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Climatic and edaphic influences on productivity and carbon sequestration of farm grown teak (*Tectona grandis,* linn.f) in Tamil Nadu, India

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Abstract

Teak (*Tectona grandis,* Linn.f) is one of the most sought-after tree crops due to the exceptional quality and high market value of its timber. Currently, the Indian subcontinent imports a significant quantity of teak to meet its growing demand. The growth and wood quality of teak are influenced by edaphic and climatic variations across sites, a factor that has been largely underexplored in research. The primary objective of the study is to analyse teak growth, wood quality, and carbon sequestration potential under farmland condition. To address this, the study was conducted across three agroclimatic zones of Tamil Nadu: North Eastern Zone (NEZ), North Western Zone (NWZ), and Cauvery Delta Zone (CDZ), focusing specifically on farmland conditions. The analysis encompassed biometric attributes, volume, and carbon sequestration potential of farm-grown teak across different age classes. The findings of the study reveal that among the three agroclimatic zones, the NEZ (15-20 years age class) recorded the highest biometric attributes, including mid diameter (MD) (0.193 m), volume (0.379 m^3), heartwood proportion (0.239 m^3), and carbon sequestration (0.683 Mg/acre).. Based on the overall performance, trees in the 15-20 years age class exhibited superior heartwood formation under farmland conditions. Therefore, this age class is recommended for teak cultivation in farmland conditions across Tamil Nadu to maximize growth, wood quality, and carbon sequestration potential.

Keywords

agroclimatic zones; carbon sequestration; farmland; heartwood volume; teak; wood quality

Introduction

Teak (*Tectona grandis* Linn.f) is one of the most predominant and prominent hardwood tree species which grows extensively in tropical conditions (1–3). Its natural growing range is predominantly concentrated in South and Southeast Asia , which together contribute more than 90 percent of the world's teak resources (4, 5). India accounts for approximately 1.68 M ha of teak plantations and 6.8 M ha of natural teak forests (6), contributing around 45% of global teak resources. Paradoxically, despite this significant share, India remains a net importer of teak, with an annual domestic production of only 0.25 M cu.m (7) compared to an annual demand of 100 M cu.m (8–10). Globally, India ranks first in teak consumption, meeting nearly 70 to 100 percent of its requirement through imports, predominantly from Africa and Latin America (11).

Given this significant demand supply gap, the promotion of teak cultivation outside forested areas, particularly on private patta lands, has gained considerable importance. Such initiatives aim to bridge the gap between teak wood demand and supply while also providing a viable revenue source for farmers.

Farm-grown teak in Tamil Nadu exhibits notable growth variations across different agroclimatic zones (12). These variations are influenced by the climatic and edaphic factors unique to each zone, resulting in significant differences in volume production (13). Additionally, long-rotation species such as teak possess the unique advantage of long-term carbon sequestration, as the wood is commonly used for furniture and construction, thereby locking carbon either for extended periods or permanently (14, 15).

However, there is a lack of systematic studies to understand the growth biometry, yield variations, and carbon sequestration potential of farm-grown teak across different agroclimatic zones. This study aims to fill this gap by providing scientific insights into variations in growth patterns, including parameters such as height, merchantable volume, girth, heart content, sap-to-heartwood ratio, and carbon sequestration potential of teak cultivated on farmland across Tamil Nadu's agroclimatic zones. The findings will enable a comprehensive evaluation of teak productivity and quality, ultimately aiding in the substantial promotion of teak cultivation in the state.

Materials and Methods

Study area

Farm-grown teak plantations were surveyed across three agroclimatic zones of Tamil Nadu, namely the NEZ, NWZ, and the CDZ, as detailed in Table 1.

Table 1. Study zones and district wise teak resources

	Zone	District covered
Zone 1	North eastern zone (NEZ)	Thiruvannamalai, Vellore, Ranipet, Thiruvallur
Zone 2	North western zone (NWZ)	Kallakurichi, Krishnagiri, Salem, Namakkal
Zone 3	Cauvery delta zone (CDZ)	Trichy, Thanjavur, Perambalur

NEZ - North Eastern Zone, **NWZ** - North Western Zone, **CDZ** - Cauvery Delta Zone.

