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Rubberwood—Potential for Pulp and Composite Board Utilization

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Abstract: Rubberwood (*Hevea brasiliensis* Muell. Arg) is underutilized in most developing countries but has potential to be a solution to the shortage of wood for pulp, paper and wood composite products at the end of its production cycle. Determining and understanding its fibre properties (fibre dimensions and morphology) is key in its utilization for pulp and paper as well as composites. This study assessed the effect of age on the fibre properties of rubberwood. Samples of wood at four ages (10, 15, 20 and 25 years) were obtained at both the axial (base and top of merchantable length) and radial direction (innerwood, middlewood and outerwood). Slivers were obtained from the samples and macerated to provide individual fibres for optical measurement. Fibre dimensions at the four ages were measured, and their morphology was determined. Fibre properties and morphology were significantly affected by age at p = 0.05. Average fibre length was 1.47 ± 0.12 mm, with non-constant variation observed across the different ages, and from pith to bark. Average lumen width was 16.87 µm, and fibre diameter ranged from 25.02 µm to 27.23 µm. The fibre properties of rubberwood potentially make it suitable for pulp and paper production as well as wood composite boards.

Keywords: rubberwood; *Hevea brasiliensis*; fibre dimensions; fibre morphology; lesser used species (LUS)

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1. Introduction

Wood, from both natural forests and plantations, is used for diverse purposes throughout the world. It is the most sought-after of all available forest resources due to its versatility in use, which makes it a suitable resource for industrial and construction end-uses [1,2]. Wood is needed to produce lumber, engineered wood products, utility poles, furniture, pulp and paper and even as a source of fuel. However, the way in which wood is employed depends mainly on its technical properties, e.g., physical, chemical, mechanical, fibre and morphological properties. Fibre studies in the past have focused mainly on the suitability of fibres for pulp and paper [3–9]. In recent years, technological advancement has led to fibre being used to produce fibreboards and fibre-reinforced thermoplastic composites [10]. With this advancement, the demand for wood and its products has increased, and there is a need to find alternative fibre sources [11].

The use of natural fibres, including those from wood, is increasing in composite applications due to their reduced cost for production, low density and potential environmental benefits [12]. Thyavihalli Girijappa et al. [13] stated that the density of natural fibres (1.2–1.6 g/cm^3) is a lot lower than that of synthetic fibres (2.4 g/cm^3); these include hemp, jute, sisal, banana, coir and kenaf, which are used in the production of lightweight composites. Natural fibres have been reported to be more sustainable and have a lower carbon footprint than other sources, such as glass and carbon fibre [12]. In addition, natural fibres can be obtained from all parts of the plant, from the roots to the leaf, stem, fruits and seeds [14]. The demand for natural fibres will continue to increase due to technological advancement, sustainability and environmental concerns. While Bast fibre such as hemp, kenaf, flax, etc., are preferred for natural fibre-reinforced composites used in automotive applications, wood fibre is the material of choice in construction industries [13].

Lesser-used Species (LUS) can complement the traditionally used species to meet demand for pulp, paper and composite products. Some of these LUS are "non-forestry" trees grown in plantations by the agricultural sector and are becoming relevant in the supply of industrial wood and fibres. These tree crops are often grown for purposes other than timber such as for the production of fruit (mango, coconut), latex (rubber tree) and oil (palm tree). These tree crops often outlive their primary purpose after several years of harvesting [2].

Hevea brasiliensis Muell. Arg (rubber tree) is indigenous to the Amazon Forest in Brazil and is cultivated in plantations for latex production (raw material used in the manufacture of natural rubber). Rubber plantations are found in many parts of the world, with more than 75 percent of rubber plantations located in Indonesia, Thailand and Malaysia [15–17]. In Nigeria, rubberwood plantations are found mostly in the south, with a noticeable expansion to areas such as Taraba and Kaduna States in order to meet the growing demand for natural rubber. The utilization of natural rubber facilitates crop diversification and can upgrade the living standards of people in rubber-growing areas [18].

Efficient wood utilization, which is a major problem faced by wood industries in tropical countries, results from a dearth of quality and up-to-date information on the technical properties of lesser-used species in these regions. Knowledge on and utilization of rubberwood has not improved in Nigeria as rubberwood is only used as source of fuelwood in rural and semi-urban communities [2]. The utilization of rubberwood is promoted in this study to extend its use in the wood products industry, thus reducing the increasing pressure on forests due to the unsustainable harvesting patterns for select species and also promoting value addition. Ohwo et al. [19] opined that for the sustainable development of Nigerian forests, it is imperative to efficiently utilize environmental resources via research, innovation and value addition. Fiber characteristics such as fibre length, fibre diameter, lumen width and cell wall thickness and its derived values influence the quality of pulp and paper [20]. This study therefore aimed to assess the fibre properties of rubberwood to promote its utilisation in the production of pulp and paper as well as wood composites.

