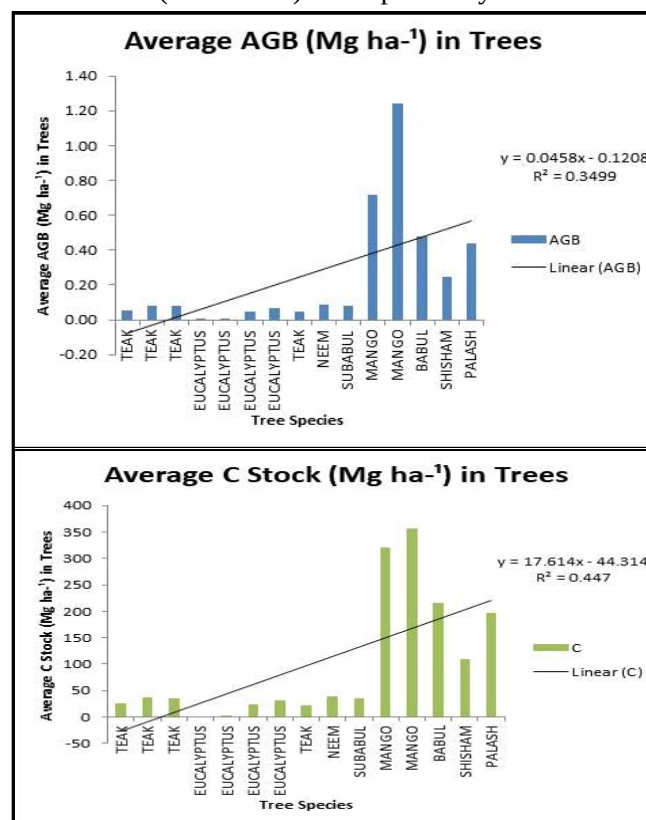
The growth dynamics and architectural attributes of the assessed tree species exhibited significant variations across the three structural treatments: pure plantations (T₁), boundary plantations (T₂), and scattered trees within agroforestry systems (T₃).

Tree Height: Vertical growth reached its peak in T₁ and T₂, where *T. grandis* registered a maximum height of 16.0 m. In contrast, the maximum height recorded within the scattered agroforestry systems (T₃) was 14.5 m for *M. indica*. The lowest vertical allocation was noted in a young *Eucalyptus spp.* stand under T₁ at 4.0 m. A moderately strong positive correlation was observed between tree height and girth ($R^2 = 0.4795$). Jain and Ansari (2013) found corresponding vertical stratification and rapid initial height increments for *Tectona grandis* inside structural lines and block structures.

Girth at Breast Height (GBH): Structural configurations severely influenced stem diameter development. While the mean collective girth across all systems was 83.72 cm, isolated/scattered tree configurations (T₃) allowed for substantial radial expansion, yielding a mean girth of 158.0 cm and a maximum of 230.0 cm in *M. indica*. Conversely, high-density pure plantations (T₁) restricted individual radial development, resulting in the lowest mean girth of 39.83 cm. Singh and Singh (2015) documented significant dimensional variation between solitary tree controls and agroforestry combinations, demonstrating that spatial constraints dictate final primary and secondary cambial thickness.

Canopy and Crown Expansion:

Crown architecture responds to spatial disposition in a major way. High crown cover area is associated with T₂ and T₃, however the widest lateral spread for *A. indica* (T₂) (15.81m) was also associated with T₂. The smallest cover area recorded was for dense *Eucalyptus* plantations (T₁, 0.95m) and indicates a strong relationship between structural flexibility of open-grown trees and lateral crown architecture ($R^2=0.5115$). As reported by Kumar *et al.*,