Climatic data for these three agroclimatic zones over the past ten years were collected using NASA's Modern-Era Retrospective analysis for Research and Applications (MERRA 2) satellite data source. Key climatic parameters, including the average mean maximum and minimum temperature (°C), average annual rainfall (mm), average relative humidity (%), and elevation (m) (16) were documented and are presented in Table 2.

Table 2. Climatic attributes of three agroclimatic zones

Zones	Mean Maximum Temperature (°C)	Mean Minimum Temperature (°C)	Annual rainfall (mm)	Relative Humidity (%)	Elevation (m)
NEZ	40.43	13.83	1109	68.92	666
NWZ	41.53	13.12	849	68.67	453
CDZ	38.49	19.38	956.3	71.66	629

NEZ - North Eastern Zone, **NWZ** - North Western Zone, **CDZ** - Cauvery Delta Zone.

Field survey

A total of 39 block plantations were surveyed to estimate growth biometry across the NEZ, NWZ, and CDZ agroclimatic zones, with a sampling intensity of 5%. Among these, 21 plantations were located in NEZ, 6 in NWZ, and the remaining 12 in CDZ. In all agroclimatic zones, three age classes of teak namely 5-10 years, 10-15 years, and 15-20 years were studied.

Estimation of growth biometry in teak plantation

Growth biometric parameters, namely Mid Diameter (MD in m), Height (Ht in m), and Clear bole height (CBH in m), were measured (17, 18) using a Laser distance meter (Leica DISTOTM D810). A tree telescope was employed in the studyto facilitate the measurement of tree diameters at various heights on standing tree. Using this advantage, the Mid Diameter was measured at 2-m intervals along the tree's height up to the clear bole height (CBH).

For each 2-meter height interval, both the bottom and top diameters were measured, and their average was calculated. By taking the arithmetic mean of all mid-diameters across the 2-meter height intervals for each tree, the average diameter of the standing tree up to the clear bole level was determined. The clear bole volume was then estimated without applying a form factor (19). This methodology ensures that the volume calculated in the study accurately reflects the actual volume of the standing tree, achieving a precision level of approximately 99%.

Estimation of volume

The volume of standing tree was estimated using the formula proposed by Chaturvedi and Khanna in 1982 (Eqn. 1)

$$V = \pi r^2 h \qquad \text{……...(Eqn. 1)}$$

Where, V = Volume, r = Radius at the mid-point, h = Total height of the tree

Estimation of sap wood (SW), heart wood (HW) and bark content (BC)

In all three agroclimatic zones, for trees across all diameter classes, a sample tree was felled to measure bark thickness, SW thickness, and HW thickness (20). Based on these measurements, the quantities of SW, bark, and HW were calculated, and the SW-to-HW ratio was derived. The growth biometry, in relation to age and climate data, was statistically analyzed using IBM SPSS and the Agricolae package in the R environment (21).

Carbon sequestration potential of farm grown Teak

Estimation of above ground biomass (AGB)

The above-ground biomass of the plantation was calculated using the formula suggested by pandya (Eqn. 2) in 2013 as:

$$\text{Above ground biomass} = \text{Volume (m}^3\text{) x Wood density(g/cm}^3\text{)} \quad \text{.........(Eqn. 2)}$$

Wood density was determined using the water displacement method.

Estimation of below ground biomass (BGB)

BGB, which includes live roots biomass but excludes fine roots, was calculated using a root: shoot ratio of 0.26 (Eqn. 3).

$$\text{Below ground biomass (BGB)} = 0.26 \text{ x AGB (ton)} \quad \text{.........(Eqn. 3)}$$

Estimation of total biomass (TB)

Total biomass was calculated using the formula suggested by sheikh (Eqn. 4) in 2011 as:

$$\text{Total biomass (TB)} = \text{Above ground biomass (AGB) + Below ground biomass (BGB)} \quad \text{.........(Eqn. 4)}$$

Estimation of weight of carbon (C)

The carbon weight was estimated by the formula given by pearson in 2005 (Eqn. 5) as:

$$\text{Wt. of C} = \text{Biomass x 0.50} \quad \text{.........(Eqn. 5)}$$

Estimation of total quantity of carbon dioxide (CO_2)

The total CO_2 equivalent was calculated using the ratio of the molecular weights of carbon dioxide (44 g) to carbon (12 g), as expressed in Equation 6:

$$\text{Total } CO_2 \text{ Equivalent} = \text{Weight of C x 3.67} \quad \text{.........(Eqn. 6)}$$

Statistical analysis

The experimental databases were statistically analysed under a randomized block design (RBD). Relationships between various parameters were evaluated using Karl Pearson's correlation analysis, conducted via IBM SPSS Statistics 21 Software.

