CLONAL AND PLANTING DENSITY EFFECTS ON SOME PROPERTIES OF RUBBER WOOD (*HEVEA BRASILIENSIS* MUELL. ARG.)

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Inter-clonal and intra-clonal wood properties and their variations from pith to bark were evaluated for wood density and anatomical features on rubber wood (*Hevea brasiliensis* Muell. Arg) from a 9-year-old plantation with planting densities of 500 and 2000 trees per hectare comprised of clones RRIM 2020 and RRIM 2025. Planting density had uneven effects on wood density and wood cell features. Intra-clonal and inter-clonal variations were significant for wood density in both clones and planting densities. Wood density demonstrated an increasing trend in the radial direction. However, at the lower planting density wood density near the bark decreased slightly. Fiber diameter, lumen diameter, and cell wall thickness showed an increasing trend from pith to bark. Best average fiber characteristics were observed at the lower planting density in clone RRIM 2025. Vessel frequency had a direct relationship with planting density in that it was higher in the higher planting density of 2000 trees per hectare. Overall, planting density had a significant effect on wood quality. The properties of clone RRIM 2025 were found to be comparatively better with longer fiber length and higher wood density than those of RRIM 2020.

Key words: Rubberwood; Clone; Planting density; Wood density; Wood anatomy

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INTRODUCTION

Rubberwood (*Hevea brasiliensis* Muell. Arg.) is one of the most important raw materials for the wood industry in Malaysia (IRRDB 2008). Rubber trees are currently planted for the production of timber (Mohd Izham 2001; Tuberman 2007). Interest in its management and utilization has been increasing over the last three decades (Norul Izani & Sahri 2008). To maintain the competitive position of the rubber wood industry in the world, sustainable wood production from managed plantations is a vital issue. Under-standing the effect of growth rate on wood quality is a fundamental requirement for practicing sustainable forest management (Rao et al. 2003).

Planting at wider spacing stimulates rapid stem diameter growth early in the rotation, which results in larger volumes of juvenile wood than what is present in slower growing trees. Silvicultural treatments applied to plantation trees during their early years greatly changes the growth rates, but the effect of accelerated growth on wood and fiber properties is not known (Lei et al. 1997). Understanding this relationship is of vital and practical importance in maximizing fiber production without decreasing wood and fiber quality. Variability in anatomical features has a significant influence on the properties of wood as a raw material (Burley & Palmer 1979). Previous studies have been centered mostly on specific gravity and fiber length (Zobel & Van Buijtenen 1989). The results of studies are often different for diffuse-porous species. In several studies, specific gravity and fiber length had been shown to have a significant relationship to growth rate (Parker et al. 1978; Lowell & Krahmer 1993). Anatomical variations in wood elements within and among the clones drew the attention of wood anatomists evaluating wood quality. Reports are available on wood quality parameters for clones of *Populus spp*., *Eucalyptus teriticornis*, and *Dalbergia sissoo* (Pande & Singh 2005).

Wood features, especially anatomical properties, which include mechanical properties and density, can predict final product characteristics (Desch & Dinwoodie 1983; Pande & Singh 2005; Norul Izani & Sahri 2008). Wood density is considered as an effective determinant of physical and mechanical properties that characterize different kinds of wood (Brown et al. 1952). It also provides an index of wood quality to which all end-users can relate (Macdonald & Hubert 2002; Walker 2006). Fiber length, an important aspect of fiber morphology, has a significant influence on mechanical strength and longitudinal shrinkage (Dinwoodie 1981). Fiber cross-sectional features such as fiber diameter, lumen diameter, and wall thickness also affect some properties of wood (Van Buijtenen 1969).

We hypothesized that differences in wood density and wood cell features are associated with planting density. We also hypothesized that one ought to be able to observe inter-clonal variation in wood density and wood cell features. To test these hypotheses, we measured xylem anatomical traits in rubber wood from trees in a trail forest in north-eastern Terengganu, Malaysia. There was also an apparent requirement for additional basic information related to the clones and planting regimes now used or under consideration in short-rotation rubber plantations.

