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Fibre Characteristics of *Delonix regia* (Hook.) Raf. Wood as Indices of its Suitability for Papermaking

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Abstract

The fibre characteristics of Delonix regia, a fast and deciduous tropical tree with form like leaves that is considered one of the most beautiful trees in the world was evaluated to assess its potential for pulp and paper making. Three trees of *D. regia* were used for the study, they were obtained at different locations within University of Ibadan main campus, Ibadan, Oyo State, Nigeria. Samples were collected at base (10%), middle (50%) and top (90%) portion of the merchantable height. At each sampling height, strips of 2.5cm were removed from the centre of the discs and divided into 3 zones namely: corewood, middlewood and outerwood based on the relative distance from the pith. Slivers were obtained from each of the zones and macerated in equal volume of glacial aceticacid and 30% hydrogen peroxide at 80oC in an oven. Data were subjected to statistical analysis of 3×3×3 factorial experiment in a completely randomized design (CRD) and Mean±SEM. However, a follow-up test was carried out using the least significant difference test (LSD) at 5% level of probability. A total of twenty whole fibres were measured in swollen conditions with a calibrated eye piece microscope from each sampling zone for fibre characteristics evaluation viz: fibre length (FL), fibre diameter (FD), lumen width (LW), cell wall thickness (WT), runkel ratio (RR), Coefficient of rigidity (CR), Slenderness ratio (SR), Flexibility ratio (FR), F-factor (FF) and solid factor (SF). The results obtained show that *Delonix regia* has the following mean value: FL (1.34mm), FD (39.42µM), LW (26.83µM), WT (6.49µM), RR (0.55%), CR (16.95%), SR (36.03%), FR (68.45%), FF (236.33) and SL (1390408.51).

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Based on the derived value such as the Runkel ratio of 0.55 which is less than 1 compared favourably with other known species for pulp and paper making. The values indicate the suitability of the specie for pulp and paper production in a place where there is shortage of wood material for this purpose.

Keywords: Delonix regia; Fibre length; Fibre diameter; Runkel ratio; Fibre suppleness; Fibre rigidity.

1. Introduction

Paper is an important material, used daily for many purposes worldwide. The global production of paper and cardboard stood at approximately 419.7 million metric tons in 2017 [1], which is expected to grow by 1.2% annually, reaching over 596 million metric tons by 2050. Researchers projected that the bulk of the new fibre requirement will be sourced from recycled paper, a position World Resources Institute and Kearney [2] questioned. According to them, it has been established that recycling the papers weakens the fibre each time it is re-processed. Increasing recovered paper content may place limitations on paper grades over time. So, the big question is "where will the estimated 1.2% tonnes of fibres increment per annum needed by the year 2050 come from". To take care of the deficit, many authors had suggested the use of local wood as alternative for fibre supply. The successful conversion of pulp into a marketable product depends on the original fibre characteristics and globally, it become imperative to beam search light on the response of the fibre to the processing variables [3]. Fibre characteristics are important in considering the utilization of any plant for pulp and paper making. Fibres are the most important factor for determining the degree of efficiency of wood species in pulping [4].The strength property of paper is a function of the fibre characteristics used. It have been described to vary widely and thus exert varied influences on bulk density, fibre strength and inter-fibre bonding [5]. Wood possessing long fibres is the most desirable in the paper industry. Pulp can be made from many species of wood but the commercial utility of a particular species depend on factors such as the suitability of their fibres in paper making. The use of tropical hardwood species, as alternative to the temperate soft wood species like Pines and Cyprus, as raw material for pulp and paper production is yielding commendable results today. Hardwood pulps are easier to bleach and possess the capability of being used to manufacture a wide range of specialty grades when blended with softwood chips. *Delonix regia* is a fast and deciduous tropical tree with form like leaves that is considered one of the most beautiful trees in the world [6]. Flame of the forest as it is called, blooms in dense cluster and burst into scarlet orange blossoms [7]. During the dry season, it losses all of its leaves and begins to sprout immediately. The tree of flamboyant is often more than 12 m high with wide spreading branches from a domed top, sometimes even reach the ground. The planned level of production in the pulp and paper mill in Nigeria has not been achieved due to insufficient availability of local materials. The most crucial of this, as identified by Udohitinah, and Oluwadare [8] is the limitation of long fibre supply, which play a dominant role in the strength properties of paper. Most tree species used for pulp and paper production like *Gmelina* and *Pinus caribaea* are threatened due to high rate of deforestation and increasing demand of their wood for other economic purposes. There is need therefore, to carry out a study on the fibre characteristics of *D. regia* species to enable us find out if these species can be used for pulp and paper production as a suitable alternatives.