2. Materials and Methods

The wood samples used for this study were harvested from intensively managed rubber plantations in the Ughelli North Local Government Area of Delta State in 2016. The climate of the sample site is moist subequatorial with a long wet season (March–October) and dry season (November–February). Mean annual rainfall is about 2800 mm. Annual average temperature is 30 ± 3 °C. The mean annual relative humidity is about 80% (Onakpoma 2019) [2]. Five trees at four ages (10, 15, 20 and 25 years) were randomly selected and felled. The felled trees were cut into 600 mm-long bolts, with 10% and 90% of the merchantable height representing the tree top and base, respectively. From the bolts, 20 mm (radial) $\times$ 20 mm (tangential) $\times$ 60 mm (longitudinal) wood blocks were obtained from the inner, middle and outer part of the stem, which were used to represent the wood cross-section (Figure 1). The samples closest to the pith represent the innerwood, while those closest to the bark represent the outerwood. Ring number was not used in this study as this would have added a lot of variability in the middlewood section since its amount differs for the middlewood section at different ages and positions. The middlewood is the midpoint between the outer and innerwood, and its position in the stem varies for the different ages and axial positions sampled.

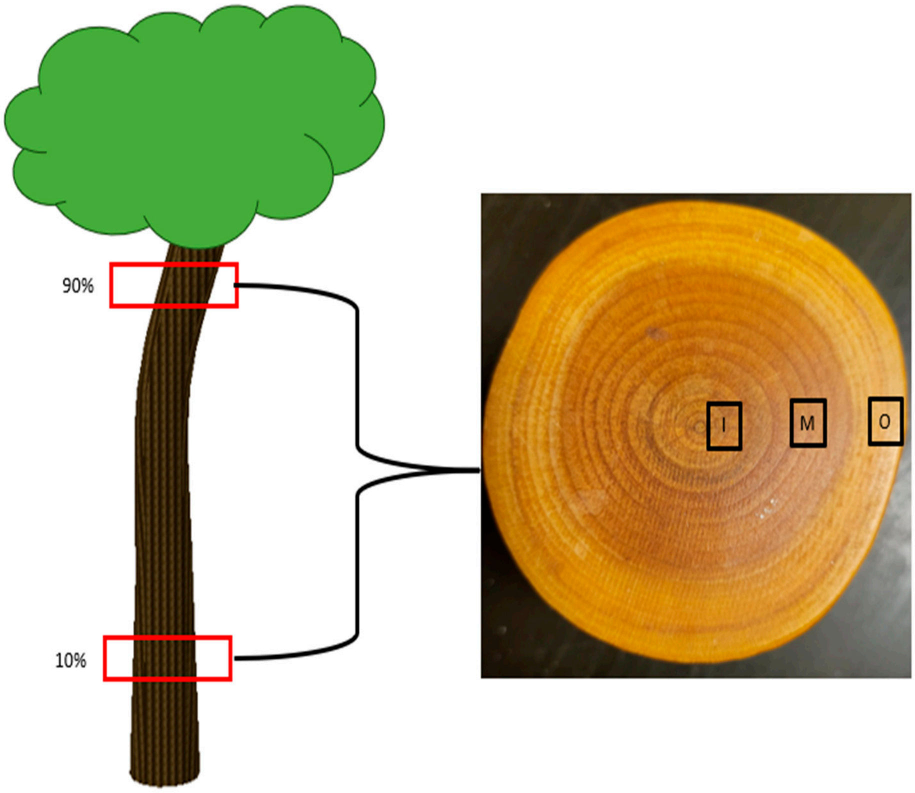


Figure 1. Schematics of the sampling strategy; I = Innerwood, M = Middlewood, O = Outerwood.

2.1. Measurement of Fibre Dimensions

Wood slivers were obtained from the blocks representing different sampling positions. These were macerated at 100 °C for 2 h in equal volumes (1:1) of 10% glacial acetic acid and 30% hydrogen peroxide, following the method of [21]. The macerated fibres were rinsed several times in water before gently shaking to free individual fibres. The suspension was mounted on a glass slide with the aid of a rubber teat, and 12,000 fibres (200 fibres per sampling position) were measured with a light microscope (objective lens of ×40). The parameters measured include the fibre length (FL in mm), lumen width (LW in μm) and fibre diameter (FD in μm). Based on these measured dimensions, fibre wall thickness (FWT), flexibility ratio (FR), slenderness coefficient (SC) and Runkel ratio (RR) were calculated using Equations (1), (2), (3) and 4, respectively.

$$\text{Fibre wall Thickness} = \frac{\text{FD} - \text{LW}}{2} \quad (1)$$

$$\text{Flexibility Ratio} = \frac{\text{LW}}{\text{FD}} \times 100 \quad (2)$$

$$\text{Slenderness Coefficient} = \frac{\text{FL}}{\text{FD}} \quad (3)$$

$$\text{Runkel Ratio} = \frac{2 \times \text{CWT}}{\text{LW}} \quad (4)$$

2.2. Data Analysis

A mixed-model analysis of variance (mixed-model ANOVA) was performed to test for the significance of the effects of age, height and radial position (5).

$$Y_{ijk} = \mu + A_i + H_j + R_k + (AH)_{ij} + (AR)_{ik} + (HR)_{jk} + (AHR)_{ijk} + e_{ijk} \quad (5)$$

where Y_{ijk} is the response variable, μ is the intercept of the model, A_i is the effect of age, H_j is the effect of height, R_k is the effect of the radial position, $(AH)_{ij}$ is the interaction effect between age and height, $(AR)_{ik}$ is the interaction between age and radial position, $(HR)_{jk}$ is the interaction between the height and radial position, $(AHR)_{ijk}$ is the interaction between the age, height and radial position, and e_{ijk} is the error introduced by the replicates. All statistical analysis was performed using the STATISTICA 12.5 software, and boxplots were created in MS Excel.

