Wood quality of farm grown teak (*Tectona grandis*, Linn.f) under different agroclimatic zones of Tamil Nadu, India

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Abstract. Teak (*Tectona grandis*) is globally recognized for its exceptional wood quality, making it one of the most sought-after timbers in the world. Teak is visually appealing because of its fine grain and golden-brown hue, and its dimensional stability ensures minimal warping or cracking under various environmental conditions. Wood quality is further influenced by factors such as growth conditions, silvicultural practices, and genetic variability. Although variations in heartwood density and proportion may have an impact on its performance, plantation-grown teak has become a viable substitute for natural forests. Wood fractionation analysis was undertaken by collecting wood samples from all four agroclimatic zones in Tamil Nadu, India of both boundary and block plantations in three different age classes, viz., 5–10, 10–15, and 15–20 years. Wood density, heartwood, sapwood, and bark content were analyzed using species specific allometric equations. Wood density attained a maximum of 0.80 g cm^3 in boundary plantations of the Western agroclimatic zone in the 15- to 20-year age class. The same Western zone (WZ) registered the maximum heartwood volume of 0.433 m^3 and maximum bark content volume of 0.097 m^3 in the same age class. Similarly, maximum sapwood volume in the same age class in the Cauvery Delta zone was 0.141 m^3. Trees from the WZ had higher heartwood ratios, suggesting that these trees might more durable.

Keywords: Teak, *Tectona grandis*, Heartwood, Sapwood, Density, Correlation, Wood quality

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Introduction

Teak (*Tectona grandis,* Linn.; Lamiaceae) is known as the "King of Timber" and is one of the most predominant and widely used hardwood timber species across the world (Balakrishnan et al. 2021; Kidanu et al. 2005; Vongkhamho et al. 2022). Teak plantations have been widely established throughout the tropics since the 1850s (Shrivastava and Saxena 2017). Teak is predominantly native to south and southeast Asia, which contribute more than 90% of the world's teak resources (Arunkumar et al. 2024). India accounts for about 1.68 M ha of teak plantations and 6.8 M ha of natural teak forests (Kollert et al. 2024), representing about 45% of the global teak resource. Ironically, India is still a net importer of teak, with annual domestic production of only about 0.25 million cubic meters (mcm) (Shrivastava and Saxena 2017) compared with a demand of 100 mcm (Hadinata and Kozakiewicz 2020). Globally, India ranks first in teak consumption, and most of this demand is met from Africa and Latin America (Shrivastava and Saxena 2017; Gatonnou et al. 2017. One part of meeting the rising demand will be optimizing the rotation period. Short rotation teak production has been promoted, particularly on private land to bridge the supply gap and provide a revenue source to farmers (Kyaw et al. 2024).

The Government of Tamil Nadu promotes teak planting through Tree Cultivation in Patta Land (TCPL) outside forested areas (Ramar and Kannan 2016). In the past decade, Tamil Nadu accounted for nearly 8700 km^2 of trees planted through farm forestry and community plantations that are grown on wastelands and public lands (Buvaneswaran et al. 2016). While the increasing plantation estate is a positive development, the characteristics of this resource in reference to the different edaphoclimatic conditions in Tamil Nadu are poorly understood. Previous studies suggest that the wood properties of teak can vary widely with climatic and edaphic factors (Moya et al. 2020).

The market value of teak has increased with demand, and unlike many other wood species, teak sapwood has the same physical strength and density characteristics as heartwood, making it easier to utilize the entire tree without concern for issues other than durability (Odusote et al. 2019). Teak heartwood extractives provide exceptional resistance to fungal and insect attack (Rosamah et al. 2020; Brocco et al. 2020; Colbu et al. 2021). Heartwood content of farm-grown teak wood, especially the extractives content as it affects durability, will play a major role in the value of this resource. Previous research (Nugroho et al. 2024; Rizanti et al. 2018) clearly showed that climatic and edaphic influences in addition to age play major roles in wood quality in teak. Hence understanding wood quality and heartwood proportion in farm grown trees will help growers maximize the value of this resource.

The objective of this study was to examine the proportions of heartwood, sapwood and bark in teak trees from four growing areas within Tamil Nadu, India.

Materials and methods

Study area

Farm-grown teak plantations aged 5–10, 10–15, and 15-20 years were surveyed in four agroclimatic zones of Tamil Nadu (Figure 1), namely the North Eastern (NEZ), North Western (NWZ), Cauvery Delta (CDZ), and Western zones (WZ).

Ten trees were harvested in each age group at each of the four sites. A 50-mm-thick cross section was cut 1 m above the

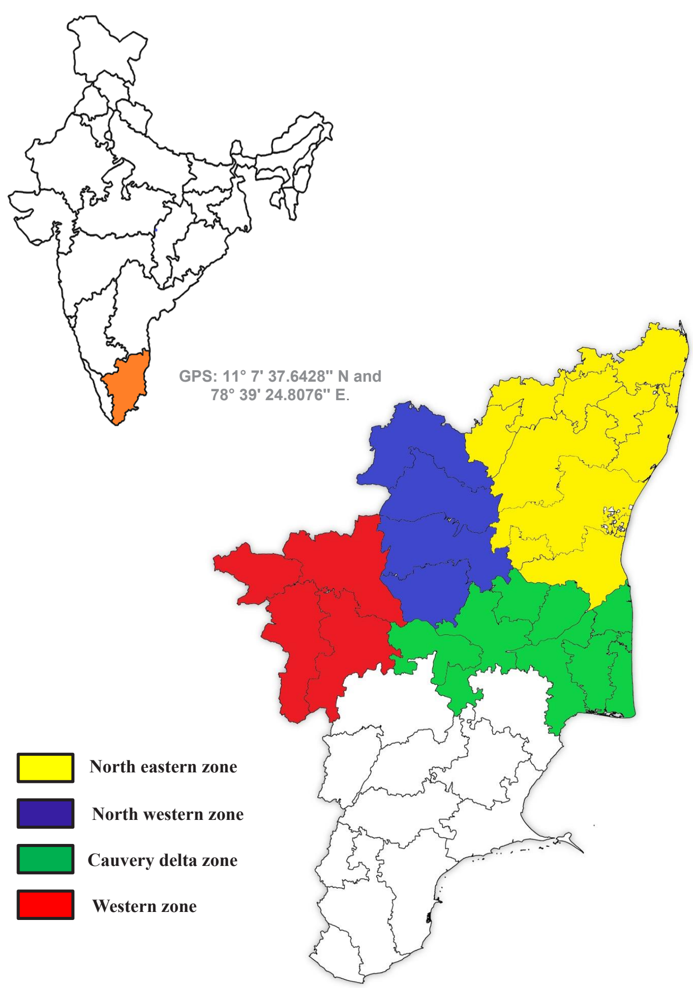

Figure 1. Locations of the study areas.

base from each tree, and the amounts of bark, sapwood, and heartwood were visually measured across two points to the nearest mm. These values were used to calculate the volume of each component. The section was then immersed in water to determine volume based upon water displacement, and the samples were oven dried at 103°C and weighed. The values were used to calculate density.

Type of plantation

The study examined trees that were both within a stand as well on the boundary of plantations in each agroclimatic zone. A total of 480 trees were examined under three age classes: 5–10, 10–15, and 15–20 years.

Estimation of wood quality parameters with reference to agroclimatic zone and age

Wood density, heartwood, sapwood, and bark content were studied for 120 wood samples in all three age classes of block and boundary plantations grown in four agroclimatic zones.

Wood density

Density is an important variable for accurate quantification of woody biomass and carbon stocks. Wood density was calculated by the ratio of the oven-dry mass of a wood sample divided by the mass of water displaced by its green volume (wood specific gravity, or WSG) (Kenzo et al. 2020) as follows:

$$\mathrm{WD} = \mathrm{dm}/\mathrm{v} \tag{1}$$

where, WD = Wood density; dm = Wood dry mass; v = Volume.

Wood fractionation

The wood samples collected from three age classes belonging to boundary and block plantations grown in the four agroclimatic zones (Plates 1 to 4) were fractionated into bark, sapwood, and heartwood content. Diameter of heartwood was measured by the average of two cross-sectional measurements of each wood sample. The heartwood volume was calculated by using the geometric cylinder volume equation. Sapwood volume was estimated by subtracting the heartwood volume from the volume (inside-bark). Finally, the wood sample was converted into 2-inch billets in order to observe the exact percentage of heartwood proportion present in the wood. The total lengths of heartwood, sapwood, and outer bark of wood samples were measured using measuring tape, and the total lengths were expressed in cm (Tewari and Mariswamy 2013).