**Fig. 3:** Average AGB in Trees and Average C Stock in Trees.

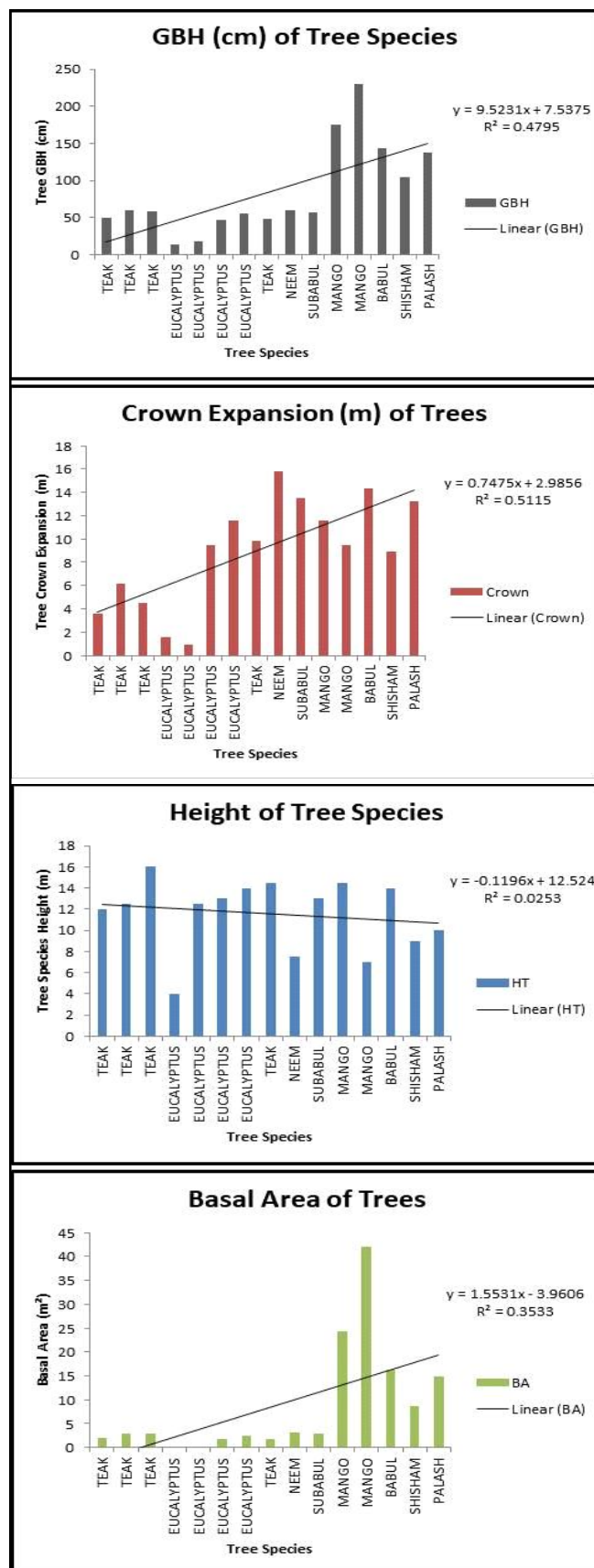


Fig. 4: GBH of Tree, Height of Trees, Crown Expansion of Trees and Basal Area of Trees under different species and treatment.