The objectives of the present study were to determine clonal differences and planting density effects on growth rate and wood properties of rubber trees (*H. brasiliensis* Muell. Arg.). To achieve these objectives, two rubber tree clones planted at different densities were evaluated. The understanding of the intrinsic differences due to planting density and clones will help manage plantations for high value fiber resources required by end uses.

MATERIAL AND METHODS

Study Site and Sample Selection

Two new 9-year clones, namely RRIM 2020 (Clone I) and RRIM 2025 (Clone II), were selected for this study. Trees of these two clones were obtained from RRIMINIS (Rubber Research Institute Mini Station) plots in Tok Dor Terengganu, Malaysia. These plots were managed by Malaysian Rubber Board in the northeastern part of Peninsular Malaysia at a latitude of $5^{\circ}\ 45^{\prime}\ 0^{\prime\prime}$ N and longitude of $102^{\circ}\ 30^{\prime}\ 0^{\prime\prime}$ E. The average precipitation during the last three years was 3752 mm (Anonymous 2010).

The main criterion in these plots was planting density (number of tree per hectare). These study trails were established to investigate the significance of spacing on tree growth and wood characteristics. All plots were established and maintained under natural conditions and geographically located nearby to each other. Nearly one hectare was allocated to each planting density. Tree samples were obtained from uniform stands (Table 1), and trees growing adjacent to roadside, big gaps or leaning trees were avoided. All sampled trees had fairly straight bole, were free of defects, and were growing on a relatively uniform terrain.

The trials had been laid out in a randomized complete block design. The planting densities for each clone were 5 x 4 m (PDI; 500 tr ha^{-1}) and 2 x 2.5 m (PDII; 2000 tr ha^{-1}). Two trees were sampled per clone from each planting density. The trees were cut at a height of 15 cm above the ground level. A cross-sectional disc of approximately 5 cm in thickness was taken from each tree at breast height for determination of anatomical and physical properties. The samples were then labelled, wrapped in plastic bags and transported to the laboratory for analysis.

Wood Density

To measure air-dry density, radial segments (from pith to bark) were cut from each of disc samples. The segments were then continuously cut to precise blocks of 1.5 x 1.5 x 1.5 cm (longitudinal x tangential x radial) dimension from pith to bark. The blocks would indicate the gradual change in wood density from center to the outer parts. All blocks were appropriately marked with the clone number, planting density, and location from the pith. The air-dry density was calculated from the weights of the air-dry blocks and the corresponding volumes determined by water displacement.

Table 1. Growth Parameters of the *H. brasiliensis*

Clone	NO. of tree per hectare ($tr \cdot ha^{-1}$)	Planting distance (m)	DBH*	BH**
			Mean(cm)	Mean(cm)
RRIM 2020	500	5.0 x 4.0	20.22 (3.88)	467 (107)
	2000	2.0 x 2.5	17.54 (3.91)	936 (110)
RRIM 2025	500	5.0 x 4.0	19.96 (2.29)	738 (121)
	2000	2.0 x 2.5	15.07(2.38)	1026 (107)

*Over bark values
**BH: Bole height
Values within brackets are standard deviations

The data were statistically analysed, and mean differences between clones and planting densities were tested using the statistical package for Social Science (PASW statistics processor, version 18).

Wood Anatomical Properties

In this step, the fiber morphology (fiber length, fiber width, and cell wall thickness), and vessel features (vessel area, vessel diameter, vessel frequency) from pith to bark were studied. Each sample block used to measure wood density was converted to smaller blocks of 1 x 1.5 x 1.5 cm. These new blocks were only taken from one side of the disc. Samples of thin sectional slides were then prepared for anatomical assessment based on the Botanical Microtechnique (Berlyn & Miksche 1976). These samples would show a continuum of cellular features changing from pith outward.