2. Materials and Methods

2.1 Collection of Sample

Three stands of trees of *D. regia* were felled in the month of June, 2018 from the University of Ibadan main campus, Ibadan, Nigeria. The estimated ages of the trees are 13, 14 and 14 years with a merchantable length of 6.10, 3.95 and 4.73 m and diameter at breast height (DBH), 109, 99 and 112 cm for T1, T2 and T3, respectively. The stem was cross-cut into billets at base (10%), middle (50%) and top (90%) of the stems. Discs were obtained from each billet and partitioned into corewood, middlewood and outerwood for determination of fibre characteristics.

3. Determination of fibre characteristics

3.1 Maceration and Microscopy

The wood samples were macerated in properly labelled test tubes containing a solution of 10% acetic acid and 30% hydrogen peroxide, mixed in the ratio of 1:2 by volume, as reported by Oluwadare and Sotannde [9]. All the test tubes containing the various samples were later kept in an oven for 4 hours and maintained at temperature of 101^{o}C, for the non-cellulose components to dissolve out, leaving majorly cellulosic fibres only. At the expiration of the 4 hours, the softened and bleached pulpy mass was gently rinsed with distilled water to remove residual chemical before the test tubes were thoroughly but carefully shaken to separate the fibrous mass into liberated individual fibres. Twenty fibres were randomly selected from each of the samples collected from the base, middle and top portions of the selected trees, making sixty samples per tree. The fibres of each sample were viewed under an light microscope for fibre dimension assessment and determination.

3.2 Parameters Determined

Under the light microscope, the following fibre parameters were assessed:

- Fibre length - this was measured by aligning the pulp fibres sideways to the graduated ruler in the microscope.

- Fibre Diameter - the fibre diameter was measured by placing the graduated ruler in the microscope in a horizontal direction at the middle of the fibre.

- Lumen width - this is the cavity of the cell from the first wall side to the second wall side.

Parameters determined as derived values using appropriate formula include:

Six derived morphological indices of the fibres were calculated from the measured dimensions based on the method adopted by Ogbonnaya and his colleagues [10]; Ververis and his colleagues [11] and Oluwadare and Sotannde, [12]. These include:

(i) $Cell\ wall\ thickness = \frac{\text{Fibre diameter} - \text{Lumen width}}{2}$ ……………………………….……..… 1

(ii) $Slenderness\ ratio = \frac{\text{Fibre length}}{\text{Fibre diameter}}$ ……………………………………………………...2

(iii) $Flexibility\ coefficient = \frac{\text{Lumen diamter}}{\text{Fibre diamter}}$ …………………………………………….…3

(iv) $Runkel\ ratio = \frac{\text{2 x Fibre cell thickness}}{\text{Lumen diametr}}$ ………………………………………………...4

(v) $Coefficient\ of\ rigidity\ \frac{Cell\ wall\ thickness}{Fibre\ diameter} x \frac{100}{1}$ …………….…….………...5

(vi) $F - Factor = \frac{\text{Fibre length}}{\text{Fibre cellwall thickness}}$ …………………………………..……..….6

(vii) $Solid\ factor = (Fibre\ diameter^2 - Lumen\ diameter^2) \times (Fibre\ length)$ ……..7

3.3 Statistical Analysis

A one-way analysis of variance (ANOVA) was used. Data were subjected to statistical analysis of 3×3×3 factorial experiment in a completely randomized design (CRD) and Mean±SEM. However, a follow-up test was carried out using the least significant difference test (LSD) at 5% level of probability.