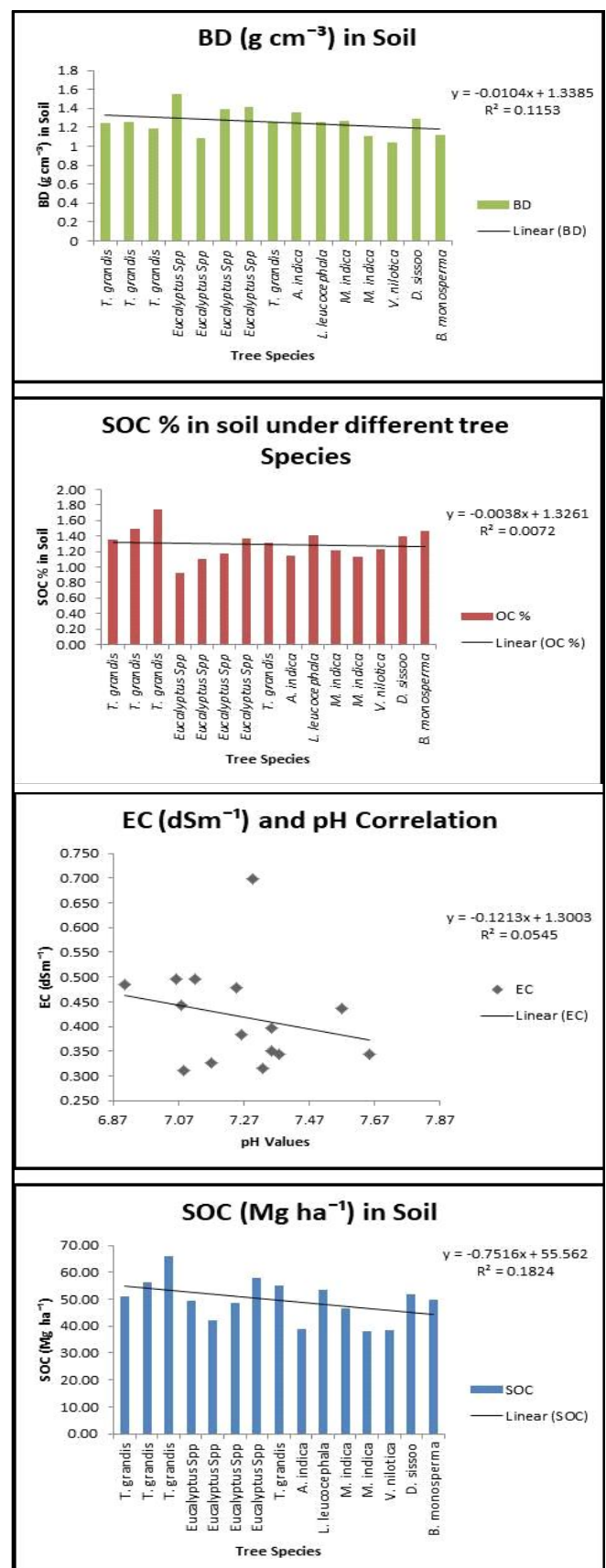


Fig. 5: BD in Soil, EC and pH Correlation, SOC % in Soil and SOC (Mg ha⁻¹) in Soil under different tree species and treatment.

Table 2: AGB accumulation and total C stock in trees of all treatments.

Treatment/ Replication	Tahsil	Tree Species	Total AGB in Tree (Mg ha ⁻¹)	Avr. AGB in Trees (Mg ha ⁻¹)	C stock in Tree (Mg C ha ⁻¹)	Avr. C stock in Tree (Mg ha ⁻¹)
T ₁ /R ₁	Gangrar	<i>T. grandis</i>	1.62	0.06	725	25
T ₁ /R ₂	Chittorgarh	<i>T. grandis</i>	2.51	0.08	1121	37
T ₁ /R ₃	Gangrar	<i>T. grandis</i>	1.40	0.08	625	35
T ₁ /R ₄	Gangrar	<i>Eucalyptus spp.</i>	0.13	0.00	58	2
T ₁ /R ₅	Chittorgarh	<i>Eucalyptus spp.</i>	0.47	0.01	211	3
T ₂ /R ₁	Gangrar	<i>Eucalyptus spp.</i>	0.35	0.05	158	23
T ₂ /R ₂	Chittorgarh	<i>Eucalyptus spp.</i>	0.48	0.07	216	31
T ₂ /R ₃	Gangrar	<i>T. grandis</i>	0.40	0.05	179	22
T ₂ /R ₄	Gangrar	<i>A. indica</i>	0.78	0.09	347	39
T ₂ /R ₅	Chittorgarh	<i>L. leucocephala</i>	0.55	0.08	246	35
T ₃ /R ₁	Gangrar	<i>M. indica</i>	0.71	0.71	320	320
T ₃ /R ₂	Chittorgarh	<i>M. indica</i>	1.24	1.24	357	357
T ₃ /R ₃	Hamirgarh	<i>V. nilotica</i>	0.48	0.48	215	215
T ₃ /R ₄	Gangrar	<i>D. sissoo</i>	0.24	0.24	109	109
T ₃ /R ₅	Chittorgarh	<i>B. monosperma</i>	0.44	0.44	196	196

(2022), low-density formations and open-grown trees have a positive influence on the architectural index criteria for crown width (8.89m) and length of structure.