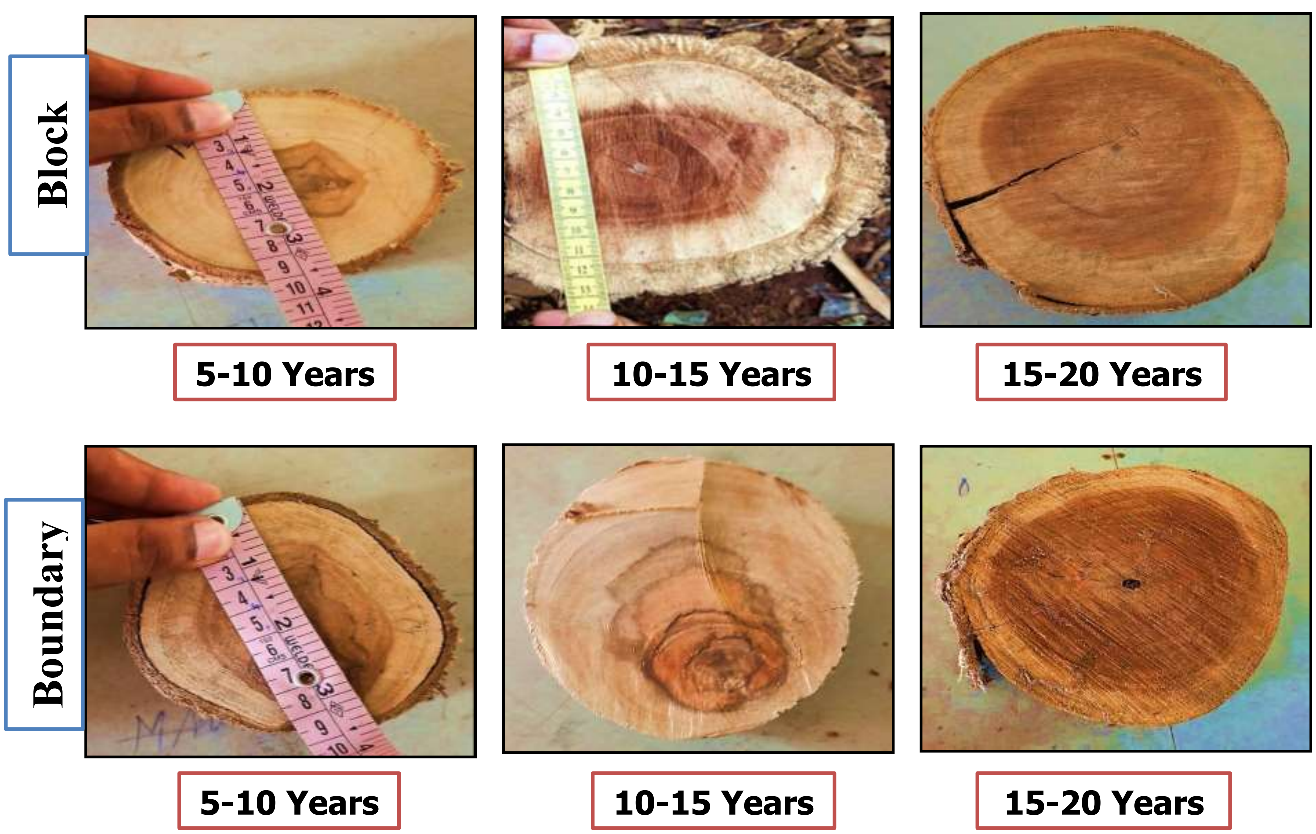

Plate 1. Wood Samples of North Eastern zone (NEZ).

Plate 2. Examples of cross cuts from tree of different ages from the North Western zone (NWZ).

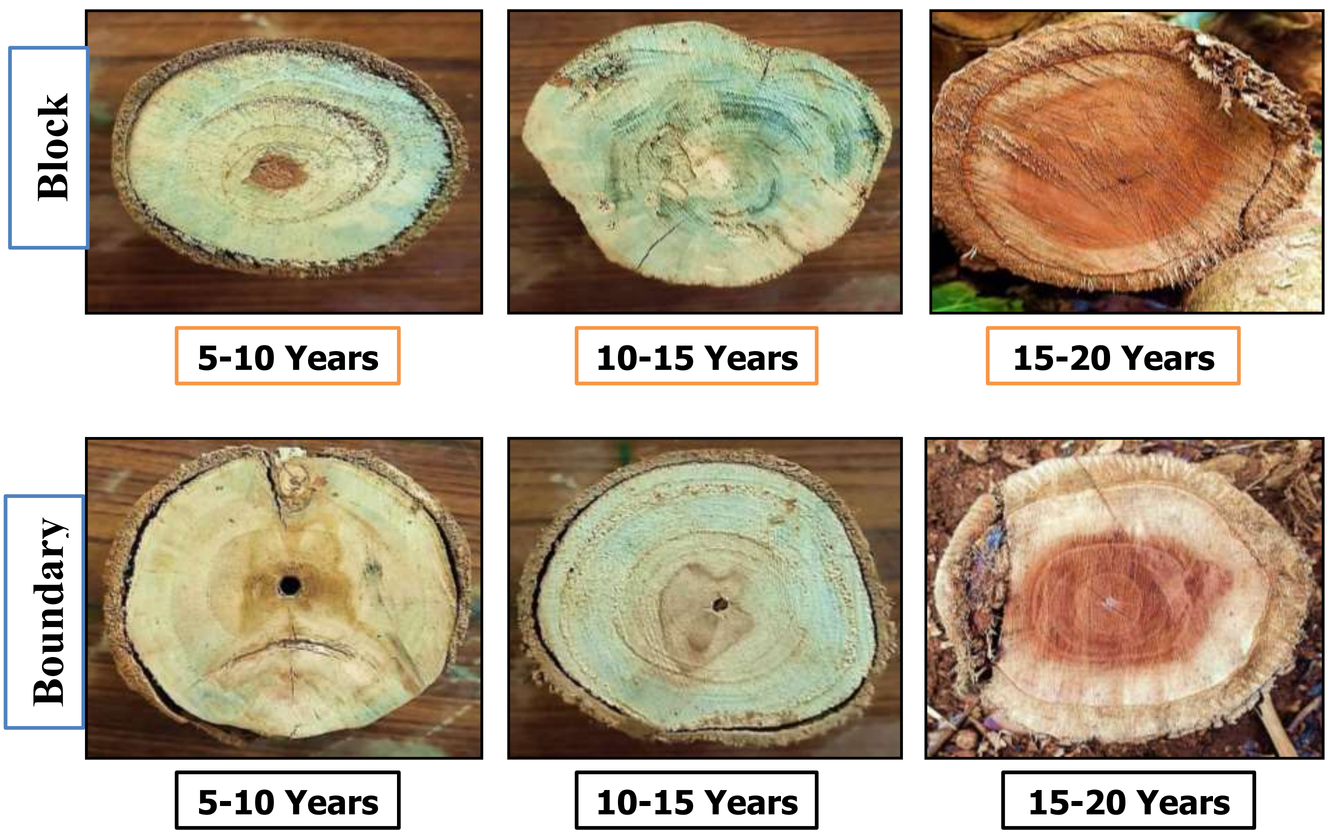

Plate 3. Examples of cross cuts from tree of different ages from the Cauvery Delta zone (CDZ).

Plate 4. Examples of cross cuts from tree of different ages from the Western zone (WZ).

Heartwood volume

The heartwood volume was estimated for each wood sample, and the average of each cross-sectional diameter was taken into account. Heartwood volume was calculated using the equation given by Moya et al. 2020:

$$hwv = g_1 + g_2/2 \times \text{length} \qquad (2)$$

where, hwv is the heartwood volume, g_1 is the face area of the minor log diameter in m^2, g_2 is the face area of major log diameter m^2.

Climatic parameters

The rainfall (mm), maximum temperature (°C), minimum temperature (°C), and relative humidity (%) data for the period between 2012–2021 for Thiruvannamalai, Salem, Thanjavur, and Coimbatore districts were collected from the Agriculture Extension Center (AEC), Tamilnadu Agricultural University Coimbatore (Figure 2).