4. Results and Discussion

4.1 Fibre Length

The images of the fibres are presented in plate 1 and the fibre length of the sampled trees averaged at 1.34±0.15 mm. The fibre length of *D. regia* followed same trend as it increased from 1.23±0.10 mm at the corewood to 1.44±0.15 mm at the outerwood across the radial position and also, decreased from 1.38±0.14 mm at the base to 1.30±0.14 at the top along the sampling height (Table 3). Among the sampled trees, TN1 had the longest fibre length averaged 1.40±0.13 mm while TN3 had the least with pooled mean of 1.27±0.19 mm (Table 1). Table 2 show that there is significant difference in the radial position and sampling height at (P <0.05). The fibre length of 1.34 mm obtained in this study is greater than 1.29 mm for *Gmelina arborea* reported by Roger and his colleagues [13]; 1.28 mm and the range of 0.99 to 1.24 mm for *G. arborea* and Ficus spp, respectively[14]; Oluwadare [15] recorded 0.65mm as fibre length of *Leucaena leucocephala*; 1.07 for *Ficus exasperata* reported by Anguruwa [16] but lower than 1.76 in *Aningeria robusta* by Ajala and Noah [17]; 1.40 in *Ricinodedron Heudelotii* by Ogunleye and his colleagues [18]; 1.38 in *Gerdenia Ternifolia* reported by Noah and his colleagues [19] and 1. 48mm in *Vitex doniana* reported by Ogunjobi and his colleagues [20] in Nigeria. Hindi and his colleagues [21] also, reported that *Leucaena leucocephala*, *Azadirachta indica* and *Simmondsia chinens* had a fibre length of 1.13, 1.04 and 0.50 mm, respectively. Since, the length of fibre greatly affects the strength of the pulp and the paper made from it [22], paper made from *D. regia* is expected to show higher quality than the others woods like *L. leucocephala, A. indica* and *S. chinens* with shorter fibres. Higher fibre length results in greater resistance of the paper to tearing [9] and are necessary in producing strong and durable papers. The longitudinal variation of wood fibre length was characterised by a decrease from the base to the top. This is in agreement with some previous studies [23-26, 18]. The theory of auxin gradient also holds for this pattern of variation in the fibre length similar to that of wood density. In relation to the radial variation of fibre length, a significant increase from Corewood to outerwood was observed. This trend was also observed [27, 23-25, 18].

The increase of fibre length from Corewood to outerwood could be explained on the basis of the increase in length of cambial initials with increasing cambial age and crown formation [23].

4.2 Fibre Diameter

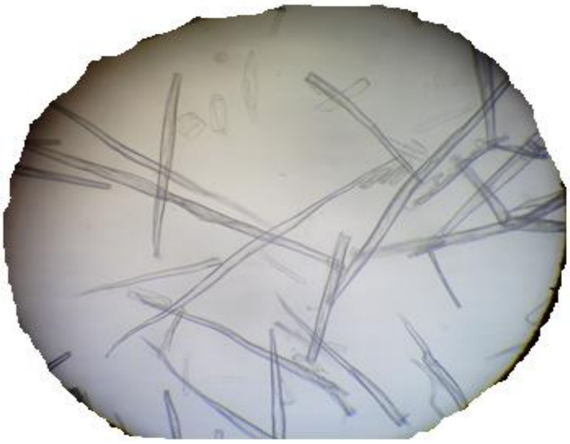

Plate 1: Macerated images of *Delonix regia*

Table 1: Mean Fibre length and Fibre diameter along the Sampling Height and Radial Position of the sampled trees