3. Results and Discussion

3.1. Fibre Length

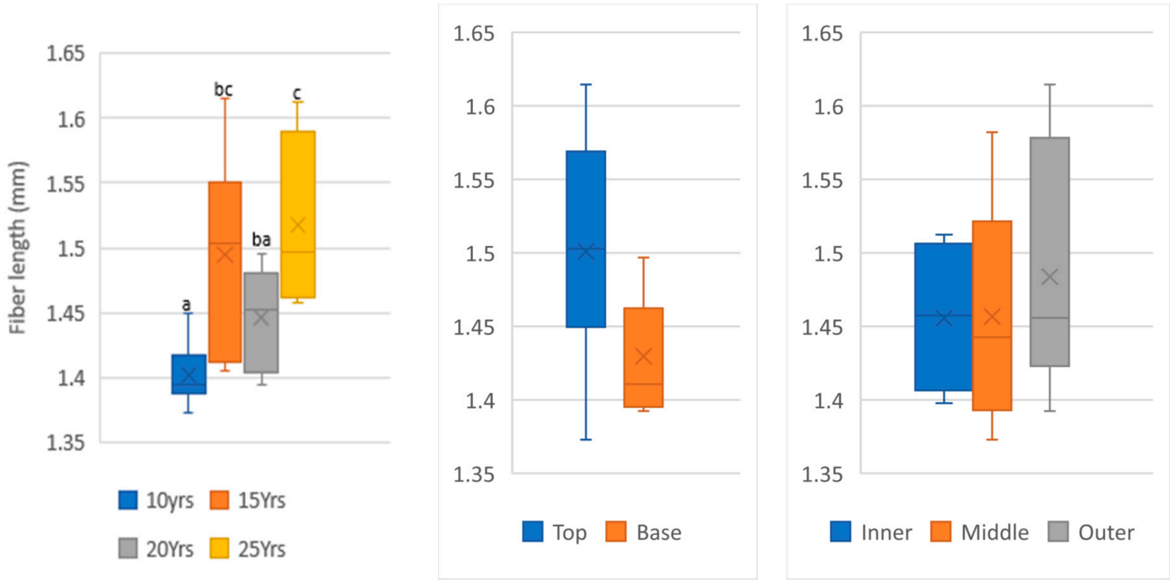
The average FL of the sampled rubberwood, from one end to the other (Figure 2), was 1.47 ± 0.121 mm. Average FL at 10 years was 1.4 mm, and it was 1.50 mm at 25 years. Results of the mixed-model ANOVA for FL showed that FL was significantly affected by age ($p < 0.05$, Table 1). FL was significantly longer at the top (1.50 ± 0.121 mm) than the base (1.43 ± 0.109 mm) ($p < 0.05$). Radially, mean FL was very similar for the different radial positions: 1.46 mm (innerwood), 1.44 mm (middlewood) and 1.46 mm (outerwood) (Figure 3).

Figure 2. Fibres of macerated *Hevea brasiliensis* Muell. Arg.

Table 1. ANOVA table for rubberwood fibre dimensions.

Source of Variation	NumDF	denDF	Fibre Length		Lumen Width		Fibre Diameter	
			F-Value	*p*-Value	F-Value	*p*-Value	F-Value	*p*-Value
Tree age	3	89	6.27	**0.000635**	5.69	**0.00127**	7.81	**0.000105**
Height	1	89	12.17	**0.000745**	13.41	**0.000416**	43.64	**0.000000**
Radial position	2	89	0.83	0.440	0.30	0.740	0.04	0.962
Tree age * Height	3	89	1.08	0.362	0.95	0.420	0.44	0.724
Tree age * Radial position	6	89	0.26	0.953	1.27	0.277	1.06	0.394
Height * Radial position	2	89	1.28	0.283	0.44	0.643	0.23	0.795
Tree age * Height * Radial position	6	89	0.53	0.781	0.27	0.948	0.33	0.919

Bold numbers show significant difference in samples ($p < 0.05$). * interaction between factors.



(a) (b) (c)

Figure 3. Boxplots showing variations in the average fibre length of rubberwood in terms of (**a**) age, (**b**) axis and (**c**) radial position. Means with same letter are not significantly different.

Apart from specific gravity, which is often referred to as the best index for wood quality, FL is also an important determinant of wood quality and utilisation because it is related to mechanical strength and shrinkage and influences paper strength properties [8,22]. Fibre length is also important in the mechanical performance of wood pulp composites. Amuthakkannan et al. [23] reported that the flexural, tensile and impact strengths increased with increasing fibre length. Thumm and Dickson [24] reported that fibres longer than 1.33 mm led to the higher flexural strength and stiffness of wood pulp composites. Longer fibres are capable of withstanding higher bending loads [23]. In fibreboards, shorter fibres are unfavourable as they are more likely to deviate from the horizontal plane, resulting in the reduced size of the contact area between fibres, which then leads to increased thickness swelling and water absorption [25]. In terms of pulp and paper properties, positive correlations have been reported between FL and tear index, tensile strength, burst strength, tear strength and folding endurance [4,26,27]. Paper quality and strength are negatively impacted by a decrease in FL [8].