Edaphic parameters

Representative soil samples were collected from each of the four agroclimatic zones and segregated into zones 0–15 and 15–30 cm from the surface. The samples were analyzed for physicochemical and soil chemical properties (Table 1). Areas with old manure, wet spots, dead plants, furrows, and compost were excluded to minimize the differences due to the presence of soil organic matter. The soil samples were air-dried, mixed well, and passed through a 2-mm sieve for the soil physio-chemical properties like soil pH and soil electrical conductivity (Jackson, 2005) and soil chemical analysis such as soil organic carbon (Walkley and Black 1934), available nitrogen (Subbiah and Asija 1956), available phosphorous (Bray and Kurtz 1945), and available potassium (Stanford and English 1949) were analyzed.

Statistical analysis

The data were subjected to an analysis of variance and then differences were examined using Pearson's correlation coefficient with SPSS (Statistical Package of the Social Science) and Agricolae under R environment (R Core Team 2012) for correlating the wood quality of farm-grown teak with the climatic and edaphic factors. Wood quality parameters were taken as dependent variables, whereas climatic and edaphic factors were considered as independent variables.

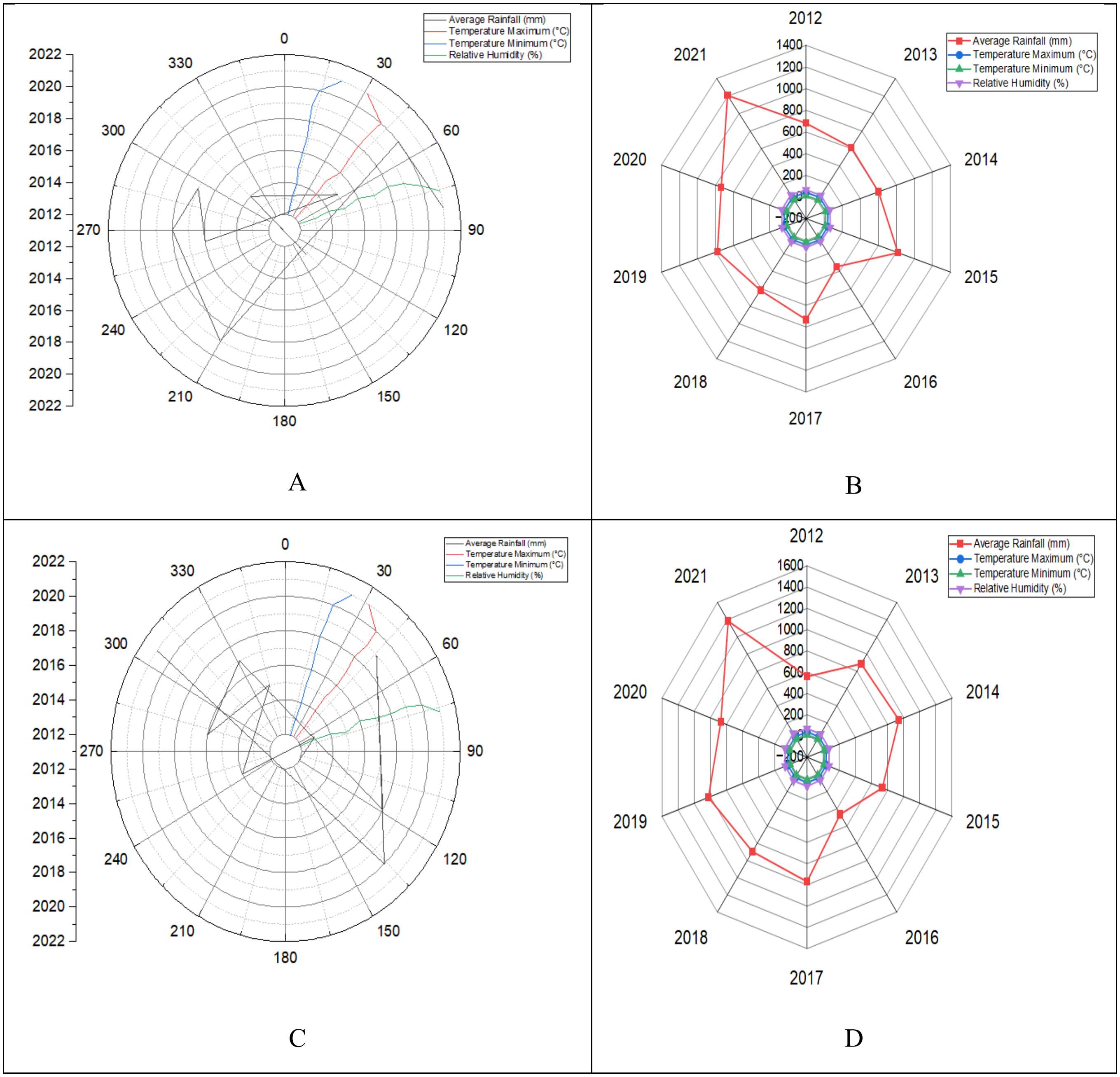

Figure 2. Climatic variables in selected agroclimatic zones: (A) North Eastern zone; (B) North Western zone; (C) Cauvery Delta zone; and (D) Western zone).

Table 1. Soil physicochemical properties evaluated in the teak plantations.

S. no.	Soil parameter	Methodology	References
1	Soil pH	Elico model pH meter	Jackson (2005)
2	Soil EC	Conductometry	Jackson (2005)
3	Available nitrogen	Alkaline permanganate method	Subbiah and Asija (1956)
4	Available phosphorus	Olsen's method	Bray and Kurtz (1945)
5	Available potassium	Neutral Normal NH4OAc, Flame photometry	Stanford and English (1949)
6	Soil organic carbon	Wet chromic acid digestion	Walkley and Black (1934)

Results

Sapwood/heartwood, bark content

North Eastern zone

Heartwood (HW), sapwood, (SW) and bark content (BC) volume varied among all three age classes. The highest heartwood (0.239 m^3), sapwood (0.114 m^3), and bark content (0.027 m^3) volumes were obtained for the age class 15–20 years in block plantations of farm-grown teak. Similarly, the lowest heartwood (0.031 m^3), sapwood (0.050 m^3), and bark content (0.007 m^3) volumes were recorded in 5- to 10-year-old stands. The average heartwood volume for plantations in the NEZ was 0.114 m^3, while average sapwood and bark content volumes were 0.072 m^3 and 0.015 m^3, respectively.

North Western zone

Maximum heartwood (0.204 m^3), sapwood (0.079 m^3), and bark content (0.021 m^3) volumes in the NWZ were obtained for the 15- to 20-year age class ($p < 0.05$) (Table 2). Similarly, minimum heartwood (0.050 m^3), sapwood (0.055 m^3), and bark content volumes (0.012 m^3) were obtained for 5- to 10-year-old timber. Average heartwood volume for NWZ plantations was 0.114 m^3, while average sapwood and bark content volumes were 0.064 m^3 and 0.015 m^3, respectively.

Cauvery Delta zone

Heartwood, sapwood, and bark content volumes in this zone varied among three age classes (Table 3). The highest heartwood (0.086 m^3), sapwood (0.075 m^3), and bark content (0.014 m^3) volumes were recorded in the 15- to 20-year age class ($p < 0.05$). The lowest heartwood (0.012 m^3), sapwood (0.040 m^3), and bark content (0.003 m^3) volumes were registered in the 5- to 10-year-old timber. Irrespective of age classes, the average heartwood volume for block plantations was 0.048 m^3, and the average sapwood volume and bark content volume were 0.056 m^3 and 0.009 m^3, respectively.

Western zone

Heartwood, sapwood, and bark volumes of trees from the three age classes of block plantations are given in Table 4. Maximum heartwood volume (0.139 m^3) was found in 15- to 20-year-old trees ($p < 0.05$), which also had the maximum sapwood (0.073 m^3) and bark (0.090 m^3) volumes. Average volumes of heartwood, sapwood, and bark volumes for all age classes were 0.082 m^3, 0.047 m^3, and 0.057 m^3, respectively.

Boundary plantations

North Eastern zone

The highest heartwood volume obtained in boundary plantations in this zone was 0.342 m^3 for 15- to 20-year-old trees ($p < 0.05$) (Table 5). This age class also has the highest sapwood (0.074 m^3) and bark (0.030 m^3) volumes. The lowest heartwood (0.070 m^3), sapwood (0.047 m^3), and bark content (0.010 m^3) volumes were registered in the 5- to 10-year age class. Average heartwood, sapwood, and bark content volumes for all three age classes in the NEZ were 0.197 m^3, 0.060 m^3, and 0.020 m^3, respectively.