Basal Area (BA): The average stand basal area was dominantly integrated at the stand level for pure forest estates (T₁) at 44.86m² with a total maximum of 90.75m² for *T. grandis*. In contrast, boundary systems (T₂) and dispersed (T₃) maintain lower mean basal areas of 18.62m² and 21.30m² respectively. Singh *et al.*, (2025) showed that there is a robust relationship between the array of stand spacing and the configuration of total basal area on multi-species tree estate across semi-arid environments.

Biomass Production and Carbon Sequestration Potentials

The total aboveground biomass (AGB) and

corresponding biological carbon storage capacity varied drastically as a function of species composition and stand density.

Aboveground Biomass Accumulation: High-density pure stands (T₁) generated the highest system-level biomass yield, averaging 1.22 Mg ha⁻¹. The absolute highest species-specific AGB was tracked in *T. grandis* (T₁) at 2.51 Mg ha⁻¹ and lowest 0.13 Mg ha⁻¹ was recorded under *Eucalyptus* spp. Boundary plantations (T₂) and scattered designs (T₃) yielded lower mean values of 0.51Mg ha⁻¹ and 0.62Mg ha⁻¹, respectively and highest 0.78 Mg ha⁻¹, 1.24 Mg ha⁻¹ under *A. indica* under T₂ and T₃ respectively. AGB displayed weak direct linear scaling when correlated strictly against single parameters like height (R² = 0.0325) or girth (R² = 0.0052). In addition, similar result given by Chavan *et al.*, (2022) that observed

**Fig. 6:** Teak based planation.**Fig. 7:** Eucalyptus based planation.

Table 3: Site wise soil physicochemical dynamics of all treatments and replications.

T/R	Tahsil	Tree Species	BD(g cm ⁻³)	pH	EC(dSm ⁻¹)	SOC(%)	SOC Mg ha ⁻¹)
T ₁ /R ₁	Gangrar	<i>T. grandis</i>	1.24	7.36	0.396	1.36	51.08
T ₁ /R ₂	Chittorgarh	<i>T. grandis</i>	1.26	7.33	0.317	1.49	56.17
T ₁ /R ₃	Gangrar	<i>T. grandis</i>	1.19	7.09	0.310	1.75	65.85
T ₁ /R ₄	Gangrar	<i>Eucalyptus spp.</i>	1.55	7.38	0.344	0.92	49.25
T ₁ /R ₅	Chittorgarh	<i>Eucalyptus spp.</i>	1.08	7.08	0.443	1.11	42.02
T ₂ /R ₁	Gangrar	<i>Eucalyptus spp.</i>	1.39	6.91	0.486	1.17	48.72
T ₂ /R ₂	Chittorgarh	<i>Eucalyptus spp.</i>	1.41	7.66	0.343	1.37	57.92
T ₂ /R ₃	Gangrar	<i>T. grandis</i>	1.26	7.57	0.438	1.31	54.99
T ₂ /R ₄	Gangrar	<i>A. indica</i>	1.36	7.36	0.351	1.14	38.87
T ₂ /R ₅	Chittorgarh	<i>L. leucocephala</i>	1.26	7.12	0.497	1.41	53.36
T ₃ /R ₁	Gangrar	<i>M. indica</i>	1.27	7.30	0.698	1.21	46.46
T ₃ /R ₂	Chittorgarh	<i>M. indica</i>	1.11	7.17	0.326	1.13	37.94
T ₃ /R ₃	Hamirgarh	<i>V. nilotica</i>	1.04	7.25	0.478	1.23	38.62
T ₃ /R ₄	Gangrar	<i>D. sissoo</i>	1.29	7.26	0.384	1.39	51.98
T ₃ /R ₅	Chittorgarh	<i>B. monosperma</i>	1.12	7.06	0.497	1.47	50.02

that precise monitoring of aboveground biomass yields across structural matrices follows non-linear power-based curves (D^{2.191}) affected by competitive planting geometry.