The reported FL of rubberwood is lower than the values reported by Tembe et al. [28] and Boerhendy et al. [29]. They respectively reported FLs of 1.59 mm and 1.68 mm for mature *H. brasiliensis*. Teoh et al. [16] and Naji et al. [30] respectively reported the FL of rubberwood to vary from 1.1 to 1.78 mm and from 1.0 to 1.46 mm, which is comparable to the obtained results (from 1.19 to 1.82 mm). In addition, Norul Izani and Sahri [31] and Suhaimi and Sahri [32] respectively reported values ranging from 1.15 to 1.21 mm and from 1.17 to 1.35 mm for rubberwood FL. The observed axial and radial variations were comparable with the findings of Haifah [33], who stated that wood from the top portion had the longest fibre as compared to the middle and bottom locations. The longest fibre, according to Haifah [33], was located in the sapwood region (outerwood). Similarly, studies in [30,34–39] reported that shorter fibres were found towards the centre of the stem and slightly increased radially for various softwoods and hardwoods, including rubberwood. Fibre length for bagasse was classified by Salehi [40] into three categories: short fibres (<0.9 mm), medium fibres (0.9–1.9 mm) and long fibres (>1.9 mm). Based on this classification, *H. brasiliensis* has been identified to have medium-length fibres. Longer fibres have higher resin content per unit surface area as compared to shorter fibres, which makes them desirable for the fabrication of panels as they result in better mechanical properties for the panels [41]. Benthien et al. [42] reported an improvement in the mechanical properties of

Scots pine (*Pinus sylvestris*) medium-density fibreboard (MDF) with an increase in FL. The MDF made from longer fibres also demonstrate higher internal bond strength as compared to those made from shorter fibres [43,44].

3.2. Lumen Width

The average LW for rubberwood was 16.87 ± 1.896 µm (ranging from 12.93 to 21.31 µm). The highest average LW was observed at 25 years (17.78 µm), while at 15 years, rubberwood had the smallest lumen width (16.02 µm). Tree age significantly affected the LW of rubberwood ($p < 0.05$, Table 1). Mean LW increased significantly from the base (16.27 ± 1.897 µm) to the top (17.46 ± 1.730 µm). Radially, LW decreased from the innerwood to the outerwood, with average values of 16.96 µm (innerwood), 16.95 µm (middlewood) and 16.69 µm (outerwood) (Figure 4).

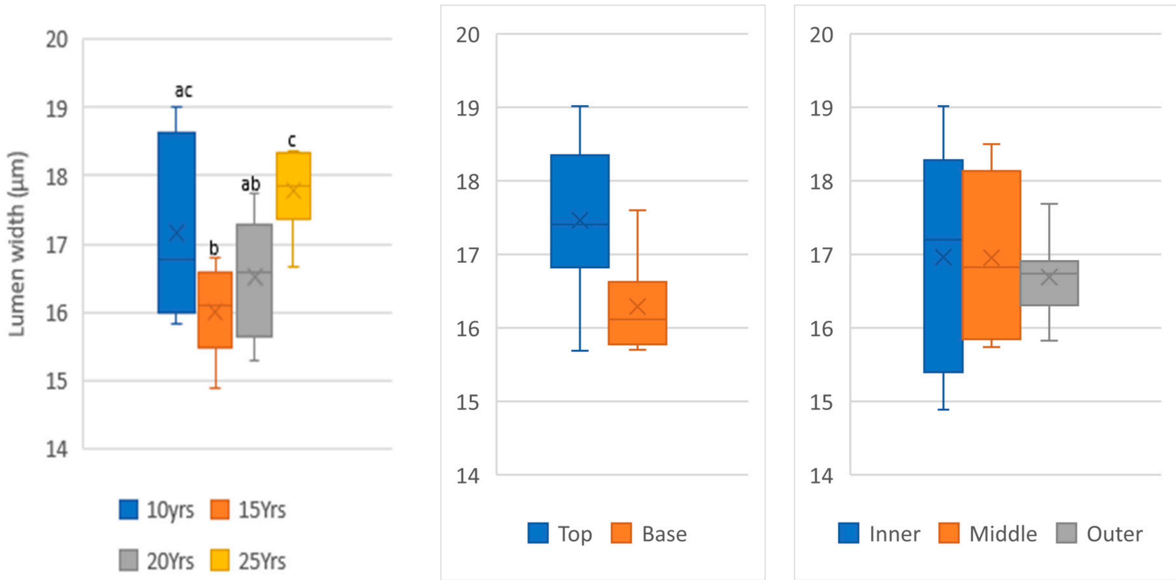


Figure 4. Boxplots showing variations in the average lumen width of rubberwood in terms of (**a**) age (**b**) axis and (**c**) radial position. Means with same letter are not significantly different.