North Western zone

The 15- to 20-year age class had maximum heartwood (0.303 m^3), sapwood (0.067 m^3), and bark content (0.022 m^3) volumes in this zone, while the 5- to 10-year age class had the lowest ($p < 0.05$) heartwood (0.099 m^3), sapwood (0.040 m^3), and bark content (0.017 m^3) volumes. The average heartwood, sapwood, and bark content volumes in all age classes were 0.210 m^3, 0.052 m^3, and 0.019 m^3, respectively.

Cauvery Delta zone

The lowest heartwood (0.037 m^3), sapwood (0.024 m^3), and bark content (0.008 m^3) volumes in this zone were observed in the 5- to 10-year-old trees, while 15- to 20-year-old trees had significantly higher heartwood (0.312 m^3), sapwood (0.141 m^3), and bark content (0.034 m^3) volumes ($p < 0.05$). Average volumes for all age classes in boundary plantations for heartwood, sapwood, and bark content volumes were 0.154 m^3, 0.078 m^3, and 0.020 m^3, respectively.

Western zone

Maximum heartwood, sapwood and bark volumes in 15- to 20-year-old trees were 0.433 m^3, 0.120 m^3 and 0.097 m^3, respectively, while heartwood, sapwood, and bark contents in 5- to 10-year-old trees were 0.113 m^3, 0.083 m^3, and 0.054 m^3, respectively.

Significantly higher heartwood volumes were found in 15- to 20-year-old teak plantations grown in this zone.

Pearson correlations for wood quality vs. climate in block plantations

Climatic factors including average annual rainfall were positively correlated with wood density, heartwood, sapwood, and bark content, with correlation coefficients of $r = 0.412$, 0.792, 0.755 and 0.103, respectively (Table 6). Similarly, relative humidity was positively correlated with wood density, heartwood, sapwood, and bark content volumes, with correlation coefficients of $r = 0.354$, 0.597, 0.442, and 0.456, respectively. Maximum temperature was negatively correlated with heartwood volume ($r = -0.085$) in trees aged 5–10 years to 15–20 years, reflecting the negative effects of higher temperatures on tree growth. Minimum temperature was also positively correlated with wood density, heartwood, and sapwood volumes. There was a strong positive correlation between heartwood volume and average rainfall ($r = 0.792$).

Table 2. Volumes of bark (BC), sapwood (SW) and heartwood (HW) in boundary and block plantations in the North Western zone (NWZ).

Age class (yr)	Block				Boundary			
	Wood density (g/cm^3)	HW volume (m^3)	SW volume (m^3)	BC volume (m^3)	Wood density (g/cm^3)	HW volume (m^3)	SW volume (m^3)	BC volume (m^3)
5-10	0.61	0.050	0.055	0.012	0.70	0.099	0.040	0.017
10-15	0.69	0.088	0.059	0.013	0.74	0.228	0.050	0.018
15-20	0.74	0.204	0.079	0.021	0.79	0.303	0.067	0.022
Mean	0.68	0.114	0.064	0.015	0.74	0.210	0.052	0.019
S.Ed	0.04	0.027	0.004	0.002	0.03	0.034	0.005	0.001
CD	0.08	0.059	0.009	0.004	0.05	0.075	0.011	0.002

Table 3. Volumes of bark (BC), sapwood (SW) and heartwood (HW) in boundary and block plantations in the Cauvery Delta zone (CDZ).

Age class (yr)	Block				Boundary			
	Wood density (g/cm^3)	HW volume (m^3)	SW volume (m^3)	BC volume (m^3)	Wood density (g/cm^3)	HW volume (m^3)	SW volume (m^3)	BC volume (m^3)
5-10	0.60	0.012	0.040	0.003	0.66	0.037	0.024	0.008
10-15	0.70	0.046	0.054	0.011	0.72	0.112	0.067	0.018
15-20	0.75	0.086	0.075	0.014	0.76	0.312	0.141	0.034
Mean	0.68	0.048	0.056	0.009	0.71	0.154	0.078	0.020
S.Ed	0.04	0.012	0.006	0.002	0.03	0.047	0.020	0.005
CD	0.09	0.026	0.013	0.004	0.06	0.103	0.044	0.011

Table 4. Volumes of bark (BC), sapwood (SW) and heartwood (HW) in boundary and block plantations in the Western zone (WZ).

Age class (yr)	Block				Boundary			
	Wood density (g/cm^3)	HW volume (m^3)	SW volume (m^3)	BC volume (m^3)	Wood density (g/cm^3)	HW volume (m^3)	SW volume (m^3)	BC volume (m^3)
5-10	0.63	0.025	0.021	0.023	0.68	0.113	0.083	0.054
10-15	0.68	0.083	0.048	0.059	0.74	0.238	0.096	0.094
15-20	0.74	0.139	0.073	0.090	0.80	0.433	0.120	0.097
Mean	0.68	0.082	0.047	0.057	0.73	0.261	0.100	0.082
S.Ed	0.03	0.033	0.015	0.019	0.03	0.093	0.011	0.014
CD	0.07	0.069	0.032	0.041	0.06	0.196	0.023	0.029

Table 5. Volumes of bark (BC), sapwood (SW), and heartwood (HW) in boundary and block plantations in the North Eastern zone (NEZ).

Age class (yr)	Block				Boundary			
	Wood density (g/cm^3)	HW volume (m^3)	SW volume (m^3)	BC volume (m^3)	Wood density (g/cm^3)	HW volume (m^3)	SW volume (m^3)	BC volume (m^3)
5-10	0.62	0.031	0.050	0.007	0.67	0.070	0.047	0.010
10-15	0.71	0.071	0.054	0.012	0.73	0.180	0.061	0.019
15-20	0.75	0.239	0.114	0.027	0.78	0.342	0.074	0.030
Mean	0.69	0.114	0.072	0.015	0.73	0.197	0.060	0.020
S.Ed	0.04	0.037	0.012	0.003	0.03	0.046	0.005	0.003
CD	0.08	0.081	0.026	0.007	0.07	0.101	0.011	0.007

Pearson correlation for wood quality vs. climate in boundary plantations

Average rainfall was positively correlated with wood density, heartwood volume, sapwood volume, and bark content volume, with correlation coefficients (r) of 0.859, 0.816, 0.384, and 0.196 at $p < 0.01$, respectively. Similarly, relative humidity was positively correlated with wood density, heartwood, sapwood, and bark content volumes, with correlation coefficients of $r = 0.831$, 0.899, 0.685, and 0.632, respectively. Maximum temperature was negatively correlated with all the wood quality parameters. A strong positive correlation ($r = 0.899$) was found between heartwood volume and relative humidity (Table 7).

Table 6. Pearson Correlations coefficients for wood quality vs. climate in block plantations.

Pearson's correlation	Wood density (g/cm³)	Heartwood volume (m³)	Sapwood volume (m³)	Bark content volume (m³)	Average rainfall (mm)	Maximum temperature (°C)	Minimum temperature (°C)	Relative humidity (%)
Wood density (g/cm³)	1							
Heartwood volume (m³)	0.774	1						
Sapwood volume (m³)	0.753	0.891	1					
Bark content volume (m³)	0.389	0.363	0.193	1				
Average rainfall (mm)	0.412	0.792	0.755	0.103	1			
Maximum temperature (°C)	0.120	-0.085	0.055	-0.502	-0.295	1		
Minimum temperature (°C)	0.338	0.347	0.535	-0.249	0.491	-0.144	1	
Relative humidity (%)	0.354	0.597	0.442	0.456	0.797	-0.694	0.365	1

Table 7. Pearson Correlation coefficients for wood quality vs. climate in boundary plantations.

Pearson's correlation	Wood density (g/cm³)	Heartwood volume (m³)	Sapwood volume (m³)	Bark content volume (m³)	Average rainfall (mm)	Maximum temperature (°C)	Minimum temperature (°C)	Relative humidity (%)
Wood density (g/cm³)	1							
Heartwood volume (m³)	0.957	1						
Sapwood volume (m³)	0.612	0.721	1					
Bark content volume (m³)	0.433	0.565	0.681	1				
Average rainfall (mm)	0.859	0.816	0.384	0.196	1			
Maximum temperature (°C)	-0.553	-0.503	-0.095	-0.190	-0.841	1		
Minimum temperature (°C)	0.320	0.229	-0.183	-0.390	0.635	-0.719	1	
Relative humidity (%)	0.831	0.899	0.685	0.632	0.840	-0.690	0.318	1

Pearson correlation for wood quality vs. edaphic factors in block plantations

Available phosphorous showed positive correlations with all wood density (r = 0.579), heartwood volume (r = 0.290), sapwood volume (r = 0.441), and bark content volume (r = 0.142) (Table 8). Similarly, soil pH was negatively correlated with wood density (r = -0.389), heartwood volume (r = -0.334), sapwood volume (r = -0.537), and bark content volume (r = -0.364). Positive correlations were also observed between available nitrogen and available potassium with wood density, with correlation coefficients of r = 0.053 and r = 0.343, respectively. Heartwood volume was negatively correlated with soil electrical conductivity (EC), organic carbon, and available nitrogen, with the correlation coefficients of r = -0.035, -0.275, and -0.362 in all four agroclimatic zones in the block plantation age classes of 5–10, 10–15, and 15–20 years (Table 9).

