Variation in Heartwood Formation and Wood Density in Plantation-Grown Red Sanders (*Pterocarpus santalinus*)

K. Suresh, Maheshwar Hegde, P. Deenathayalan, P. Karthick Kumar, M. Thangapandi, B. Gurudev Singh and N. Krishnakumar

Abstract *Pterocarpus santalinus* L. f. (Red Sanders) is narrowly endemic to the Seshachalam, Veligonda, Lankamala and Palakonda hill ranges in Andhra Pradesh. The wood and wood products of Red Sanders continue to be in high demand and are traded internationally in large volumes that find use in the musical instruments, furniture, handicrafts, cosmetics, medicine and food industry. Over exploitation without commensurate replenishment of natural stands and illegal logging has posed a severe threat to the very existence of this precious timber species and classified as globally threatened in the IUCN Red List. Good-quality heartwood of Red Sanders is illegally traded and fetches very high price in the global market. As harvest of heartwood from natural population may not be sustainable, any future plan of harvest of Red Sanders wood and export should be from cultivated sources. About 5000 ha of plantations of Red Sanders exists in various states in South India. Little information is available about the quality and quantity of heartwood formation in plantations compared to natural populations. In this backdrop, the current study was conducted to evaluate the variation in heartwood, sapwood and bark content, and wood density of plantation-grown Red Sanders trees of various age classes located in various places. The core wood samples from various locations were collected using increment borer based on standard sampling procedure. The heartwood, sapwood and bark content were measured as a percentage of the cross-sectional area at breast height. Wood density was determined using core wood samples taken at breast height of the tree. The variation in heartwood content and wood density of Red Sanders were found to be influenced by the age and size of the trees.

Keywords Red sanders · Plantation · Heartwood content · Wood density

K. Suresh · M. Hegde (✉) · P. Deenathayalan · P. Karthick Kumar
M. Thangapandi · B. Gurudev Singh · N. Krishnakumar
Institute of Forest Genetics and Tree Breeding,
R. S. Puram, Coimbatore 641002, India
e-mail: hegdem@icfre.org

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Introduction

Pterocarpus santalinus L. f. (Red Sanders) is a narrowly endemic species naturally distributed over an area of about 0.4 million ha mainly in the hilly tracts in Chittoor, Cuddappah, Nellore, Prakasam and Kurnool districts of Andhra Pradesh (IFGTB 2011). The species occurs in 'Dry Red Sanders-Bearing Forest' which is classified as '5A/C2 Forest Type' (Champion and Seth 1968). Red Sanders is highly valued for its heavy, dark claret-red heartwood which yields 16% of red coloring matter to santalin, a natural dye used to color liquors, pharmaceutical preparations, food stuffs, etc. (Ramakrishna 1962; Anuradha and Pullaiah 1998). It is renowned for its characteristic timber of exquisite color, beauty and superlative technical qualities and ranks among the finest luxury wood in the world which is highly useful for making high-value musical instruments, cabinets, ornamental veneers, toys, dolls and was used in incense.

The Red Sanders is under severe threat in its native range, owing to its endemism to small area, poor regeneration and overexploitation due to illegal felling. Despite a ban on felling and sale, good-quality Red Sanders are illegally traded since they fetch very high price in the global market. Based on the grain type, the Red sanders trees may be divided into two types in commerce, viz. wavy-grained and straight-grained which occur mixed in the forest or plantations (Lohidas and Dayanand 1984; Dayanand and Lohidas 1988). The wavy-grained variants are preferred in the global markets and fetch higher price compared to normal-grained types. State Forest Departments of Tamil Nadu, Kerala and Andhra Pradesh have raised Red Sanders plantations in several locations other than its natural ranges during last 50 years. A few number of tree growers and farmers are also cultivating this species in farm land in Andhra Pradesh, Tamil Nadu, Orissa and Karnataka and in other states, and about 3000 ha of Red Sanders plantations currently exists (IFGTB 2011).