Morphological Indices	Species	Wood Type	Base	Middle	Top	Pooled Mean
Fibre Length (mm)						
	TN1	Corewood	1.31±0.04	1.22±0.02	1.25±0.07	1.26±0.06
		Middlewood	1.46±0.03	1.42±0.06	1.45±0.05	1.44±0.05
		Outerwood	1.37±0.02	1.60±0.07	1.51±0.04	1.49±0.11
		Mean	**1.38±0.13**	**1.41±0.17**	**1.40±0.13**	**1.40±0.13[a]**
	TN2	Corewood	1.19±0.04	1.39±0.04	1.15±0.04	1.24±0.11
		Middlewood	1.31±0.03	1.46±0.17	1.17±0.03	1.32±0.16
		Outerwood	1.51±0.06	1.36±0.12	1.44±0.03	1.48±0.15
		Mean	**1.37±0.12**	**1.40±0.15**	**1.25±0.15**	**1.35±0.17[b]**
	TN3	Corewood	1.29±0.06	1.10±0.02	1.14±0.01	1.18±0.09
		Middlewood	1.31±0.03	1.26±0.05	1.30±0.09	1.29±0.06
		Outerwood	1.51±0.06	1.21±0.02	1.34±0.14	1.34±0.14
		Mean	**1.37±0.11**	**1.19±0.08**	**1.24±0.09**	**1.27±0.19[c]**
Fibre diameter (µm)						
	TN1	Corewood	38.25±0.22	43.15±1.33	43.38±1.45	41.60±2.70
		Middlewood	37.28±1.01	35.82±1.50	40.71±0.41	37.94±2.37
		Outerwood	37.12±0.81	38.59±1.63	36.75±1.55	37.48±1.47
		Mean	**37.55±0.84**	**39.18±3.46**	**40.28±3.09**	**39.01±2.85[a]**
	TN2	Corewood	37.45±2.38	37.80±1.11	40.69±2.08	38.65±2.28
		Middlewood	39.25±2.59	36.52±0.61	39.72±2.16	38.50±2.24
		Outerwood	37.20±1.25	34.43±2.44	35.01±1.46	35.55±2.00
		Mean	**37.97±2.10**	**36.25±2.02**	**38.47±3.12**	**37.56±2.56[b]**
	TN3	Corewood	40.86±1.94	42.45±3.29	41.46±0.75	41.59±2.07
		Middlewood	41.81±0.54	41.77±10.65	38.28±1.41	40.62±5.66
		Outerwood	43.69±1.22	50.47±11.50	34.56±1.48	42.90±9.04
		Mean	**42.12±1.71**	**44.90±9.04**	**38.10±3.18**	**41.70±6.10[c]**

*Means± Standard error of mean of 3 replicate samples.TN 1, 2 and 3 = Tree number 1, 2 and 3

The fibre diameter was 39.42 µm as the pooled mean of the sampled trees. The fibre diameter recorded a regular pattern as it increased from 39.21±2.63 µm at the base to 41.84±1.78 at the top of the sampling height and decreased from 40.61±2.67 µm at the corewood to 39.64±4.46 µm at the outerwood across the radial position (Table 3). Among the trees, TN3 had the highest fibre diameter of 41.70±6.10 µm while TN3 had the least with 37.56±2.56 µm (Table 1). As seen in (Table 2), there is a significant effects among the sampled tress and interaction between them (P <0.05). The observed increase in fibre diameter in sampling height is associated with the increasing age of the tree may be due to the many molecular and physiological changes that occur in the vascular cambium as well as the increase in the wood cell wall thickness during the tree aging process [13]. The same trend was also reported by Ajala and Noah, [17] on *Aningeria robusta* while an inconsistent pattern was observed along the radial direction. The fibre diameter of 39.42 µm is higher than what was reported for teak in Nigeria (32.83 µm) [26], 18.5 – 27.5 µm in *Gmelina arborea* in Costa Rica [28], 23.57 µm in *Gmelina* in Nigeria [14], It is also greater than 36.09 and 34.25 µm for *R. racemosa* and *R. harrisonii*, respectively [29] For comparison with tropical hard wood species, it is higher than the range of 18.69 – 28.93 reported suitable for pulp and paper production.

Table 2: Anova results of Fibre Morphology of the selected sampled trees

Sources of Variation	**Degree of Freedom**	**Fibre Length**	**Fibre Diameter**	**Lumen Width**	**Cell wall Thickness.**
Tree (T)	2	0.001*	0.001*	0.001*	0.218 ns
Sampling Height (SH)	2	0.001*	0.427 ns	0.666 ns	0.341 ns
Radial Position (RP)	2	0.001*	0.088 ns	0.001*	0.479 ns
T*SH	4	0.001*	0.001*	0.001*	0.163 ns
T*RP	4	0.018ns	0.061 ns	0.155 ns	0.716 ns
SH*RP	4	0.047ns	0.005*	0.001*	0.873 ns
T*SH*RP	8	0.001*	0.427 ns	0.064 ns	0.725 ns
Error	54				
Total	80				

*p-values > 0.05 are not significant

Table 3: Effect of Variation in Tree species, Sampling Heights and Radial position of Fibre Morphology of the sampled trees