Pearson correlation for wood quality vs. edaphic factors in boundary plantations

Electrical conductivity and organic carbon were positively correlated with wood density (r = 0.225 and r = 0.352), heartwood volume (r = 0.300 and r = 0.436), sapwood volume (r = 0.493 and r = 0.376), and bark content volume (r = 770 and r = 0.493) (Table 10). pH was negatively correlated with wood density, heartwood volume, sapwood volume, and bark content volume, with correlation coefficients of r = -0.554, -0.635, -0.563, and -0.204, respectively. Available nitrogen, phosphorus, and potassium were negatively correlated with wood density, with coefficients of r = -0.099, -0.118, and -0.129, while correlations for these three elements with heartwood volume were r = -0.124, -0.078, and -0.275, respectively.

Discussion

Wood fractions of teak in block plantations

As expected, heartwood volume increased with increasing age and diameter (Tables 3 to 6), while bark content decreased. Tewari and Mariswamy (2013) also found that heartwood volume increased and bark volume decreased with increasing age and diameter at breast height (DBH).

The highest heartwood volume in block plantations was 0.239 m³ (age class of 15–20 years) was recorded from the northeastern zone. A previous study at Karnataka found that maximum heartwood volume of 0.167 m³ was recorded in a 36-year-old plantation. The studies show that heartwood volume increased with increasing age and diameter (Tewari and Mariswamy (2013). Similar studies were reported in teak with 20-year-old plantations in Thailand (Wanishdilokratn et al. 2024) and Indonesia (Nugroho et al. 2024).

Table 8. Soil physicochemical properties of four agroclimatic zones.

				Surface soil (0-15 cm)				
SI. No.	Location	Age class (yr)	Soil pH	EC (dS/m)	Organic carbon (%)	Available nitrogen (Kg/ha)	Available phosphorus (Kg/ha)	Available potassium (Kg/ha)
1	Arani (NEZ)	10-15	8.13	0.12	0.60	177	16.0	268.0
2	SU Vanam (NEZ)	5-10	7.17	0.16	0.56	173	20.0	295.0
3	Uthangarai (NWZ)	15-20	8.10	0.12	0.60	165	11.0	235.0
4	Naduvur (CDZ)	5-10	8.43	0.18	0.48	153	17.0	275.0
5	Pudur (WZ)	15-20	7.60	0.18	0.83	172	13.0	264.0
				Subsurface soil (15-30 cm)				
1	Arani (NEZ)	10-15	8.70	0.18	0.62	185	18.3	358.0
2	SU Vanam (NEZ)	5-10	7.01	0.17	0.59	180	25.0	312.0
3	Uthangarai (NWZ)	15-20	8.44	0.22	0.84	173	15.0	257.0
4	Naduvur (CDZ)	5-10	8.47	0.21	0.52	161	20.0	290.0
5	Pudur (WZ)	15-20	6.72	0.25	1.11	179	16.4	276.0

Table 9. Pearson correlation coefficients for wood quality vs. edaphic factors in block plantations.

Pearson's Correlation	Wood density (g/cm^3)	Heartwood volume (m^3)	Sapwood volume (m^3)	Bark content volume (m^3)	pH	Electrical conductivity (dSm^{-1})	Organic carbon (%)	Nitrogen (kg ha^{-1})	Phosphorus (kg ha^{-1})	Potassium (kg ha^{-1})
Wood density (g/cm^3)	1									
Heartwood volume (m^3)	0.765	1								
Sapwood volume (m^3)	0.826	0.899	1							
Bark content volume (m^3)	0.296	0.299	0.157	1						
pH	-0.389	-0.334	-0.537	-0.364	1					
Electrical conductivity (dSm^{-1})	-0.111	-0.035	-0.193	0.717	-0.180	1				
Organic carbon (%)	-0.272	-0.275	-0.280	0.501	-0.474	0.624	1			
Nitrogen (kg ha^{-1})	0.053	-0.362	-0.046	-0.038	-0.357	0.061	0.431	1		
Phosphorus (kg ha^{-1})	0.579	0.290	0.441	0.142	-0.285	0.171	-0.326	0.239	1	
Potassium (kg ha^{-1})	0.343	0.027	0.238	-0.035	0.056	0.155	-0.221	0.502	0.681	1

Table 10. Pearson correlation coefficients for wood quality vs. edaphic factors in boundary plantations.

Pearson's correlation	Wood density (g/cm^3)	Heartwood volume (m^3)	Sapwood volume (m^3)	Bark content volume (m^3)	pH	Electrical conductivity (dSm^{-1})	Organic carbon (%)	Nitrogen (kg ha^{-1})	Phosphorus (kg ha^{-1})	Potassium (kg ha^{-1})
Wood density (g/cm^3)	1									
Heartwood volume (m^3)	0.944	1								
Sapwood volume (m^3)	0.445	0.601	1							
Bark content volume (m^3)	0.313	0.479	0.626	1						
pH	-0.554	-0.635	-0.563	-0.204	1					
Electrical conductivity (dSm^{-1})	0.225	0.300	0.493	0.770	-0.180	1				
Organic carbon (%)	0.352	0.436	0.376	0.493	-0.473	0.624	1			
Nitrogen (kg ha^{-1})	-0.099	-0.124	0.324	-0.072	-0.357	0.061	0.431	1		
Phosphorus (kg ha^{-1})	-0.118	-0.078	0.511	0.108	-0.285	0.171	-0.326	0.239	1	
Potassium (kg ha^{-1})	-0.129	-0.275	0.172	-0.104	0.056	0.155	-0.221	0.502	0.681	1

The proportions of sapwood, heartwood, and bark varied with age in the selected agroclimatic zones of Tamil Nadu (Figure 3). Heartwood percentages in the present study ranged from 22.39% to 83.51%, sapwood percentages ranged from 11.23% to 71.64%, and bark content percentages ranged from 5.26% to 32.78% in the three age classes. Conversely, Kollert et al. (2024) found that heartwood percentage varied from 37.05% to 56.33%, sapwood percentage varied from 12.95% to 23.04%, and bark content percentage varied from 27.77% to 43.52% in different ages (11–36 years). The studies all concluded that heartwood percentage increased and bark content decreased with increasing age and diameter, whereas the sapwood proportion remained relatively similar. A stable sapwood proportion would be consistent with the need for the trees to maintain sufficient transport capacity to maintain the foliage.

Wood density and specific gravity are both used to indicate the amount of actual wood substance present in a unit volume of wood, and both terms can be calculated from one another (Zobel and Talbert 1984). Wood density or wood specific gravity is considered as one of the most important wood properties contributing to wood quality.

Wood density in block plantations ranged from 0.60 g/cm^3 to 0.75 g/cm^3 in the three age classes. Shukla et al. (2007) reported that the average wood density of *Acacia auriculiformis* was highest in 13-year-old trees (0.62 g/cm^3), followed by 12-year-old (0.60 g/cm^3) and 8-year-old trees (0.57 g/cm^3).