Though growth rate is reported to be faster under plantations raised in rich soils compared to natural population (ICFRE 1992), not much information is available regarding growth rate of the species according to location, climate and soil outside its natural range. The heartwood is the main economic part of the tree in Red Sanders. Information regarding extent of formation of heartwood and quality of heartwood in Red Sanders plantations compared to its natural range is also not available. In this backdrop, the current study was conducted to evaluate the variation in heartwood, sapwood and bark content, and wood density of plantation-grown Red Sanders trees of various age classes grown in various locations across southern India.

Materials and Methods

Reconnaissance survey was carried out to find various age class plantations across various regions in Tamil Nadu, Andhra Pradesh, Karnataka and Kerala states in southern India. Various age class plantations available were visited for collection of

growth as well as wood data during 2011–2014. Totally, 27 plantations were selected from 9 forest divisions (Table 1). Sampling of the selected plantations was done based on the total area of the plantation with at least 3% sampling intensity. Sample plots of size either 50 m × 50 m or 20 m × 20 m (in small size plantations) dimensions were laid. Quantitative and qualitative growth data of trees, such as diameter at breast height (DBH), total tree height, clear bole height, branching habit, stem form, health, phenology and wood grain pattern, were collected in all the sample plots laid. Red Sanders trees possess characteristic thick dead outer bark (dead corky tissue) that is blackish brown in color resembling the skin of crocodile. The cracks are divided into rectangular plates by deep vertical and horizontal

Table 1 Details of Red Sanders plantations sampled and climatic factors of their locations

District/state	Plantations	Age (years)	Min temp (°C)	Max temp (°C)	Rainfall (mm)	Dry months
Tiruvannamalai, Tamil Nadu	Vallimalai	28	22.6	32.7	1022	7
	Allikuttai	32	23.1	33.1	1071	7
	Arani	39	23.1	33.2	1031	7
	Kasthambadi	49	23.1	33.2	1063	7
	Thaniyar	94	21.6	31.8	1007	7
Vellore, Tamil Nadu	Banavaram-1	23	23.3	33.3	988	7
	Banavaram-2	24	23.3	33.3	988	7
	Banavaram-3	28	23.3	33.3	988	7
	Rettapettai	32	23.0	33.1	973	7
	Kalpudur	40	22.8	32.9	961	7
	Nelakanrayanpet	41	23.1	33.2	967	7
	Kalmelkuppam	54	23.0	33.1	973	7
	Ammoor	56	23.0	33.1	973	7
Tiruvallur, Tamil Nadu	Nayapakkam	31	23.7	33.5	1102	6
	Pullarampakam	36	23.8	33.5	1099	6
	Avajipetai	37	23.8	33.5	1101	6
	Nemalur	37	23.9	33.6	1112	7
	Malanthur	41	23.8	33.5	1101	6
	Vengal	42	23.8	33.5	1101	6
	Mylapore	47	23.8	33.5	1101	6
Andhra Pradesh	Tirupathi	30	22.1	32.2	870	7
Kadapa, Andhra Pradesh	Kodur-1	67	23.2	33.3	840	9
	Kodur-2	78	23.2	33.3	840	9
Tumkur, Karnataka	Ankapura	15	19.1	30.1	575	10
Bengaluru, KA	Jarakabande	26	18.1	29.4	774	9
Thrissur, Kerala	Palappilly	31	23.6	31.5	2950	4
Ernakulam, Kerala	Kodanad	31	23.7	31.5	3230	4

fissures. The inner bark lies next to outer bark. To study the variation in heartwood formation, wood samples were collected from these plantations using increment borer by laying 10 m × 10 m subplots within all the sample plots and the samples were taken back in airtight container to the laboratory at the Institute of Forest Genetics and Tree Breeding (IFGTB), Coimbatore. Heartwood length, sap wood length, bark thickness and wood density were analyzed from these wood samples, and the difference in heartwood content and wood density among various plantations was studied. The heartwood, sapwood and bark content were measured as a percentage of the cross-sectional area at breast height. The core wood samples were dried and weighed, and the wood density was calculated as the ratio of oven-dried weights to green volume. Various climatic data like rainfall, minimum and maximum temperatures pertaining to locations of plantations were obtained through DIVA-GIS to compare these site factors with tree growth and wood parameters measured.