Microscopic Images and Cell Morphology Measurements

Cross sectional microscopic images from each sample were collected using an Image Analyzer Microscope (Leica QWin model). The fiber diameter, cell wall thickness, and lumen diameters of 50 randomly selected fibers (magnified 40x) were measured by the image processing software calibrated with a stage micrometer. Additionally, the number of vessel elements (magnified 10x) was determined by counting the vessels present within a field (1 mm^2) and expressed as the number of vessels per square millimeter. With the data obtained, fiber cell wall thickness, lumen diameter, number of vessels per mm^2 (vessel frequency), mean vessel diameter (average of radial and tangential vessel diameter), mean vessel area (mm^2), and vessel proportion (percentage of the total area covered by vessels) were calculated. Cell-wall thickness was computed from the measured double cell-wall thickness divided by two.

RESULTS AND DISCUSSION

Wood Density

Average air-dry density measured from pith to bark showed a slight decrease in value at the last block near the bark as it increased and then decreased towards the bark. This pattern was found at planting density of 500 tr ha^{-1} in clone RRIM 2020 (Fig. 1). This phenomenon can be related to the early maturation of trees (Fang & Yang 2003; Pande & Singh 2005). The mean air-dry densities for planting densities of 500 tr ha^{-1} and 2000 tr ha^{-1} were 0.60 and 0.53 g cm^{-3} for clone RRIM 2020, and 0.65 and 0.56g cm^{-3} for clone RRIM 2025, respectively. The difference due to planting density for clone RRIM 2020 was about 11% and for clone RRIM 2025 it was about 16%. There was a negative relationship between planting density and wood density. In other words, there was increasing average wood density with wider planting spacing. A relatively fixed pattern of variation was observed in the radial direction for the two planting densities (Table 2). In general, wood density of hardwoods showed less steady patterns compared to the softwoods (Panshin & De Zeeuw 1980; Lim & Fujiwara 1997). As both clones were from the same site, environmental variation would be minimal (Beaudoin et al. 1992).

Independent sample tests indicated that variation in wood density due to planting density was significant ($p \leq 0.05$). A specific trend was observed in radial direction and distance from pith (Table 2). These observations support the fact that younger parts of trees generally have lower wood density, and density increases with increasing age (Bao et al. 2001; Githiomi & Kariuki 2010). A lower density in younger parts can be attributed to shorter fiber lengths and thinner cell walls (Table 4).

Table 2. Mean Wood Densities of the Two *H. brasiliensis* Clones at the Two Planting Densities (g cm^{-3})

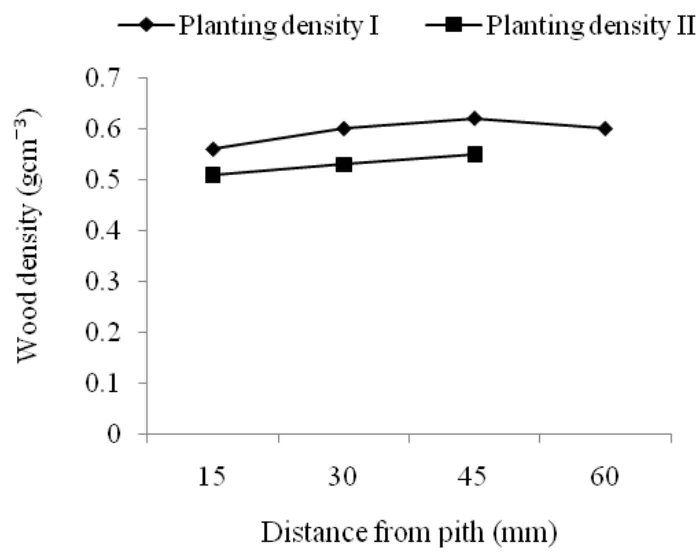
Clone	PD I				PD II		
	Distance from pith (mm)						
	15	30	45	60	15	30	45
RRIM 2020	0.56^{a}	0.60^{b}	0.62^{b}	0.60^{b}	0.51^{a}	0.53^{b}	0.55^{b}
RRIM 2025	0.62^{a}	0.66^{b}	0.65^{a,b}	0.67^{b}	0.52^{a}	0.56^{b}	0.58^{b}

Means within rows with the same alphabets are not significantly different (p≤0.05, t-test). The mean difference is significant at the 0.05 level.