Wood fractions of teak in boundary plantations

Teak grown in boundary plantations had the highest heartwood volumes when compared to block plantations. This may be

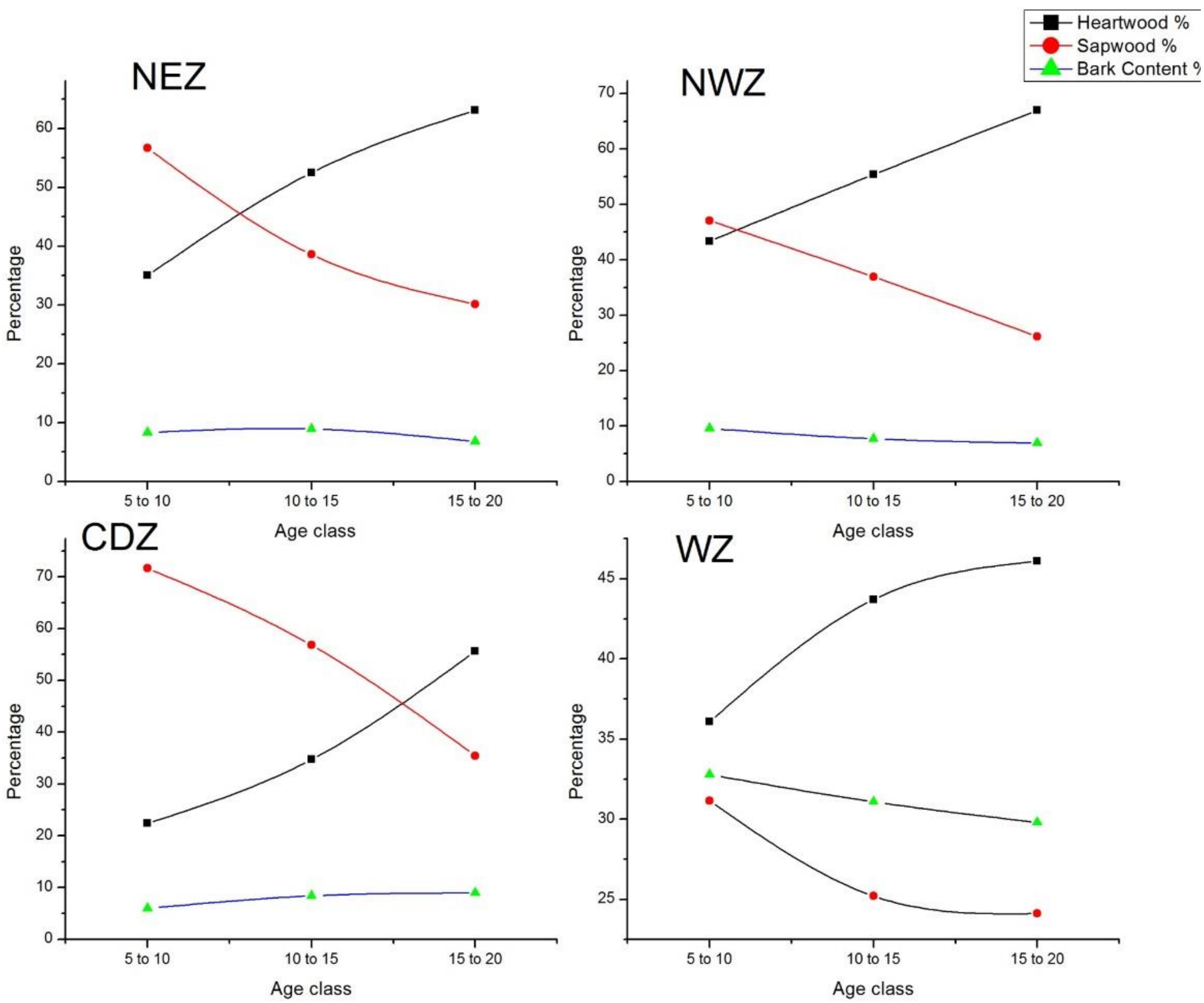

Figure 3. Wood fractions of teak in block plantations

attributed to wider spacing adaptability for boundary planting (5 m × 5 m, 7 m × 7 m, or 10 m × 10 m) compared to closer spacing (2 m × 2 m or 3 m × 3 m) of block planting. Zahabu et al. (2015) also concluded that wider spacing was more favorable for teak grown in boundary plantations in farmlands of Tanzania. Enhanced wood production from teak boundaries has been attributed to low competition for light, water, and nutrients from neighboring trees (Pandey and Brown 2000).

Teak grown in boundary plantation in selected agroclimatic zones had the maximum heartwood volume in 15- to 20-year-old trees in terms of cubic meter and percentage (Figure 4). The highest heartwood volume (0.433 m^3) was registered in the western zone with the spacing of 5 × 5 m. The present findings were in line with Zahabu et al. (2015) and showed increased heartwood proportion as planting spacing increased in boundary plantations. Bhat (1995) and Kokutse et al. (2004) also found an increase in the heartwood proportion of teak with increased spacing in farm plantations of Kerala, India and Togo, respectively.

Wood density of teak gradually increased (0.66 g/cm^3 to 0.80 g/cm^3) with increased age, from 5 to 20 years. Cordero and Kanninen (2003) also observed that wood density increased (0.73 g/cm^3 to 0.77 g/cm^3) as age increased from 10 to 47 years, but growth rate declined. The results were positively correlated with those of Wanneng et al. (2014) who compared density of three age groups (5, 10, and 15 years) of teak and found that density with the maximum age group of 15 years would be acceptable for industrial utilization.

Edaphoclimatic influence on wood quality in block plantations

Integrating trees on farms is beneficial for farmers, especially those struggling to cope with the impacts of climate change (Gonsalves 2014). Rainfall, relative humidity, and maximum

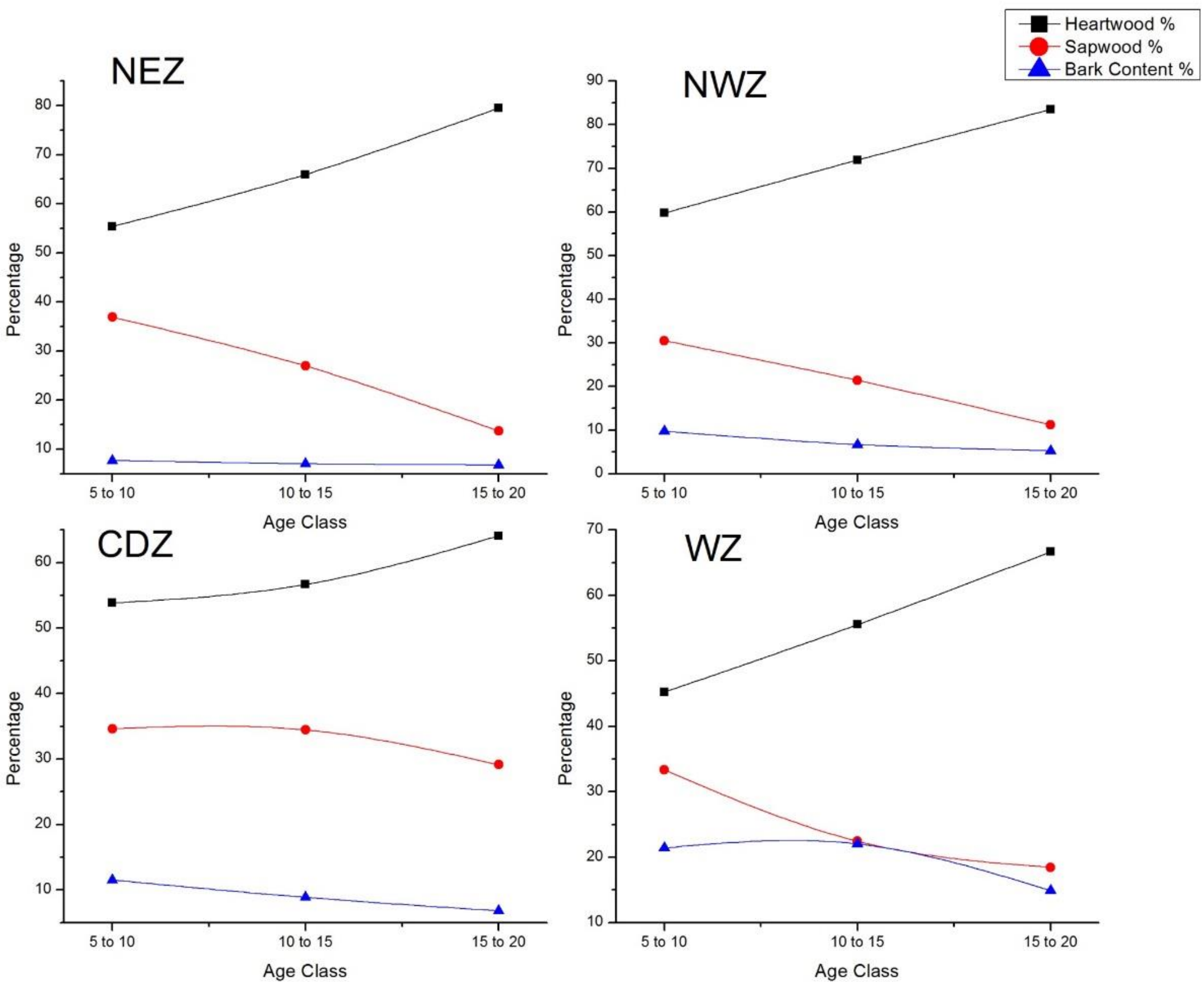

Figure 4. Wood fractions of teak in boundary plantations

and minimum temperature were correlated with heartwood volume in all three age classes in all four zones in Tamil Nadu (Figure 5). Climatic factors were positively correlated with heartwood volume under the average rainfall (r = 0.792), minimum temperature (r = 0.347), and relative humidity (r = 0.597). The present study confirms the findings of Pimpale et al. (2000), who found that the highest increase in mean annual increment (MAI) of a 5-year-old teak plantation was registered in 1999 at Akola, Maharashtra, where maximum annual rainfall was above average. Mean growth rate of teak ranged from 4.5 mm/year/tree (initial years) to 5.2 mm/year/tree (30 years onwards); however, slower growth was observed when annual rainfall was less than 800 mm (Palanisamy et al. 2009). Previous studies indicate that teak grows well in areas with 800-2500 mm rainfall annually at an elevation of about 1200 m (Sabastian et al. 2018).