Sources	**FL (mm)**	**FD (µm)**	**LW (µm)**	**CWT (µm)**
Sampling Height				
Base	1.38±0.14[a]	39.21±2.63[a]	26.85±2.47[a]	6.34±0.61[a]
Middle	1.34±0.16[b]	40.11±6.59[a]	26.59±3.37[a]	6.86±2.63[a]
Top	1.30±0.14[c]	41.84±1.78[a]	27.04±3.47[a]	6.25±0.55[a]
Radial Position				
Corewood	1.23±0.10[a]	40.61±2.67[a]	28.37±2.65[a]	6.17±0.38[a]
Middlewood	1.35±0.12[b]	39.02±3.82[a]	26.46±2.74[b]	6.63±1.67[a]
Outerwood	1.44±0.15[c]	39.64±4.46[a]	25.65±3.33[b]	6.66±2.17[a]
Pooled Mean	**1.34±0.15**	**39.42± 4.46**	**26.83±3.10**	**6.49±1.59**

FL= Fibre length, FD = Fibre Diameter, LW = Lumen width, CWT= Cell call thickness*Means± Standard error of mean of 3 replicate samples. Values with the same alphabet in each column are not significantly different at α = 0.05

4.3 Lumen Width (µm)

There was no difference in lumen width along the sample position, except across the radial direction (P <0.05) (Table 2). The highest was found to exist at TN3 with 28.25±3.46 µm while the least value was at TN2 with 25.44±2.31 µm (Table 4). The pooled mean width therefore is 26.83±3.10 µm (Table 3). Lumen width increased from base to top with a slight decreased in the middle while a general decrease from corewood to outerwood was observed radially. A similar trend was reported by Ajala and Noah, [17] on *Aningeria robusta.* It disagrees with the results of Ogunleye and his colleagues [18] who reported a decrease from the base upward and an increase from corewood to outerwood on *Ricinodendron heudelotii.* The variation in cell-wall thickness may be responsible for the change in lumen width. The average lumen width of 26.83±3.10 µm observed in this study is higher than 16.18µm in *Aningeria robusta* [17], 14.80 reported by Noah and his colleagues [19] on *Gerdenia ternifoli*a, 18.92 and 17.55 in *Rhizophora racemosa Rhizophora harrisonii* respectively reported by Emerhi, [29],15.94 reported by Izekor and Fuwape [26] for Teak and 17.42 reported by Ogunkunle [14] for Gmelina, within the range (14,80 -20.99) reported for ficus species, 9.87 reported for *Lecaena leucocephala* and 13.0 reported for Gmelina by Ajala [30]. In addition, the lumen width is also greater than the range (2.47 – 4.94) with a mean of 3.31 reported for some indigenous hardwood species in the tropical rainforest ecosystem [31]. The lumen compared favorably with the species prominent in pulp and paper manufacturing.

4.4 Cell wall thickness (µm)

There is no significant difference in cell wall thickness of the sampled tress both along the sampling height and radial position among the tree samples (P > 0.05) (Table 2). Along the sampling height, there is an increased from 6.34±0.61 µm at the base to 6.25±0.55 µm at the top with a slight increase in the middle while an increased from 6.17±0.38 µm at the corewood to 6.66±2.17 µm radially were observed (Table 3). Overall, cell wall thickness accounted for 6.49±1.59 µm of the sampled trees (Table 3). Among trees, TN3 had the highest cell wall thickness of 6.94±2.59 µm while TN1 had the least (6.23±0.49 µm) (Table 4). The mean value of cell wall thickness for this specie (6.49 µm) is higher than what was reported for *Ricinodendron heudelotii* (4.6 µm) by Ogunleye and his colleagues [18], *Vitex doniana* (4.9µm) by Ogunjobi and his colleagues [20], *Leucaena leucocephala* (2.90 µm) by Oluwadare and Sotannde [9]and Teak by Izekor and Fuwape [26], it is within the range (5.0 – 10.0 µm) reported for Pine, a reputed long fibre pulp species by PPRI [32]. The thicker cell walls of these species could be a setback to the production of good quality paper, but comparison with Pines confirmed the suitability of this genus as raw material for pulp and paper industries. However, the value is less than 8.58 µm for *Rhizophora racemosa* and 9.45 µm for *Rhizophora harrisonii* [29], 7.89 µm for 20 years old Teak [26].Cell wall thickness decreased from base to top longitudinally while a general increase from corewood to outerwood was observed radially. The pattern of variation observed in this study is consonance with the work of Ogunleye and his colleagues [18].