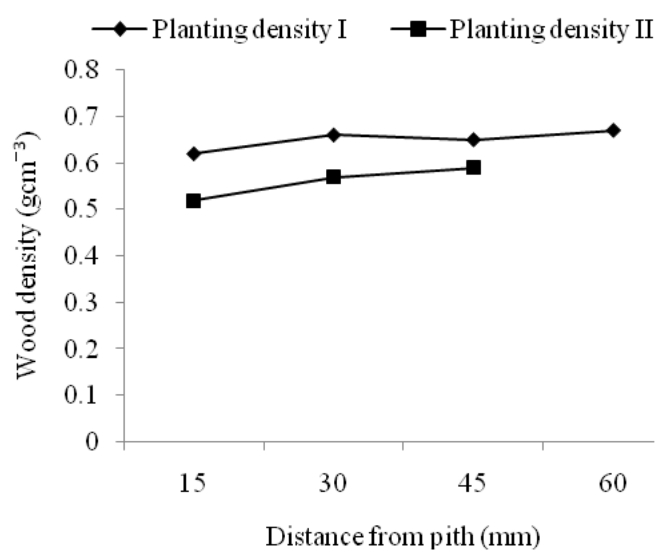
The mean air-dry wood density was significantly different ($p \leq 0.005$) within same planting densities for both clones (Table 6). The highest wood density was evident in clone RRIM 2025 at the lower planting density (0.65 g cm^{-3}), and the lowest density was observed in clone RRIM 2020 at the higher planting density (0.54 g cm^{-3}). This reveals that wood density was higher in trees with wider spacing. The trees with wider initial spacing developed larger crowns. It also implies that trees with larger crowns have much more branches and leaves, which produce higher amounts of carbohydrates, resulting in an increase in tree height and diameter growth that leads to increased wood volume (Brown et al. 1952; Zobel & Van Buijtenen 1989; Macdonald & Hubert 2002; West 2006). This is reflected in Table 1. In addition to volume, it is postulated that wood density will increase. In this case, fibers are important. Each single fiber cell increases cell wall thickness. The data on cell wall thickness supports this theoretical consideration (Table 4).

The approximate specific gravity of rubberwood is 0.56 (Teoh et al. 2011). In earlier studies on ten clones and five different species of rubber (*H. brasiliensis*), the mean basic densities observed ranged between 0.51-0.57 g cm^{-3} and 0.58-0.60 g cm^{-3}, respectively (Reghu et al. 2006; Norul Izani & Sahri 2008). In general, the density of diffuse-porous hardwoods is influenced by planting distance, but results are variable (Bowyer et al. 2007). For instance, Brown (1978) and Norul Izani and Sahri (2008) found no relationship between planting density and wood density in diffuse-porous hardwoods, while other studies revealed that planting density has some effect on wood density (Panshin et al. 1973; Zobel & Van Buijtenen 1989). It was also noted that the wood density increases from the first ring, levels off, and then decreases with ring number (Tylor 1968, cited by (Zobel & Van Buijtenen 1989).

Similar results were obtained in the current study in which wood density values also showed a decreasing pattern towards the last distance away from the pith at the lower density of both clones.