Lumen width (the inner diameter of the fibre) has an important role in the pulp and paper manufacturing process and composite production. A larger LW enables better pulp beating because it allows liquids to penetrate into fibre voids [7,45]. The specific gravity of wood is low if the LW is large [31]. Woodson [46] reported a negative correlation between the specific gravity and mechanical properties of MDF. Hence, it can be inferred that fibres with a large LW will produce fibreboards with better mechanical properties than ones that have narrower diameters.

The mean value of 16.87 µm observed in this study is higher than the mean value (15.81 µm) reported in [29]. Norul Izani and Sahri [31] reported the LW of rubberwood fibres to range between 10 and 12 µm, whereas Naji et al. [30] reported a higher range (from 16.43 to 26.56 µm). Haifah [33] reported that the widest lumens in hybrid Acacia fibres was found in the innerwood region, which corresponded to the widest lumen width (21.31 µm) observed for rubberwood.

3.3. Fibre Diameter

Fibre diameter ranged from 21.50 to 31.81 µm, its widest being at 25 years (27.23 µm) and its narrowest at 15 years (24.86 µm). The age of the trees significantly affected the FD ($p < 0.05$, Table 1). The FD along the bole was significantly higher at the tree-top (27.02 ± 2.009 µm) compared to the base (24.73 ± 1.908 µm) ($p < 0.05$) (Figure 5).

Average FD across the bole was 25.86 µm (innerwood), 25.94 µm (middlewood) and 25.83 µm (outerwood).

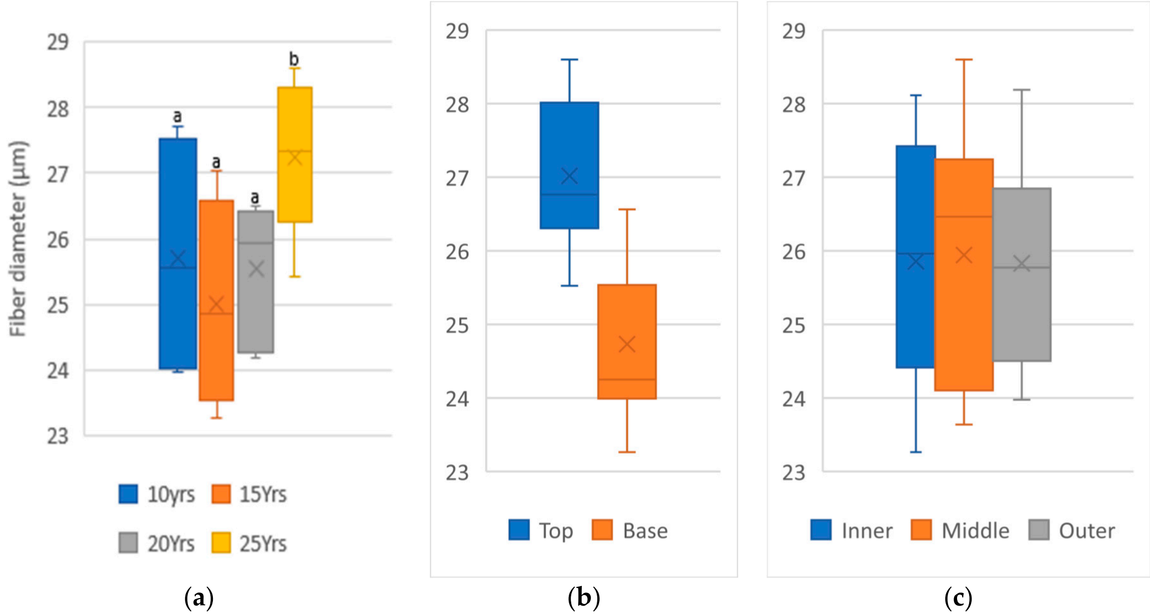


Figure 5. Boxplots showing variations in the average fibre diameter of rubberwood in terms of (**a**) tree age (**b**) axis and (**c**) radial position. Means with same letter are not significantly different.

Yahaya [47] reported that a large FD will increase the strength properties of wood. Teoh et al. [16] and Naji et al. [30] respectively reported that the FD of rubberwood ranged from 26 to 30 µm and from 26.33 to 32.84 µm, whereas Norul Izani and Sahri [31] obtained FD values ranging from 23.5 to 24.9 µm.

A large fibre diameter weakens the interfibre bonding between individual fibres as their surface area is low compared to their volume. An increased surface area allows for a more effective load transmission between the fibres and the matrix as well as more points of contact. Fibres with a high aspect ratio (long FL and small FD) are rigid and impart brittleness to the composites, thus ensuring a more effective stress transfer that will result in the higher mechanical strength of composites [48].

3.4. Fibre Wall Thickness

The mean fibre wall thickness for rubberwood was 4.50 ± 0.555 µm, with values ranging from 3.59 µm to 6.47 µm. Fibre wall thickness increased progressively from 10 to 25 years. Fibre wall thickness along the bole was higher at the top (mean 4.78 ± 0.480 µm) versus those collected from the base (4.23 ± 0.478 µm) of the stem, as shown in Figure 6. Fibre wall thickness increased from the innerwood to the outerwood, with mean values of 4.45 µm (innerwood), 4.49 µm (middlewood) and 4.57 µm (outerwood).