Results

Farm-grown teak plantations from the NEZ, NWZ, and CDZ of Tamil Nadu were analysed for their biometric attributes across 3 different age classes. The total height and average mid diameter of *Tectona grandis* were observed to increase progressively with age. Similarly, wood composition, including heartwood, sapwood, and bark content, showed a consistent increase with advancing age classes.

Biometric estimation of *Tectona grandis*

The biometric attributes, namely mid diameter, height, and volume, exhibited significant variations across different agroclimatic zones and age classes of farm-grown teak. Among the three agroclimatic zones, teak plantations in the NEZ demonstrated the highest biometric value (Table 3) viz., mid diameter (0.193 m), height (12.92 m), and volume (0.379 m^3). Conversely, plantation in the cauvery delta zone recorded the lowest biometric values: mid diameter (0.101 m), height (5.80 m), and volume (0.0033 m^3).

Table 3. Growth biometry of farm-grown teak in block plantations

Zones	Age class (Years)	Mid Diameter (m)	Height (m)	Volume (m³)
NEZ	5-10	0.118	7.54	0.087
	10-15	0.139	9.04	0.137
	15-20	0.193	12.92	0.379
	Mean	0.150	9.83	0.201
	S.Ed	0.013	0.53	0.052
	CD	0.029	1.18	0.114
NWZ	5-10	0.128	9.05	0.117
	10-15	0.135	9.30	0.160
	15-20	0.182	9.64	0.304
	Mean	0.148	9.33	0.194
	S.Ed	0.009	0.10	0.033
	CD	0.020	0.22	0.073
CDZ	5-10	0.101	5.80	0.056
	10-15	0.141	6.77	0.131
	15-20	0.153	7.20	0.154
	Mean	0.132	6.59	0.114
	S.Ed	0.009	0.24	0.017
	CD	0.020	0.53	0.037

NEZ - North Eastern Zone**, NWZ -** North Western Zone**, CDZ -** Cauvery Delta Zone**, S.Ed -** Standard Error of Difference**, CD -** Critical Difference**.**

Wood composition of *Tectona grandis*

In addition to biometric attributes, the wood parameters (Fig.1) also showed significant variations across agroclimatic zones and age classes. The teak plantations in the NEZ exhibited the highest values for HW, SW, and bark content volume, with HW volume (0.239 m^3), SW volume (0.114 m^3), and bark content volume (0.027 m^3). The favourable climatic condition, including an average annual rainfall of 1109 mm and medium alluvial soils, in the NEZ likely contributed to these superior values. On the other hand, the CDZ recorded the lowest values for these parameters: HW volume (0.0122 m^3), SW volume (0.040 m^3), and bark content volume (0.003 m^3) (Table 4).

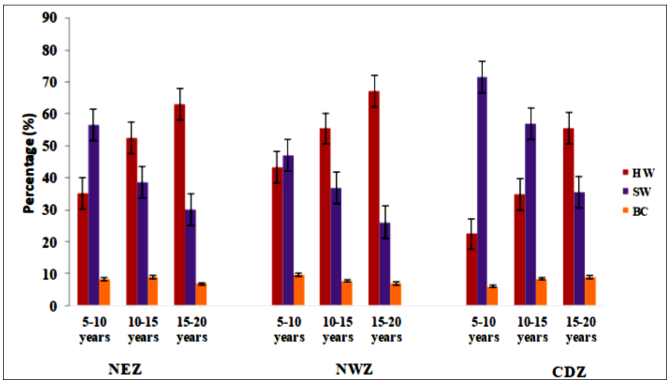

Fig 1. Comparison of wood parameters of farm grown teak under three agroclimatic zones. *significant at the 0.01 level (2-tailed), **NEZ** - North Eastern Zone, **NWZ** - North Western Zone, **CDZ** - Cauvery Delta Zone, **HW** - Heart-

Carbon sequestration potential of *Tectona grandis*

The carbon sequestration potential of farm-grown teak varied significantly across the agroclimatic zones and age classes. Among the three zones, the NEZ recorded the highest total carbon equivalent (0.683 Mg/acre), followed by NWZ(0.556 Mg/acre), and the CDZ (0.282 Mg/acre).