(A)



(B)

Figure 1. Variation in wood density from pith to bark at two planting densities in (A) clone RRIM 2020 and (B) clone RRIM 2025

From the above results, it was evident that wood density varied with clone and planting density. In view of the fact that these clones and related planting densities are largely attempts to fulfill the requirements of the paper and pulp industry, it is noteworthy to consider the basic ideal density, which is in the range of 0.48 to 0.57 g cm^{-3} (Ikemori et al. 1986).

Table 3. Independent Samples Test for Wood Density between the Two Planting Densities of Clones RRIM 2020 and RRIM 2025 of *H. brasiliensis*

Clone No.	PD	WD* (g.cm^{-3})	SD**	t-test for Equality of Means	
				t	Sig.(2-tailed)
RRIM 2020	I	0.59	0.030	8.29	< 0.001
	II	0.54	0.026		
RRIM 2025	I	0.65	0.025	15.86	< 0.001
	II	0.56	0.035		

*WD =Wood density
**SD =Standard deviation

Furthermore, correlations of wood density with different wood element attributes viz. fiber length, fiber diameter, fiber lumen, wall thickness, vessel frequency, vessel diameter, and vessel area were variable (Table 6). There were no significant differences in these features along radial direction and distance. Similar results were also observed by Pande et al. (2005) in *Dalbergia sisso* and Chauhan et al. (2001) in *Populus deltoides* clonal trees (cited by Pande and Singh 2005).

Anatomical Properties

The mean values of anatomical properties within planting density with the standard deviations across the radial direction are given in Table 4. Statistical analyses indicated that these variations were mostly significant along the direction. There was however no clear pattern on the changes of all cell features from pith to bark. As Zobel et al. (1989) mentioned, this is a confusing issue. However, there was an ascending general trend from pith to bark for the anatomical features studied except vessel frequency and vessel area.

Fiber length

The minimum fiber lengths were observed in the first block at the pith, and maximum fiber length was observed in the outermost block. In clone RRIM 2020 the average range in fiber length in the lower and higher planting densities showed an increase of about 16% and 39%; while 18 and 19% were evidenced in clone RRIM 2025 respectively. In general, the fiber length of rubberwood varies from 1100 to 1780 μm (Teoh et al. 2011). The fiber lengths measured for five different rubber tree species ranged from 1145 to 1214 μm (Norul Izani & Sahri 2008). Suhaimi and Sahri (2003) reported a mean fiber length of 1172 and 1350 μm for clone RRIM 623 and 1297 and 1537 μm for clone RRIM 600 at age 22 and 35 years, respectively.

Bhat et al. (1984) reported an average fiber length of 1200 μm, while Ashari (1986) observed a mean fiber length of 1100 μm (Suhaimi & Sahri 2003). Significant variation from pith to bark shows the effect of cambium age on the wood element dimension. A similar pattern has repeatedly been stated for poplars and their hybrids (Fang & Yang 2003).

Table 4. Variation in Wood Elements from Pith to Bark at Different Planting Densities of *H. brasiliensis* Clones I and II