Table 4: Mean Lumen width and Cell wall thickness along the Sampling Height and Radial Position of the sampled trees

Morphological Indices	**Species**	**Wood Type**	**Base**	**Middle**	**Top**	**Pooled Mean**
Lumen width (μm)						
	TN1	Corewood	24.97±0.40	30.94±1.18	31.64±1.27	29.18±3.30
		Middlewood	25.79±0.87	24.04±1.15	28.17±1.15	26.00±2.02
		Outerwood	25.34±0.80	26.14±1.39	24.10±1.17	25.19±1.33
		Mean	**25.37±0.72**	**27.04±3.25**	**27.97±3.43**	**26.79±2.87[a]**
	TN2	Corewood	25.73±1.59	25.79±0.85	28.75±2.06	26.76±2.03
		Middlewood	25.91±2.82	23.89±1.06	27.14±1.81	25.65±2.09
		Outerwood	25.13±2..12	23.04±2.08	23.56±1.19	23.91±1.86
		Mean	**25.59±1.97**	**24.24±1.74**	**26.48±2.74**	**25.44±2.31[b]**
	TN3	Corewood	28.56±2.30	29.84±2.49	29.10±0.88	29.17±1.84
		Middlewood	29.76±1.45	24.61±1.12	28.85±4.84	27.74±3.51
		Outerwood	30.46±0.84	31.02±2.99	22.07±1.29	27.85±4.66
		Mean	**29.60±1.65**	**28.49±3.58**	**26.67±4.29**	**28.25±3.46[c]**
Cell wall thickness (μm)						
	TN1	Corewood	6.64±0.16	6.31±0.45	5.87±0.27	6.28±0.43
		Middlewood	5.99±0.43	5.89±0.22	6.70±0.62	6.19±0.55
		Outerwood	5.89±0.38	6.22±0.38	6.54±0.70	6.22±0.52
		Mean	**6.18±0.46**	**6.14±0.37**	**6.37±0.62**	**6.23±0.49[a]**
	TN2	Corewood	5.86±0.49	6.00±0.36	6.18±0.12	6.01±0.34
		Middlewood	6.67±0.20	6.97±1.41	6.29±0.32	6.64±0.79
		Outerwood	7.26±0.98	5.69±0.21	5.73±0.30	6.22±0.94
		Mean	**6.60±0.83**	**6.22±0.94**	**6.06±0.34**	**6.30±0.75[a]**
	TN3	Corewood	6.15±0.40	6.38±0.49	6.18±0.11	6.23±0.34
		Middlewood	6.02±0.48	8.58±4.90	6.57±1.13	7.06±2.78
		Outerwood	6.61±0.21	9.72±6.36	6.24±0.48	7.53±3.59
		Mean	**6.26±0.43**	**8.23±4.28**	**6.33±0.64**	**6.94±2.59[a]**

*Means± Standard error of mean of 3 replicate samples. TN 1, 2 and 3 = Tree number 1, 2 and 3.

The trends of the variation in axial and radial directions between trees of *Delonix regia* for fibre morphologies are shown in the figures below, which further supports the claims of the result discussed in the tables.

Figure 1: Histogram chart of *D. regia* Fibre length distribution for Corewood samples.