When compared across age classes, teak plantations aged 15-20 years exhibited the highest carbon sequestration in all zones (Table 5).

Karl Pearson's correlation analysis was performed to evaluate the relationship between growth biometrics and carbon sequestration potential of farm-grown teak across the three agroclimatic zones in Tamil Nadu. The result indicated a significant positive correlation between biometric parameters and total carbon sequestrated by teak (Table 6). There is a positive correlation between mid-diameter (k=0.939, $p<0.01$), height (k=0.834, $p<0.01$), volume (k=1.000, $p<0.01$), above ground biomass (k=1.000, $p<0.01$), below ground biomass (k=1.000, $p<0.01$),and total carbon (k=1.000, $p<0.01$).

These results suggest a strong positive relationship between the growth parameters of teak and its carbon sequestration potential, highlighting the species' significant role in carbon storage.

Discussion

When comparing the growth biometrics of farm-grown teak across age classes and agroclimatic zones, the highest values were consistently observed in the 15-20 years age class ($p<0.05$). However, for the same age classes, the trees exhibited uniform growth biometrics across all three zones ($p > 0.05$). The interaction effect between zone and age class was not statistically significant for the observed growth biometrics. The variations in growth biometrics were attributed to differences in edaphic and climatic conditions across the agroclimatic zones, as supported by earlier studies (22,23). Similar findings were reported by Reddy and Madiwalar (24), who observed that teak growth in Karnataka was positively influenced by increasing rainfall and favorable soil profiles in different agroclimatic

Table 4. Wood composition parameters of farm-grown teak plantations in three agroclimatic zones

Zones	Age Class (Years)	HW Volume (m^3)	SW Volume (m^3)	BC Volume (m^3)
NEZ	5-10	0.031	0.050	0.007
	10-15	0.071	0.054	0.012
	15-20	0.239	0.114	0.027
	Mean	0.114	0.072	0.015
	S.Ed	0.037	0.012	0.003
	CD	0.081	0.026	0.007
NWZ	5-10	0.050	0.055	0.012
	10-15	0.088	0.059	0.013
	15-20	0.204	0.079	0.021
	Mean	0.114	0.064	0.015
	S.Ed	0.027	0.004	0.002
	CD	0.059	0.009	0.004
CDZ	5-10	0.012	0.040	0.003
	10-15	0.046	0.075	0.011
	15-20	0.086	0.054	0.014
	Mean	0.048	0.056	0.009
	S.Ed	0.012	0.006	0.002
	CD	0.026	0.013	0.004

NEZ - North Eastern Zone, **NWZ -** North Western Zone, **CDZ -** Cauvery Delta Zone, **HW -** Heartwood, **SW -** Sapwood, **BC -** Bark Content, **S.Ed -** Standard Error of Difference, **CD -** Critical Difference**.**

Table 5. Carbon sequestration potential of farm grown Teak

Zones	Age class (Years)	AGB (Mg/acre)	BGB (Mg/acre)	TB (Mg/acre)	Wt. of C (Mg/acre)	Total CO_2 (Mg/acre)
NEZ	5-10	0.069	0.018	0.087	0.044	0.160
	10-15	0.108	0.028	0.137	0.068	0.251
	15-20	0.299	0.078	0.372	0.186	0.683
	Mean	0.159	0.041	0.199	0.099	0.364
	S.Ed	0.024	0.006	0.029	0.015	0.054
	CD	0.052	0.013	0.064	0.033	0.119
NWZ	5-10	0.092	0.024	0.116	0.058	0.214
	10-15	0.127	0.033	0.159	0.080	0.293
	15-20	0.240	0.063	0.303	0.151	0.556
	Mean	0.153	0.040	0.193	0.096	0.354
	S.Ed	0.015	0.004	0.019	0.009	0.035
	CD	0.033	0.009	0.042	0.020	0.077
CDZ	5-10	0.044	0.011	0.055	0.028	0.102
	10-15	0.104	0.027	0.131	0.065	0.240
	15-20	0.121	0.032	0.154	0.077	0.282
	Mean	0.090	0.023	0.113	0.057	0.208
	S.Ed	0.008	0.002	0.010	0.005	0.018
	CD	0.018	0.004	0.022	0.011	0.040