Clone	Cell Features	Planting density I					Planting density II			
		Distance from pith (mm)					Distance from pith (mm)			
		15	30	45	60	**Mean**	15	30	45	**Mean**
RRIM 2020	Fiber Length(μm)	1148^{a} (175)	1239^{b} (188)	1332^{c} (166)	1279^{b,c}(157)	**1249***	996^{a}(148)	1179^{b} (171)	1385^{c}(218)	**1187***
	F. diameter (μm)	26.33^{a} (3.89)	29.48^{b} (5.16)	30.16^{b} (4.31)	32.54^{c} (3.32)	**29.63***	28.18^{a}(4.35)	27.26^{a} (4.40)	32.42^{b} (4.67)	**27.26***
	F. lumen (μm)	17.32^{a} (3.52)	20.17^{b} (4.68)	20.39^{b} (3.96)	23.25^{c} (3.86)	**20.28^{ns}**	17.01^{a} (3.07)	19.79^{b} (4.44)	24.09^{c}(4.52)	**20.30^{ns}**
	Wall thickness (μm)	4.63^{a} (0.83)	4.75$^{a, b}$ (0.87)	4.97$^{a, b}$ (0.87)	5.16^{b} (1.13)	**4.88^{ns}**	4.08^{a} (0.95)	4.52^{a} (1.33)	4.63^{a} (1.39)	**4.41^{ns}**
	V. frequency(mm^{-2})	9.97^{c} (2.95)	5.17$^{a, b}$ (1.80)	6.56^{b} (1.91)	4.6^{a} (2.24)	**6.58***	12.17^{b}(4.62)	5.7^{a} (2.05)	5.1^{a} (2.91)	**7.83***
	V. diameter (μm)	127^{a} (51)	188^{b} (52)	183^{b} (66)	208^{b} (45)	**177***	108^{a}(32)	154^{b}(61)	173^{b} (55)	**144***
	V. area (μm^{2})	178 10^{3a} (34 10^{3})	176 10^{3a} (56 10^{3})	184 10^{3a} (62 10^{3})	167 10^{3a} (82 10^{3})	**167 10^{3*}**	161 10^{3a} (43 10^{3})	156 10^{3a} (63 10^{3})	132 10^{3a} (60 10^{3})	**150 10^{3*}**
	V. proportion%	17.96	17.71	18.48	16.77	**16.71**	16.21	15.67	13.29	**14.97**
RRIM 2025	Fiber Length(μm)	1217^{a} (179)	1248^{a} (215)	1457^{b} (242)	1438^{b} (185)	**1340***	1168^{a} (212)	1266^{a} (246)	1394^{b} (222)	**1276***
	F. diameter (μm)	26.55^{a} (3.58)	32.77^{c} (3.16)	29.16^{b} (5.04)	31.71^{c} (5.07)	**28.54***	27.78^{a} (4.64)	32.84^{b} (5.70)	34.70^{b} (5.16)	**31.78***
	F. lumen (μm)	16.43^{a} (3.38)	22.29^{c} (5.04)	19.78^{b} (4.47)	20.94$^{b, c}$ (4.92)	**18.92***	20.01^{a} (4.17)	25.13^{b} (5.63)	26.56^{b} (4.82)	**23.90***
	Wall thickness (μm)	4.26^{a} (1.19)	4.39^{ab} (0.75)	4.84$^{b, c}$ (0.72)	5.39^{c} (1.53)	**4.71***	3.89^{a} (0.81)	3.96^{a} (0.82)	4.10^{a} (1.17)	**3.98***
	V. frequency(mm^{-2})	6.07^{b} (2.26)	3.07^{a} (1.20)	2.73^{a} (1.80)	2.6^{a} (2.36)	**3.62***	7.07^{b} (2.97)	3.03^{a}(1.38)	2.2^{a} (1.61)	**4.1***
	V. diameter (μm)	152^{a} (50)	176^{a,b} (44)	217^{c} (57)	201$^{b, c}$ (71)	**186***	122^{a} (43)	170^{b} (60)	177^{c} (62)	**156***
	V. area (μm^{2})	134 10^{3a} (35 10^{3})	100 10^{3a} 39 10^{3a}	93 10^{3a} (50 10^{3})	85 10^{3a} (57 10^{3})	**103x$10^{3n.s}$**	115 10^{3b} (31 10^{3})	103 10^{3b} 39 10^{3}	71 10^{3a} (47 10^{3})	**97 10^{3ns}**
	V. proportion%	13.50	10.08	9.36	8.50	**10.36**	11.56	10.35	7.13	**9.68**

Means within rows followed by the same letter are not significantly different at the 0.05 probability level.
ns = not significant
* = Significant ($p \leq 0.05$) in the same row
V= Vessel
Values in parenthesis are standard deviations

There is a close relation between fiber length, mechanical properties, and shrinkage, and these are considered as significant factors determining wood quality (Dinwoodie 1981). Most papers published on this matter have noted that the shortest fiber length is near the center of the tree and there is a slight increase in fiber length towards the bark (Zobel & Van Buijtenen 1989; Bao et al. 2001; Honjo et al. 2005; Walker 2006).