**Fig. 8:** Neem based boundary planation.**Fig. 9:** Teak based boundary plantation.

Vegetation Carbon Stocking: Biomass-derived carbon formatting mirrored AGB profiles. The overall carbon storage pool averaged 338.86 Mg C ha⁻¹ across all sites. Pure plantations (T₁) acted as the premier carbon sinks, sequestering an average of 548.0 Mg C ha⁻¹ and maxing out at 1121.0 Mg C ha⁻¹ under *T. grandis*. Scattered systems (T₃) and boundary rows (T₂) safely stored mean values of 239.0 Mg C ha⁻¹ and 229.2 Mg C ha⁻¹, respectively. Tanwar *et al.*, (2019) found that closed block farm forestry structures generate the highest collective biomass carbon pools compared to open agri-horti or scattered pasture frameworks.

Soil and Physicochemical Dynamics

Canopy coverage and management type altered the physical and chemical matrices of the semi-arid topsoil profile (0–30 cm depth).

**Fig. 10:** Shisham based Scattered Trees in Agroforestry.

Bulk Density (BD): Physical soil compaction was lower directly beneath tree canopies, particularly inside scattered agroforestry matrices (T_3), which recorded an optimal low BD of 1.04 g cm^{-3} . The highest bulk density (1.55 g cm^{-3}) was tracked under managed *Eucalyptus* stands (T_1). Similar results given by Patel and Deb (2020) in which they define that canopies cushion the soil from heavy rains while decomposing organic matter and fine roots create macro-pores and improve structure.

pH and Electrical Conductivity (EC): The mean edaphic pH settled at a near-neutral value of 7.26, dipping to its most favourable level (6.91) in *Eucalyptus* boundary rows. System-wide electrical conductivity remained within safe non-saline parameters, averaging 0.420 dS m^{-1} across the district. Similar results given by Singh *et al.*, (2025) describe that Leaf litter decay releases natural organic acids that buffer and counteract alkaline soils in addition tree canopies shield the ground from extreme heat, suppressing evaporation and preventing underground salts from rising to the surface.

Soil Organic Carbon (SOC) Status: Vertical stratified checking confirmed higher SOC saturation in the upper horizon (0–15 cm) at 1.44% versus the lower horizon (15–30 cm) at 1.18%. *T. grandis* systems under T_1 yielded the highest total soil carbon concentration at 65.85 Mg ha^{-1} . The SOC storage for each of the three treatments showed that for total SOC storage, T_1 ($264.37 \text{ Mg ha}^{-1}$) had $> T_2$ ($253.86 \text{ Mg ha}^{-1}$) $> T_3$ ($225.01 \text{ Mg ha}^{-1}$). This is consistent with work done by Thakur *et al.*, (2024), Yadav *et al.*, (2022) and Singh & Singh (2023), where they indicated that the canopy will produce leaf litter and the roots produce organic material that accumulates to create organic matter in the topsoil, leading to vertical

stratification with 1.44% SOC in the 0-15 cm horizon (with a maximum of 1.96% under *T. grandis*) compared to 1.18% in the 15-30 cm layer. Canopy size has an effect on the rate of litter fall and the amount of SOC stored in the soil, whereby larger canopies provide higher litter fall and greater SOC storage compared to open fields.

Conclusion

The selection of species as well as structural management have significant impact on the processes of biomass accumulation, structure of the ecosystem and soil carbon dynamics in semi-arid areas of the planet. For instance, high-density plantations of monoculture (T_1), especially plantations composed of *Tectona grandis*, provide the best overall potential for carbon sequestration (showing the highest values of basal area, above ground biomass, carbon stocks and total accumulation of organic carbon in soils). In contrast, open scattered plantations (T_3) and edge configurations (T_2) favor the individual growth of stems and crowns, and have positive effects on soil conditions by decreasing soil density. In all systems studied, topsoil layers (0-15 cm) are richer in organic carbon compared to lower layers. This is due to litter fall in canopies and organic matter input into the soil. All types of systems studied maintain a stable neutral pH and low salinity indicating the ecological stability of these systems. Overall, the strategy involving pure plantations along with the use of boundary and scattered agricultural practices shows a good combination of biomass yield enhancement, increasing organic carbon in soils and effective climate change mitigation in the semi-arid land.

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Fig. 11: Palash based Scattered Trees in Agroforestry.

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