NEZ - North Eastern Zone, **NWZ -** North Western Zone, **CDZ -** Cauvery Delta Zone, **AGB -** Above Ground Biomass, **BGB -** Below Ground Biomass, **TB -** Total Biomass, **Wt. of C -** Weight of Carbon, **Total CO_2 -** Total Carbon dioxide Equivalent, **S.Ed -** Standard Error of Difference, **CD -** Critical Difference.

Table 6. Correlation between growth biometrics and carbon sequestration potential of farm grown teak

Pearson's Correlation	Mid Diameter (m)	Height (m)	Volume (m^3)	Above Ground Biomass (Mg/acre)	Below Ground Biomass (Mg/acre)	Total Biomass (Mg/acre)	Weight of Carbon (Mg/acre)	Total Carbon dioxide Equivalent (Mg/acre)
Mid Diameter (m)	1							
Height (m)	.655**	1						
Volume (m^3)	.939**	.834**	1					
Above Ground Biomass (Mg/acre)	.939**	.834**	1.000**	1				
Below Ground Biomass (Mg/acre)	.939**	.833**	1.000**	1.000**	1			
Total Biomass (Mg/acre)	.939**	.834**	1.000**	1.000**	1.000**	1		
Weight of Carbon (Mg/acre)	.939**	.834**	1.000**	1.000**	1.000**	1.000**	1	
Total Carbon Equivalent (Mg/acre)	.939**	.834**	1.000**	1.000**	1.000**	1.000**	1.000**	1

****.** Correlation is significant at the 0.01 level (2-tailed).

zones.

In terms of wood parameters, the maximum values were again recorded for the 15-20 age class (Fig. 1). The study also found that the heartwood ratio increased with age and mid-diameter (MD), while bark content decreased with increasing age and MD. These observations align with the findings of Tewari and Mariswamy (22), who reported similar trends in teak growth under varying agroclimatic zones in Karnataka. Teak grown in the Northeastern Zone exhibited the highest total carbon equivalent compared to the other two zones. This can be attributed to the higher wood density and favorable edaphic and climatic conditions in this zone, which support long-term carbon sequestration under farm-grown conditions. Carbon sequestration in trees is directly linked to biomass, as highlighted by studies conducted by Odusote et al. (25) and Balasooriya et al. (26). Priya and Bhat (27) also reported comparable carbon sequestration potential in teak plantations across different agroclimatic zones of Southern India, emphasizing the significant influence of climatic and edaphic factors on carbon storage.

Similar studies analyzing the carbon sequestration potential of various teak clones were conducted by Subba and Honnurappa (28), and Rahmawati et al. (29), further corroborating the findings of this study. These studies underscore the importance of zone-specific climatic and soil conditions in enhancing the carbon sequestration capacity and overall growth performance of teak plantations.

Conclusion

The critical analysis of wood parameters and growth biometrics with respect to age across different agroclimatic zones was conducted. The study concludes that the NEZ, particularly in 15-20 year age class, exhibited the highest growth and wood parameter values. Furthermore, a positive correlation was established between growth biometrics and the carbon sequestration potential of farm-grown teak, highlighting the Northeastern Zone as having the highest carbon sequestration potential. .

These findings suggest that the age of the plantation, along with variations in average climatic parameters across zones, can serve as key indicators for wood quality, carbon sequestration, and growth performance. This information can assist farmers in determining the optimal harvest period for teak plantations, ensuring both economic viability and environmental sustainability.

The scope of this study was limited to three agroclimatic zones in Tamil Nadu. Future research should extend to all agroclimatic zones of the state to provide a more comprehensive comparison of the growth, wood quality, and carbon sequestration potential of farm-grown teak. Such studies would enhance the precision and applicability of these findings for broader agricultural and forestry practices.

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Authors' contributions

SN, AB, MS and RR contributed in the conceptualization, investigation, and preparation of original draft. BS, CN, GS, VM and KS contribute in review, editing, and preparation of the final draft.

Compliance with ethical standards

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

Ethical issues: None

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