Results and Discussion

The age of surveyed plantations varied from 15 to 94 years across various locations. Details of plantations in which sample plots were laid out for testing heartwood formation, growth data of sampled trees and proportion of sampled trees with heartwood formation are provided in Table 2. The growth data and wood data collected from sampled trees were also grouped according to the age classes (Table 3). Out of 27 plantations, only five plantations were more than 50 years of age. The majority of the plantations surveyed occurred in the age classes of 21–30, 31–40 and 41–50 years. Number of trees sampled in 27 plantations (sample plot size 10 M × 10 M) varied from 2 to 108 based on the size of the plantation area and also stocking of trees. Some of the locations like Kalpudur, Rettapettai and Ammoor in Tiruvannamalai had large areas of plantation and good stocking; therefore, the number of sample plots was increased. Generally, the Red Sanders trees attain medium height of 8–10 meters in plantations as well as in natural locations. However, in some of the high rainfall locations like Palappilly and Kodanad in Kerala, the average tree height reached 16–18 m at 31 years age. In some of the very old plantations like Thaniyar in Vellore Division (94 years age) and Kodur in Andhra Pradesh (78 years), the average tree height was high (Table 2). The average girth at breast height (GBH) varied from 52.0 (in 15-year-old plantation) to 160.63 cm (in 94-year-old Thaniyar plantation).

The growth data collected in sample plots of 50 m × 50 m size (data not shown here) revealed that the GBH slightly increased linearly with the age. However, the average GBH did not always linearly increase with the age because of location effects in some of the plantations. For instance, in some plantations of 21- to 30-year girth class, the GBH was higher than that in 31–40 girth class plantations. In case of Kodur plantations situated at Andhra Pradesh which was above 60 year old, trees had lower girth than those in few of the 28-year-old plantations.

Table 2 Details of sample plots laid for testing heartwood formation, growth data of sampled trees and proportion of sampled trees with heartwood formation

Location	Plantation	Age (years)	No. of sample plots	No. of trees sampled	Average GBH (cm)	GBH range (cm)	Average height (m)	Height range (m)	Percent sampled trees with heartwood formation
Tiruvannamalai Tamil Nadu	Vallimalai	28	3	17	103.5	76–136	10.86	10–12	57.14
	Allikuttai	32	3	9	67.94	48–85	10.67	6–13.8	100.00
	Arani	39	4	29	55.96	21–118	11.52	6–16.5	79.17
	Kasthambadi	49	3	11	106.11	84–137	11.49	9–14	100.00
	Thaniyar	94	3	7	160.63	116–200	16.96	10–23.5	100.00
Vellore Tamil Nadu	Banavaram-1	23	3	11	100.00	70.0–122.0	10.9	8.0–14	100.00
	Banavaram-2	24	3	13	95.46	72–134	13.79	10.0–16	100.00
	Banavaram-3	28	3	8	85.25	70–122	10.56	9.0–12	100.00
	Rettapettai	32	13	66	67.22	40–98	9.64	7–12.8	100.00
	Kalpudur	40	15	108	55.64	35–81	10.61	6.5–13.5	96.30
	Nelakanrayanpet	41	4	19	61.28	34–96	8.56	4.0–12	100.00
	Kalmelkuppam	54	6	19	110.79	94–146	10.96	6.5–14.5	100.00
	Ammoor	56	6	36	115.29	64–188	12.19	8.5–16	100.00
Tiruvallur Tamil Nadu	Nayapakkam	31	3	9	52.38	37–78	9.59	5.5–15	100.00
	Pullarampakam	36	3	7	69.79	57–82	10.76	4.5–15	100.00
	Avajipetai	37	3	8	61.16	37–74	10.13	4–15	100.00
	Nemalur	37	3	8	61.44	38–92	9.8	4.5–13.8	75.00
	Malanthur	41	3	9	114.00	91–148	9.38	5–14	100.00
	Vengal	42	3	9	114.00	94–130	10.30	6–14.6	100.00