Previous studies have also shown that teak grows well on deep, well-drained alluvial soils but poorly on dry sandy, shallow or hard pan, acidic, laterite, black cotton or waterlogged soils. It tolerates heat and drought and soil pH's ranging from 5.0 to 8.0 (Kulkarni 2000). Soil pH (r = -0.334), soil EC (r = -0.035), soil organic carbon (r = -0.275), and soil available nitrogen (r = -0.362) were all negatively correlated with the heartwood volume of teak (Figure 6). Conversely, available phosphorus (r = 0.290) and potassium (r = 0.027) were positively correlated with the heartwood volume. Watanabe et al. (2016) found positive correlations with available phosphorus and potassium and negative correlations with pH, soil EC, and available nitrogen and the quality of teak heartwood. Zhang et al. (2016) found that shallow soils were an important factor limiting tree heartwood ratios, while deeper soils were associated with higher tree growth and improved wood quality.

Edaphoclimatic influence on wood quality in boundary plantations

Tree growth is strongly influenced by climatic factors like rainfall, temperature (maximum and minimum), and relative humidity. In the current study, teak heartwood volume was highly positively correlated with rainfall (r = 0.816) and relative humidity (r = 0.899). The results are in line with 5-year-old *Pinus radiata* (Alvarez et al. 2012) that exhibited positive correlations between heartwood volume and mean annual rainfall. In the present study, maximum temperature was negatively correlated with heartwood volume (r = -0.503). Similar negative correlations between maximum temperature and heartwood volume were recorded in *Pinus radiata* plantations (Yang et al. 2018). The results illustrate the obvious influences of mean annual rainfall, temperature, and relative humidity on tree growth and heartwood volume of teak (Figure 7).

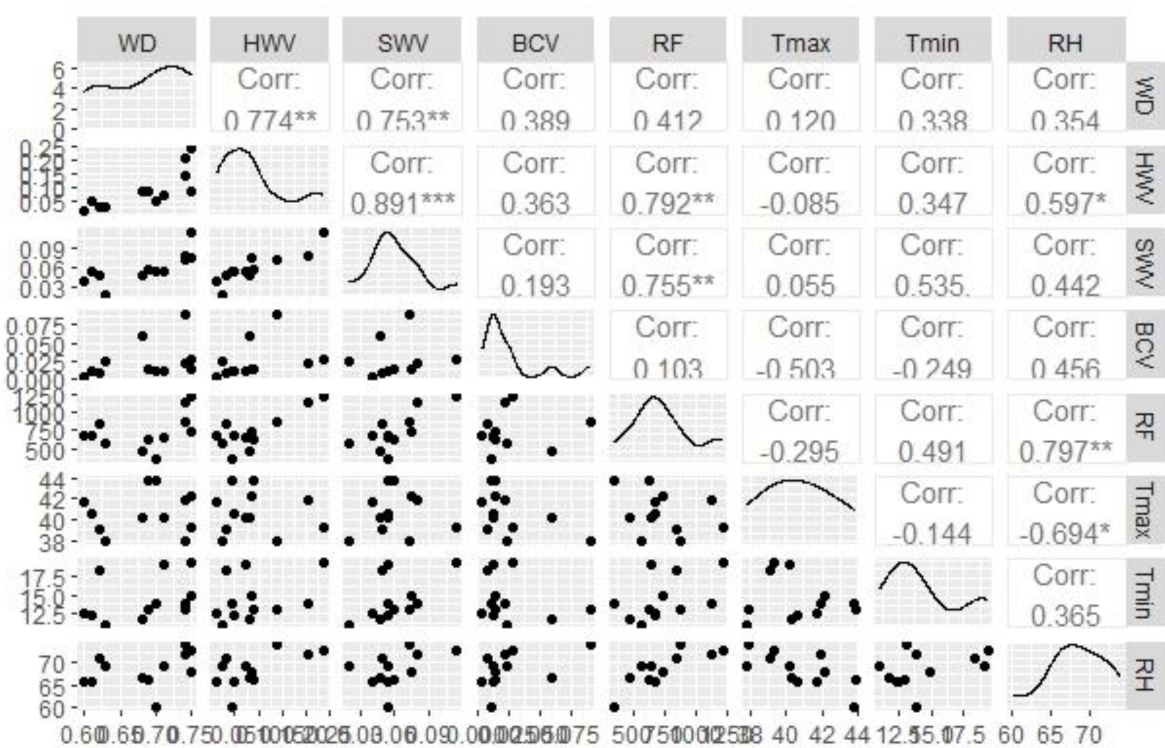

Figure 5. Relationships between wood quality and climate factors in block plantations.

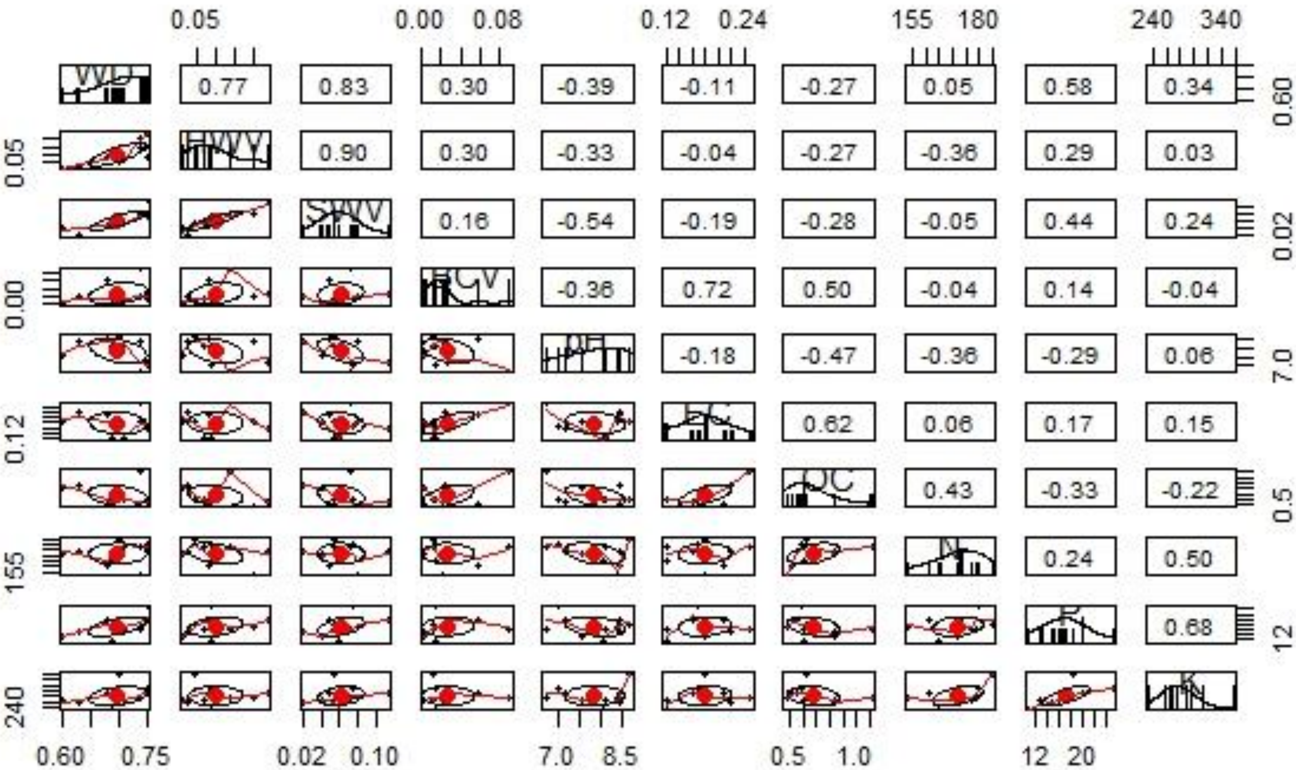

Figure 6. Relationships between wood quality and soil characteristics in block plantations.