Table 5. Pearson's Correlation Coefficients between Wood Density and Anatomical Properties of *H. brasiliensis* Clones at the Two Different Planting Densities

Clone	Planting density(PD)	Cell features	Air-dry density (Add)	Fiber Length (Fl)	Wall thickness (Wt)	Vessel Diameter (Vd)	Area (Va)
RRIM 2020	PD I	Add	1				
		Fl	0.027	1			
		Wt	0.139	0.973**	1		
		Vd	0.032	0.319	0.931**	1	
		Va	0.007	-0.054	0.982**	0.722**	1
	PD II	Add	1				
		Fl	0.533**	1			
		Wt	0.644**	0.777**	1		
		Vd	0.537*	0.939**	0.858**	1	
		Va	0.595**	0.101	0.809**	0.976**	1
RRIM 2025	PD I	Add	1				
		Fl	0.439**	1			
		Wt	0.046	0.483**	1		
		Vd	0.267	0.958**	0.518**	1	
		Va	0.351	0.026	0.483*	0.936**	1
	PD II	Add	1				
		Fl	0.565**	1			
		Wt	0.317	0.977**	1		
		Vd	-0.151	0.951**	0.918**	1	
		Va	-0.202	-0.027	0.918**	0.987**	1

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).
PD = Planting density

Comparing the two clones, RRIM 2025 had the longer fiber length. There is usually a rapid increase in cell length in the first 10 to 20 years in hardwoods, followed by a leveling off (Oteng-Amoako et al. 1983; Knigge and Koltzenburg 1965; Bisset and Dadswell 1949; Taylor 1968 (cited by (Zobel & Van Buijtenen 1989; Butterfield et al. 1993)). Information obtained from the present study indicates that intra-clonal and inter-clonal fiber length variations in radial direction were significantly different ($p \leq 0.005$) between planting densities, and clones. There was a strong correlation between fiber length, diameter, and cell wall thickness (Table 6).

Fiber diameter

Fiber diameter at planting densities of 500 and 2000 trha^{-1} in RRIM 2020 showed 23.59% and 15.10% increase; and 19.40% and 24.90% increase for RRIM 2025, respectively. The fiber diameter of rubberwood falls between 26 to 30 µm (Teoh et al. 2011). Norul Izani and Sahri (2008) reported average fiber diameters for five different rubber tree species of between 23.5 and 24.9 µm. Analysis of variance of data from the present study showed significant difference in radial fiber diameters ($p \leq 0.05$) in sample from each planting density. In addition, the independent sample tests also indicated significant differences of fiber diameter due to intra-clonal variations. The inter-clonal fiber diameter variations were not-significantly different ($p \leq 0.05$) at the lower planting density for the two clones, but were significantly different at the higher planting density in both clones (Table 6).

Table 6. Paired Sample Tests for Wood Density and Anatomical Properties of *H. brasiliensis* between Planting Densities and Clones

Property	PD I Clone I X PD I Clone II			PD II Clone I X PD II Clone II		
	SD	t	Sig.	SD	t	Sig.
Air-dry density	0.037	7.18	<0.001	0.032	3.29	<0.001
Fiber Length	224	5.7	<0.001	98	11.00	<0.001
F. Diameter	5.7	1.05	**0.300**	2.71	11.22	<0.001
F. Lumen	5.76	1.05	**0.300**	1.84	24	<0.001
Wall Thickness	1.39	1.65	**0.100**	0.85	6.27	<0.001
Vessel frequency	1.22	26	<0.001	1.85	18	<0.001
V. Diameter	64	2.19	<0.001	15.12	9.77	<0.001
V. area	26126	30	<0.001	23037	22	<0.001

Note: Bold type indicates no significant difference at the 0.05 probability level.
PD = Planting density
SD = Standard deviation

Fiber diameter has a significant effect on wood quality. The most desirable condition is to have long and narrow cells. Fiber cell diameter (width) has been little emphasized *within* species, while choices *among* species are often influenced by cell diameter and lumen size (Artuz-Siegel et al. 1968, cited by Zobel et al. 1989).