(continued)

Table 2 (continued)

Location	Plantation	Age (years)	No. of sample plots	No. of trees sampled	Average GBH (cm)	GBH range (cm)	Average height (m)	Height range (m)	Percent sampled trees with heartwood formation
	Mylapore	47	3	13	87.92	46–130	10.71	7–13.5	100.00
Andhra Pradesh	Tirupathi	30	3	11	68.05	13–84	9.81	4.5–15	53.85
	Kodur-1	67	1	4	76.78	57–95	11.44	7–16	100.00
	Kodur-2	78	1	5	91.94	61–115	19.89	7–25	100.00
Karnataka	Ankapura	15	1	3	52.00	19–57	12.1	6–15.5	66.67
	Jarakabande	26	1	2	59.75	39–78	9	7–13	100.00
Kerala	Palappilly	31	1	4	73.50	53–110	16.53	6–27	100.00
	Kodanad	31	1	4	96.25	60–132	18.47	11.5–26	100.00

Table 3 Age class-wise mean DBH, bark content, sap wood, heartwood content and wood density in sampled trees in Red Sander plantations

Age class (in years)	No. of plantations	Av. DBH (cm)			Av. Bark content (%)			Av. Sapwood content (%)			Av. Heartwood content (%)			Av. Wood density		
		Mean	Std. Dev	Range	Mean	Std. Dev	Range	Mean	Std. Dev	Range	Mean	Std. Dev	Range	Mean	Std. Dev	Range
<20	1	16.56	–	–	49.76	–	–	48.72	–	–	1.52	–	–	0.868	–	–
21–30	6	27.18	5.70	19.03–32.96	33.71	6.78	27.18–46.53	34.35	10.27	24.91–50.06	31.94	12.56	17.41–47.90	0.865	0.070	0.776–0.961
31–40	10	21.06	4.01	16.68–30.65	41.11	8.10	27.11–50.0	35.06	2.49	31.30–38.29	23.83	8.11	15.69–40.87	0.888	0.095	0.760–1.03
41–50	5	30.79	7.15	19.52–36.51	33.70	6.66	28.29–44.03	29.13	3.99	24.71–33.68	37.18	10.07	23.13–45.53	0.841	0.088	0.753–0.970
51–60	2	36.00	1.02	35.28–36.72	30.67	1.15	29.86–31.49	28.33	3.58	25.80–30.86	49.49	7.27	44.35–54.63	0.880	0.009	0.874–0.886
>61	3	34.96	14.23	24.45–51.16	25.94	2.79	22.76–27.98	24.55	4.64	19.56–28.53	49.51	7.18	44.20–57.68	0.940	0.064	0.871–0.996

Therefore, it is evident that location factors and probably density of tress in plantations (stocking) had effect on GBH.

The proportion of sampled trees with heartwood is also given in Table 2. In Tiruvannamalai Forest Division, Vallimalai (28 years) and Arani (39 years), 57.14 and 79.12% of trees sampled had heartwood, respectively. In Vellore Division, in Kalpudur (40 years age) 96.30% trees sampled had heartwood. In rest of the plantations, all the sampled trees had heartwood. In Tiruvallur Division, in Nemallur (37 years) plantation only 75% trees had heartwood. Out of 2 plantations visited in Karnataka, in one plantation at Anakupura, Tumkur (15 years), 66.67% trees sampled had heartwood. The heartwood development was found in 15-year-old trees, indicating that heartwood in Red Sanders trees is initiated before 15 years of age. High tree-to-tree variation within plantations was found for height, girth and heartwood content.