Wood specific gravity, shrinkage and strength are all related to FWT [31]. The fibre wall thickness increases with increasing age [45] and is attributed to the effects of an increase in fibre diameter combined with a commensurate decrease in lumen size. The values and pattern of variation in this study is consistent with those reported by Izekor and Fuwupe [6] and Harmean et al. [49], who observed that fibres with the thickest walls are found in the outerwood region, while those with the thinnest walls are located in the innerwood region at the bottom of the stem. Others have reported the wall thickness of fibres in rubberwood to range from 5.1 to 7.0 µm [16], from 4.08 to 5.69 µm [30] and from 6.08 to 6.51 µm [31].

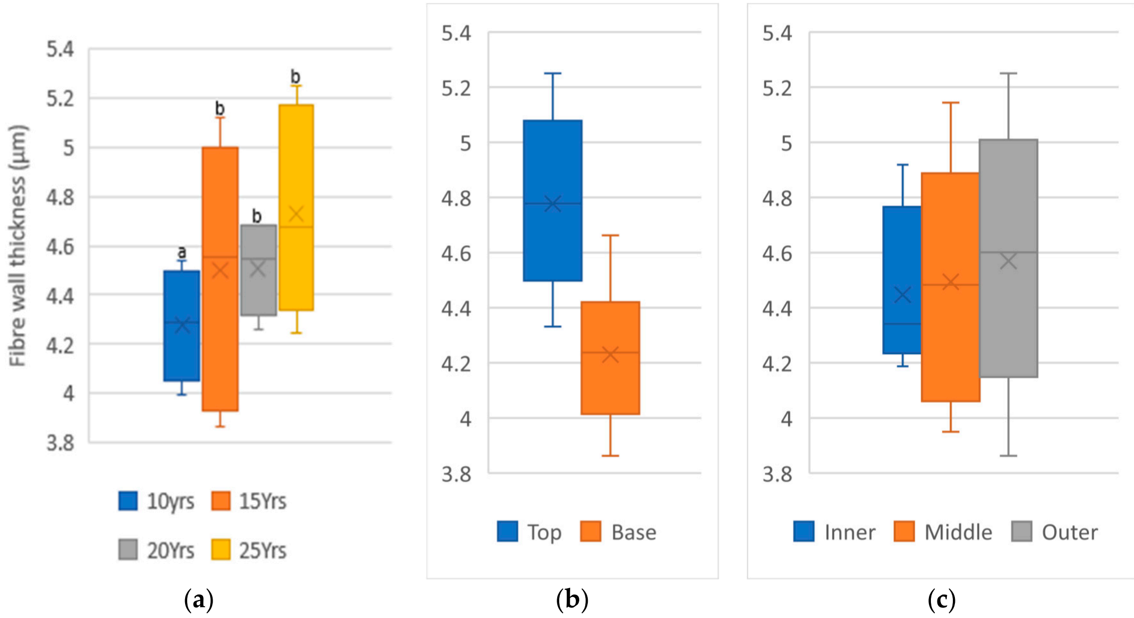


Figure 6. Boxplots showing variations in the average fibre wall thickness of rubberwood in terms of (**a**) tree age (**b**) axis and (**c**) radial position. Means with same letter are not significantly different.

In standing trees, thick-walled fibres endow the stem with firmness and rigidity. However, when the objective is either to use them for pulp and paper production or for wood fibre composites, thick fibre walls are not desirable as they do not bend readily and are resistant to collapse upon pulping. This impedes interfibre bonding, while the opposite is achieved for thin-walled cells [50,51]. Pulps produced from thin-walled fibres are less coarse, making them suitable for the manufacture of many grades of paper [45]. Thick-walled fibres produce paper that has a poor printing surface, a higher bulk weight with lower tensile strength, poor burst strength, high tearing strength and low folding endurance [52]. However, thick cell walls in composite board production will increase load-carrying capacity as thick-walled fibres are likely to have fewer voids and pores, which will make them more capable of resisting an applied external load as compared to thin-walled fibres [48].

3.5. Slenderness Ratio

The average SR of rubberwood was 56.86 ± 5.021 and ranged from 45.24 to 75.78 for the various ages, with 15 years having the highest mean value of 59.98. Tree age significantly influenced SR ($p < 0.05$, Table 2). The SR was significantly higher at the base (57.99 ± 5.169) compared to the top of the tree (55.72 ± 4.666). Radially, SR was the lowest for the middlewood (56.34) and the highest for the outerwood (57.54) as shown in Table 3.

Slenderness ratio is related to the tear resistance of paper [45]. Fibres with a high SR are long and thin with a high tearing resistance, whereas short and thick fibres have lower SR with low tearing resistance [8]. It has been reported that an SR above 33 for fibrous materials is considered to be good for pulp and paper production [53]. The strength properties of paper positively correlate with the SR; for example, Ona et al. [27] reported a positive correlation between SR and folding endurance.