Fiber lumen diameter

The results showed the strong effect of planting density on the fiber lumen diameter. There was a positive correlation between fiber lumen diameter with fiber diameter and fiber wall thickness ($p \leq 0.01$). The lumen diameter of some species of rubberwood have been reported to be in the range of 10.00 to 12.00 µm (Norhayati 1995; Norul Izani & Sahri 2008).

Inter-clonal variation in fiber lumen diameter showed non-significant differences in mean values at the lower planting density in both clones (at a confidence level of 95%), while this variation showed a significant difference between clones at the higher planting density (Table 6).

Wall thickness

Fiber wall thickness, like the fiber features, increased from pith to bark. In RRIM 2020, the wall thickness showed 11.5% and 13.5% increase, respectively. These increasing values in the clone RRIM 2025 were 26.5% and 5.4%. Teoh et al. (2011) reported an average cell wall thickness of 5.1 to 7.0µm, while the mean fiber wall thickness measured by Norul Izani and Sahri (2008) ranged from 6.08 to 6.51µm in five different rubber tree species.

Non-significant differences in fiber wall thickness due to intra-clonal variation in clone RRIM 2020 showed that planting distance had no demonstrable influence on fiber wall thickness (Table 4). Inter-clonal variation also showed no significant difference between fiber wall thicknesses at the lower planting density, but was significant at the higher planting density (Table 6).

Cell wall thickness has a considerable effect on wood quality and this feature is greatly related to wood density (Butterfield et al. 1993). Cell wall thickness also affects the bending, tear, and tensile strengths of paper (Norul Izani & Sahri 2008). Cell wall thickness largely changes within and between species and within a tree as well (Zobel & Van Buijtenen 1989).

Vessel Anatomy

Vessel frequency and area showed an ascending trend from pith to bark, while this trend was descending for vessel diameter (Table 3). The highest vessel frequency (mm^{-2}) was found near the pith (first distance), and vessel numbers dropped sharply from pith outwards. While the vessel diameters were in close range, the vessel frequency observed cannot be compared with the five different rubber tree species of older age (Norul Izani & Sahri 2008). The results of a *t*-test revealed that intra-clonal and inter-clonal differences in vessel frequency, diameter, and area between clones were significant, except for vessel area in clone RRIM 2025 ($p \leq 0.05$).

Growth rate has an effect on cellular composition and tissue percentage, although no generalization can be made (Zobel and Van Buijtenen 1989; Rao et al. 2003).Vessel number and diameter are some important factors that reveal vessel proportion in the wood structure. High vessel number along with large vessel diameter leads to an increase in vessel proportion. The results showed insignificant and negative correlations between wood density and vessel features, but there were high positive correlations between vessel features (Table 6).

CONCLUSIONS

The results of the present study indicate that wood density and wood cell features in both clones and planting densities differed considerably. A pattern of changing trend in wood cell characteristics from pith to bark was demonstrated. Intra- and inter-clonal variations were influenced by planting density. Most features showed an increasing trend from pith to bark, but no significant differences were observed in some characteristics. In features related to wood density characteristics (viz., fiber length, fiber wall thickness, and vessel characteristics), between clones and planting densities, the lower density of 500 tr ha^{-1} in clone RRIM 2025 was observed to have a remarkably higher effect on cell quality (wood density, fiber length, cell wall thickness).

It was clear that wood quality, which is significantly correlated to fiber length, is strongly influenced by forestry management. This factor should therefore be considered whenever product quality is significantly correlated to fiber length.

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