The average bark, sapwood and heartwood area expressed as percent of total cross-sectional area of stem at breast height in the sampled trees across age classes is provided in Table 3. The mean bark proportion was higher in lower girth class plantations, i.e., below 40-year plantations as compared to plantations above 60 years old. Heartwood proportion ranged between 1.52% in 15-year-old plantation to 57.68% in 94-year-old plantation. Sapwood proportion decreased with the age. The above 60-year-aged plantations had an average of 24.55% sapwood. Generally, trees with higher DBH had high heartwood content even when they occurred in lower age classes. Average wood density ranged from 0.841 to 0.940 across different age classes (Table 3). Considerable variation was also observed in heartwood content and wood density within trees based on age, growth and location. Heartwood proportion increased slightly with increasing age, while sapwood gradually decreased.

Location-wise and plantation-wise bark, sapwood and heartwood proportions and wood density are given in Table 4. Considerable variation in wood density in sampled trees across plantation was observed. Average wood density was relatively lower (0.760 and 0.790, respectively) in Kodanad and Palappilly plantations which are located in high rainfall areas of Kerala. However, some of the plantations located in drier areas of Tamil Nadu, for example, Malanthur (0.753), Vengal (0.787), Vallimalai (0.776) and Mylapore (0.805) had relatively lower wood density. The Nayapakkam (1.03) and Pullarampakkam (1.01) had higher average wood density which was above 1.0. Very high variations were observed among trees within same plantations for wood density, heartwood, sapwood and also bark contents. The average bark and sapwood proportions were higher in lower age class plantations and also in trees with lower girth. The heartwood content was generally high in higher aged plantations. However, all three plantations in Banavaram which were aged 23–28 years characteristically had higher heartwood proportions (36.93–47.90%). Two 31-year-old Palappilly and Kodanad plantations also had higher heartwood proportions (34.11–40.87%). This was mainly due to higher average DBH of trees. These plantations had higher DBH than many of the older plantations.

Table 4 Variation in bark, sapwood, heartwood content and density with location of Red Sanders

Location	Plantation	Age (years)	Avg. DBH (cm)	Av. Bark content (%)	Av. Sap Wood (%)	Av. Heart Wood (%)	Heartwood % range	Av. Basic density	Basic density range (min–max)
Tiruvannamalai Tamil Nadu	Vallimalai	28	32.96 (1.35)	30.78 (1.14)	43.70 (2.86)	25.53 (2.71)	7.95–39.80	0.776 (0.024)	0.632–0.951
	Allikuttai	32	21.64 (1.43)	40.90 (3.14)	36.64 (2.83)	22.46 (4.90)	3.5–43.19	0.862 (0.015)	0.767–0.902
	Arani	39	17.82 (1.40)	50.00 (2.89)	34.31 (1.85)	15.69 (2.97)	0.00–51.91	0.864 (0.015)	0.751–1.071
	Kasthambadi	49	33.79 (1.90)	28.39 (1.43)	28.23 (1.25)	43.28 (2.23)	31.17–52.73	0.888 (0.024)	0.755–1.003
	Thaniyar	94	51.16 (3.69)	22.76 (1.67)	19.56 (2.45)	57.68 (3.70)	38.91–68.92	0.871 (0.035)	0.747–1.006
Vellore Tamil Nadu	Banavaram-1	28	31.85 (1.45)	27.18 (1.88)	24.91 (2.73)	47.90 (3.79)	24.25–69.60	0.839 (0.029)	0.611–0.983
	Banavaram-2	24	30.4 (1.53)	30.31 (1.53)	26.44 (1.73)	43.26 (2.95)	28.19–70.28	0.832 (0.022)	0.692–0.954
	Banavaram-3	23	27.15 (1.27)	34.95 (1.48)	28.12 (2.65)	36.93 (2.94)	25.81–50.43	0.846 (0.030)	0.754–1.027
	Rettapettai	32	21.41 (0.57)	37.24 (1.04)	37.21 (0.76)	25.56 (1.28)	1.22–46.04	0.802 (0.009)	0.660–1.097
	Kalpudur	40	17.72 (0.31)	43.68 (0.71)	38.29 (0.74)	18.03 (0.92)	0.01–44.53	0.842 (0.006)	0.667–1.116
	Nelakanrayanpet	41	19.52 (1.16)	44.03 (1.48)	32.84 (1.50)	23.13 (2.12)	2.39–40.84	0.970 (0012)	0.816–1.037
	Kalmelkuppam	54	35.28 (1.07)	31.49 (1.19)	30.86 (2.48)	37.65 (2.81)	9.31–53.78	0.874 (0.024)	0.650–1.025