For composite boards, Arabi et al. [54] reported that the modulus of elasticity and the modulus of rupture increased with an increase in SR. An increase in SR will improve the bending properties of MDFs [43], therefore producing a higher aspect ratio, which is more desirable in wood composite panels [55,56]. Stark and Rowlands [57] concluded that the aspect ratio (slenderness ratio) of the fibre rather than fibre size had a more significant effect on the stiffness and strength of wood composites.

Table 2. ANOVA table for rubberwood fibre morphology.

Source of Variation	NumDF	denDF	Fibre Wall Thickness		Slenderness Ratio		Flexibility Ratio		Runkel Ratio	
			F-Value	*p*-Value	F-Value	*p*-Value	F-Value	*p*-Value	F-Value	*p*-Value
Tree age	3	89	4.81	**0.00369**	6.58	**0.000441**	2.99	**0.0359**	2.827	**0.0428**
Height	1	89	44.42	**0.000000**	6.84	**0.0104**	3.51	0.0641	3.200	0.0769
Radial position	2	89	0.76	0.473	0.68	0.511	0.57	0.569	0.543	0.583
Tree age * Height	3	89	5.81	**0.0011**	0.98	0.407	4.61	**0.00472**	4.500	**0.00540**
Tree age * Radial position	6	89	0.52	0.789	1.11	0.361	1.05	0.395	1.014	0.421
Height * Radial position	2	89	1.54	0.220	1.35	0.265	1.31	0.274	1.280	0.283
Tree age * Height * Radial position	6	89	0.34	0.913	0.32	0.925	0.27	0.950	0.219	0.970

Bold numbers show significant difference in samples ($p < 0.05$). * interaction between factors.

Table 3. Average values for the different morphological characteristics of rubberwood, for different ages and tree positions.

Variables		Slenderness Ratio	Flexibility Ratio	Runkel Ratio
Tree age	10 Years	55.04 ^{a}	66.60 ^{a}	0.50 ^{a}
	15 Years	59.98 ^{b}	64.06 ^{b}	0.57 ^{b}
	20 Years	56.76 ^{a}	64.56 ^{b}	0.55 ^{b}
	25 Years	55.91 ^{a}	65.26 ^{ab}	0.54 ^{b}
Height	Top	57.99 ^{a}	65.73 ^{a}	0.53 ^{a}
	Base	55.90 ^{a}	64.40 ^{a}	0.56 ^{a}
Radial position	Innerwood	56.83 ^{a}	65.33 ^{a}	0.54 ^{a}
	Middlewood	56.50 ^{a}	65.27 ^{a}	0.53 ^{a}
	Outerwood	57.58 ^{a}	64.64 ^{a}	0.55 ^{a}

Means with same letters are not significantly different.

3.6. Flexibility Ratio

The mean flexibility ratio for rubberwood of all ages was 65.13 ± 3.647, with values ranging from 53.66 to 72.71 at different ages. The FR of rubberwood at 10 to 15 years decreased and then increased at 25 years. Flexibility ratio was significant for tree age ($p < 0.05$, Table 2), and it was significantly higher at the base of the tree (65.73 ± 3.645) compared to the top (64.53 ± 3.588). The flexibility ratio decreased from the innerwood to the outerwood, with mean values of 65.42 (innerwood), 65.32 (middlewood) and 64.65 (outerwood).

The flexibility coefficient, which determines the degree of fibre bonding in a paper sheet, is influenced by LW and FD [8]. The degree of fibre bonding in paper manufacture and pulp composite board production is dependent largely on the flexibility of individual fibres [58]. Smook [59] reported a range of values (0.55–0.70) for hardwoods. Fibres with an FR greater than 0.75 are considered to be highly elastic, while those between 0.50 and 0.75 are considered elastic [60]. The fibres of the rubberwood we examined are therefore flexible (elastic) and satisfy the requirements for suitability as a raw material for paper and pulp composite boards. The FR in this study (0.65) is similar to that reported by Boerhendy et al. [29] for Indonesian rubberwood (0.67).

3.7. Runkel Ratio

The average RR of rubberwood for the four different ages examined varied from 0.38 to 0.86, with an average of 0.54 ± 0.090 (Table 3). Runkel ratio of rubberwood at 10 to 15 years increased and then decreased at 25 years. Runkel ratio was significantly affected by tree age ($p < 0.05$, Table 2) and significantly increased from the stem base (0.53 ± 0.088) to the top (0.55 ± 0.091). Radially, RR increased from the innerwood to the outerwood at 10, 20 and 25 years, whereas at 15 years, the RR decreased. Mean values in the radial direction were 0.54 (innerwood), 0.53 (middlewood) and 0.55 (outerwood).

Runkel ratio has been used to determine the suitability of fibre for pulp and paper production. Fibres with a ratio < 1 have been reported to be suitable for the fabrication of paper as they are more flexible and will readily collapse, thus producing paper with large areas of interfibre bonds and good mechanical strength properties [8,51,61,62]. The lower the Runkel ratio, the greater the collapse. Fibreboards are often produced without adhesives—their strength comes from interfibre bonding between individual fibres that are flattened and pressed against one another [63]. Zwawi [64] reported that a strong interfibre bond must be ensured to achieve the most desired mechanical properties in bio-composite production. This is achieved mainly when fibres are flexible and can collapse more readily when beaten. Ona et al. [27] reported RR to be correlated to paper conformability and pulp yield. The average RR of 0.54 in this study is lower than that reported by Boerhendy et al. [29] for Indonesian rubberwood (0.61).