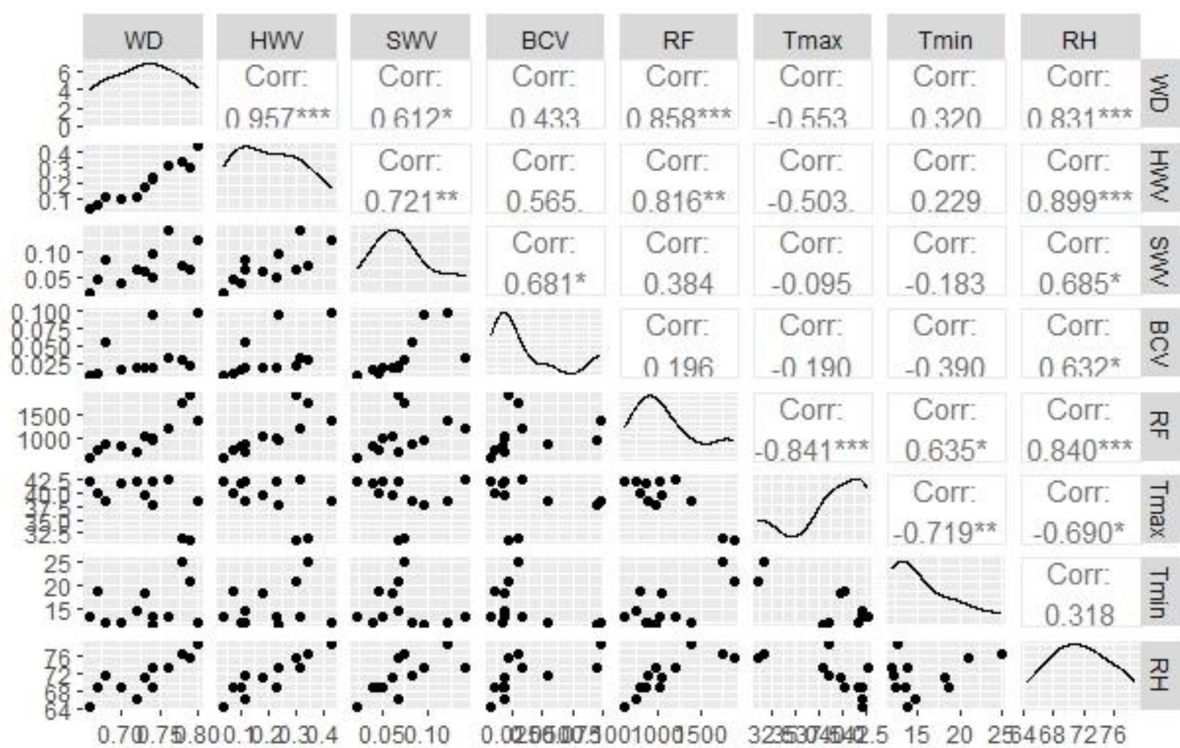

Figure 7. Relationships between wood quality and climate in boundary plantations.

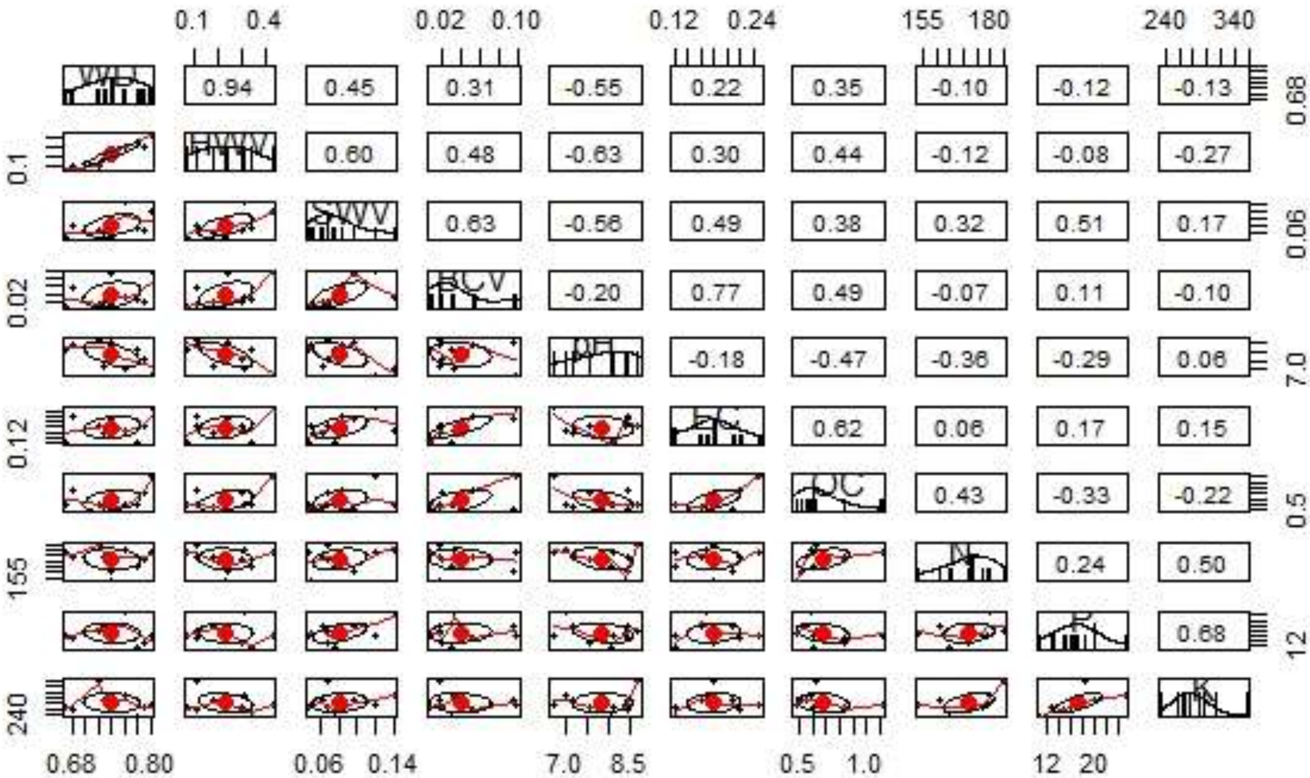

Figure 8. Relationships between wood quality and Soil characteristics in boundary plantations

Soil physicochemical and chemical properties strongly influenced the growth parameters in the boundary plantations. Soil macronutrients such as available nitrogen, phosphorus, and potassium play significant roles in the wood quality of farm-grown teak. Increasing soil pH was negatively correlated with all wood quality attributes, while soil EC exhibited a significant positive correlation. Previous studies have found that soil pH and EC influence growth, wood quality, and tree distribution. Aparanji (2000) found significant relationships between the volume increment of teak and soil physicochemical properties. The soil organic carbon was positively correlated with heartwood volume in radiata pine (Gunaga et al. 2011 and Alvarez et al. 2012).

Available nitrogen, phosphorus and potassium were all negatively correlated with all wood quality parameters (Figure 8). These results support previous studies with other species (Watanabe et al. 2016 and Gunaga et al. 2011). The positive influence of soil factors on wood quality and productivity of tree species have also been previously reported for teak (Aparanji 2000), *Pinus radiata* (Alvarez et al. 2012), *Ailanthus excelsa* (Rajasugunasekar et al. 2017) and *Picea abies* (Johansson et al. 2014).

Conclusion

Heartwood, sapwood, and bark volumes all varied among all three age classes and also with all four agroclimatic zones. Teak grown in block plantations had the highest heartwood and sapwood volumes in the northeastern zone for 15- to 20-year-old trees. However, maximum bark content was obtained in the western zone for 15- to 20-year-old trees. The northeastern zone registered the maximum clear bole volume, indicating that this zone was well-suited in terms of wood yield and quality. Maximum heartwood and bark volumes in boundary plantations were observed in 15- to 20-year-old trees in the western zone. Maximum sapwood volume was observed for 15- to 20-year-old trees in the Cauvery Delta. Boundary plantations in the western zone tended to have higher wood volumes and heartwood content, suggesting that this area is the most suitable zone for growing teak in boundary plantations.

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