(continued)

Table 4 (continued)

Location	Plantation	Age (years)	Avg. DBH (cm)	Av. Bark content (%)	Av. Sap Wood (%)	Av. Heart Wood (%)	Heartwood % range	Av. Basic density	Basic density range (min–max)
	Ammoor	56	36.72 (1.31)	29.86 (1.050)	25.80 (1.25)	44.35 (1.62)	24.06–62.97	0.886 (0.012)	0.786–1.054
Tiruvallur Tamil Nadu	Nayapakkam	31	16.68 (1.39)	48.47 (3.95)	35.75 (1.13)	15.79 (4.59)	0.004–40.26	1.030 (0.03)	0.930–1.200
	Pullarampakam	36	22.22 (1.12)	49.88 (2.61)	31.30 (3.32)	18.82 (3.92)	10.83–34.54	1.010 (0.03)	0.880–1.160
	Avajipetai	37	19.48(1.43)	45.41 (3.77)	32.02 (1.94)	22.57 (4.16)	1.86–33.93	0.960 (0.03)	0.820–1.060
	Nemalur	37	19.57 (2.24)	39.16 (5.07)	36.42 (3.26)	24.42 (7.21)	0.01–53.07	0.953 (0.014)	0.897–1.005
	Malanthur	41	36.31 (6.27)	28.29 (2.38)	26.18 (1.43)	45.53 (1.84)	36.97–54.15	0.753 (0.019)	0.622–0.799
	Vengal	42	36.31 (4.76)	31.31 (2.40)	24.71 (2.63)	43.98 (4.05)	22.72–64.02	0.787 (0.035)	0.638–0.969
	Mylapore	47	28 (1.95)	36.46 (2.79)	33.68 (1.62)	29.86 (3.34)	4.62–46.01	0.805 (0.028)	0.693–0.969
Andhra Pradesh	Tirupathi	30	21.67 (0.96)	32.53 (1.56)	50.06 (1.63)	17.41 (2.40)	0.28–32.76	0.935 (0.02)	0.779–1.048
	Kodur-1	67	24.45 (2.46)	27.07 (1.05)	28.73 (2.43)	44.20 (3.42)	35.71–51.72	0.952 (0.05)	0.790–1.027
	Kodur-2	78	29.28 (3.16)	27.98 (0.84)	25.36 (2.09)	46.66 (1.72)	42.97–51.7	0.996 (0.03)	0.936–1.11
Karnataka	Ankapura	15	16.56 (2.12)	49.76 (4.5)	47.38(3.33)	0.70 ((1.19)	0.0–3.86	0.868 (0.013)	0.850–0.893

(continued)

Table 4 (continued)

Location	Plantation	Age (years)	Avg. DBH (cm)	Av. Bark content (%)	Av. Sap Wood (%)	Av. Heart Wood (%)	Heartwood % range	Av. Basic density	Basic density range (min–max)
	Jarakabande	26	19.03 (2.79)	46.53 (8.08)	32.88 (6.38)	20.59 (14.46)	6.13–35.05	0.961 (0.038)	0.922–0.999
Kerala	Palappilly	31	23.41 (4.02)	34.11 (4.17)	36.66(2.2)	34.11 (4.17)	23.08–41.3	0.79 (0.03)	0.718–0.849
	Kodanad	31	30.65 (5.10)	27.11 (4.53)	32.02(2.40)	40.87 (4.28)	29.29–48.87	0.760 (0.04)	0.683–0.848