3.8. Fibre Properties of Rubberwood Compared with Other Tropical Wood Species

The fibre characteristics and morphology of wood have direct impacts on the panel properties of MDFs [65]. When compared with other tropical species (Table 4), the FL of *H. brasiliensis* is greater than that of *Gliricidia sepium*, *Delonix regia* and *Senna siamea* [9], *Rhicinodendron heudelotti* [8], *Gmelina arborea* [5], *Leucaena leucocephala* [4] and Ficus *species* [5]. Harmaen et al. [66] reported that MDFs made from 100% rubberwood fibres had significantly better physical and mechanical properties than MDFs made from 100% empty fruit bunch fibres, which are oil palm wastes generated in an oil mill, because the rubberwood fibres are relatively longer than empty fruit bunch fibres.

Table 4. Fibre properties of some tropical hardwood species from Nigeria.

Species	FL (mm)	LW (µm)	FD (µm)	CWT	Reference
Glirisidia sepium	1.14	12.18	21.78	4.91	[9]
Delonix regia	1.34	26.83	39.42	6.49	[9]
Senna siamea	1.29	11.46	20.71	4.95	[9]
Rhizophora racemosa	1.76	18.92	36.09	8.58	[7]
Rhizophora harrisonii	1.54	17.55	34.25	9.45	[7]
Tectona grandis	1.73	15.6	29.47	7.89	[6]
Rhicinodendron heudelotti	1.36	32.3	41.5	4.6	[8]
Triplochiton scleroxylon	1.35	12.5	20.3		[36]
Gmelina arborea	1.28	20.06	26.46	3.83	[5]
Leucaena leucocephala	0.65	9.87	15.67	2.9	[4]
Ficus species	0.99–1.28	14.85–20.99	18.69–28.93	1.94–4.99	[5]
Hevea brasiliensis *	1.4–1.52	16.02–17.78	25.02–27.23	4.28–4.73	

* Present study. FL = Fiber length; LW = Lumen width; FD = Fiber diameter; CWT = Cell wall thickness.

The LW of *H. brasiliensis*, when compared with other tropical hardwoods (Table 4), is greater than that of *G. sepium* and *S. siamea* [9], *Tectona grandis* [6], *L. leucocephala* [4] and Ficus species [5]. The lumen widths of *D. regia* [9], *Rhizophora racemose* and *R. harrisonii* [7] and *R. heudelotti* [8] were greater than our reported value.

The FD of *H. brasiliensis* (Table 4) is greater in comparison with tropical species such as *G. sepium* and *S. siamea* [9], *L. leucocephala* [4] and Ficus species [5]. The fibre diameters of *D. regia* [9], *R. racemose* and *R. harrisonii* [7], *T. grandis* [6] and *R. heudelotti* [8] were much higher than our reported value for *H. brasiliensis*.

When compared with other tropical species, the FWT of *H. brasiliensis* is less than that of *G. sepium, D. regia* and *S. siamea* [9], *R. heudelotti* [8] and Ficus species [5], but greater than that of *G. arborea* [5] and *L. leucocephala* [4], as shown in Table 4.

The average SR reported in [8] for *R. heudelotii* (35.85) is less than the 56.86 obtained in this study. However, Ogunkunle [5] and Sharma et al. [67] respectively reported that *G. arborea* had an average SR of 50.06 and 39.1, while a range of 42.38–71.99 was reported for different Ficus species in [5], which is similar to the range for rubberwood in this study (45.24–75.78).

Others have reported values of 0.77 for *R. heudelotti* [8], 0.73 for *G. arborea* and 0.63–0.79 for Ficus species [5]. An FR of 0.76 for *G. arborea* was reported by Sharma et al. [67], which is higher than the FR in this study.

Ogunleye et al. [8] reported an average RR of 0.31 for *R. heudelotti*, which is lower than the RR observed in this study. However, Ogunkunle [5] reported a value of 0.39 for *G. arborea* and a range of 0.26–0.68 for Ficus species.

The limitations of this study include the need for a validation experiment in order to study the effect of the fibre dimensions of rubberwood on pulp and paper quality as well as on manufactured composite boards. However, the effects discussed were drawn from related studies, which have demonstrated a correlation between fibre properties and pulp, paper and composite board production.

4. Conclusions

In this study, the fibre properties of rubberwood from trees of different ages were measured to elucidate the effect of age on fibre and morphological properties and to reveal the potential of rubberwood utilization for the fabrication of pulp products and composite boards. Our research indicates that rubberwood is potentially suitable for the production of pulp and paper and other fibrous composite boards. There was little or no variation in the fibre properties of the different ages sampled. Fibres of all ages fell within the suitable range for pulp and paper and composite board production. Rubberwood at 15 years had the best combination of qualities for the production of pulp, paper and composite boards. Rubberwood is grown mainly for the production of latex, with a productive age of approximately 30 years. At this age, they can be harvested and used for pulp, paper and other fibrous composite boards.

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