Relationship Among Growth, Wood Characters and Location Factors of Plantations

Pearson's correlation studies for growth and wood characters in Red Sander plantations sampled are given in Table 5. Tree age had significantly high positive correlation with (DBH) ($r = 0.572$) and heartwood proportion ($r = 0.602$) and significant negative correlation with sapwood and bark proportions ($r = -0.574$ and -0.469). DBH was positively correlated with heartwood (0.837), and wood density had moderate negative correlation with rainfall ($r = -0.393$) and DBH ($r = -0.406$) and was positively correlated with bark proportions ($r = 0.449$).

Perez et al. (2004) studied the heartwood content in several age class plantations of *Bombacopsis quinata*, a high-valued timber species of Costa Rica. No clear differences in heartwood content could be observed between trees of similar age from dry and wet zones. Heartwood content increased with age of the trees. Arun Kumar (2011) studied growth and heartwood content variability in two Red Sanders plantations of age 20 and 45 years in Karnataka and concluded that considerable variability exists for girth and heartwood content in the younger aged plantation. It was found that heartwood formation had not been initiated in trees less than 30-cm girth, and there was a strong relationship between girth and heartwood in both the plantations. Heartwood initiation was observed in 70% of the trees in 20-year-old plantation and 97% of the trees in the case of 45-year-old plantation.

To summarize the results, it was observed that in all the plantations there was high variability among trees within plantations for growth characteristics, bark, sapwood and heartwood content. There were no clear-cut variations in heartwood content and growth of Red Sander trees across locations, indicating climatic factors

Table 5 Correlations among growth and wood characters in Red Sander plantations sampled

	Age (years)	Rainfall (mm)	Diameter at breast height (DBH)	Bark proportion (%)	Heartwood proportion (%)	Sapwood proportion (%)
Age (years)	1					
DBH	0.572*	0.067 ns	1.000			
Bark proportion (%)	−0.469*	−0.276 ns	−0.777*	1.000		
Heartwood proportion (%)	0.602*	0.181 ns	0.837*	−0.884*	1.000	
Sapwood proportion (%)	−0.574*	−0.013 ns	−0.650*	0.473*	−0.831*	1.000
Basic wood density	0.202 ns	−0.393*	−0.406*	0.449*	−0.299 ns	0.028 ns

*$P < 0.01$

may have less influence on the heartwood formation and content in Red Sanders trees. DBH had highly significant positive relationship with heartwood content ($r = 0.837$) irrespective of age. The general belief is that faster the tree grows, lesser will be the heartwood content. However, the results in the present study indicated that the higher growth rate actually resulted in higher content of heartwood. Although plantations located in high rainfall areas of Kerala had lower wood densities, it was not very clear that there were differences in wood density among trees of similar age from dry and wet zones because some of the plantations located in drier areas of Tamil Nadu also had similar wood densities. It is also contrary to general belief that the Red Sanders trees grown in wet zones possess lower wood density compared to those grown in dry areas. The results indicated that the Red Sanders trees can be successfully grown in varied eco-geographic and climatic conditions outside its natural ranges which are entirely different from those present in its natural locations. The tree-to-tree variability for growth and heartwood content within a plantation indicates that there is scope for selection and genetic improvement for these characteristics. The heartwood proportion analysis across age classes of plantations indicated that Red Sanders trees can safely be harvested for moderate amount of heartwood in 40- to 50-years rotation age in plantation conditions. Generally, the trees planted singly or in rows along the boundaries attain good girth at lower age. The heartwood content can be increased, and thereby, rotation age can be reduced, provided higher growth rate is achieved in plantations. Too high growth rate may also have adverse impact on wood density because wood density had moderate negative correlation with DBH. Genetic improvement in Red Sanders needs to be initiated for high heartwood content, higher wood density and higher growth rate to reduce the rotation age and also to increase the productivity.

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