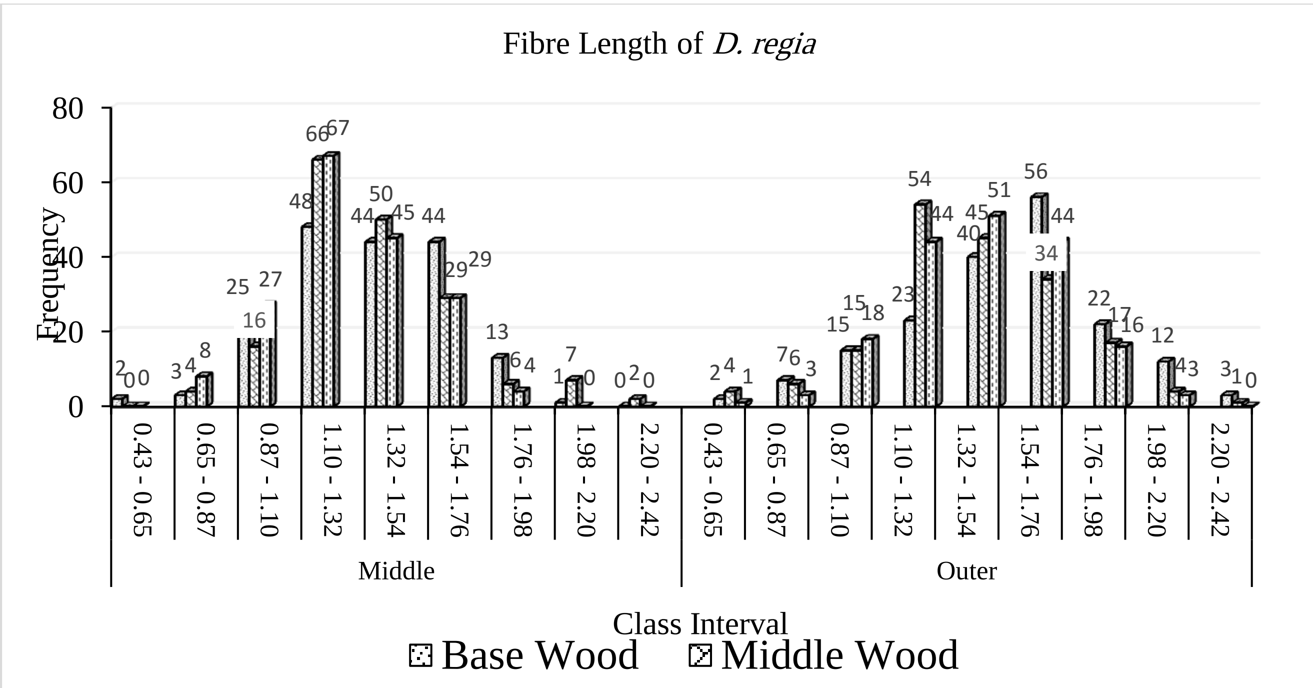

Figure 2: Histogram chart of *D. regia* Fibre length distribution for Middle and Outerwood samples

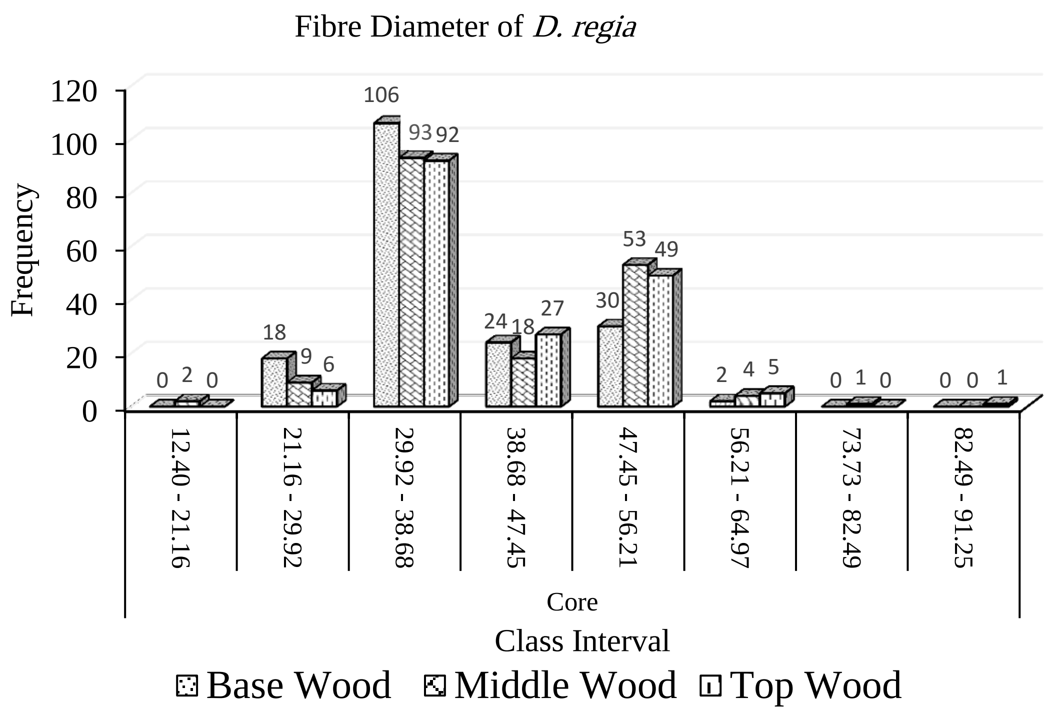

Figure 3: Histogram chart of *D. regia* Fibre Diameter distribution for Corewood samples

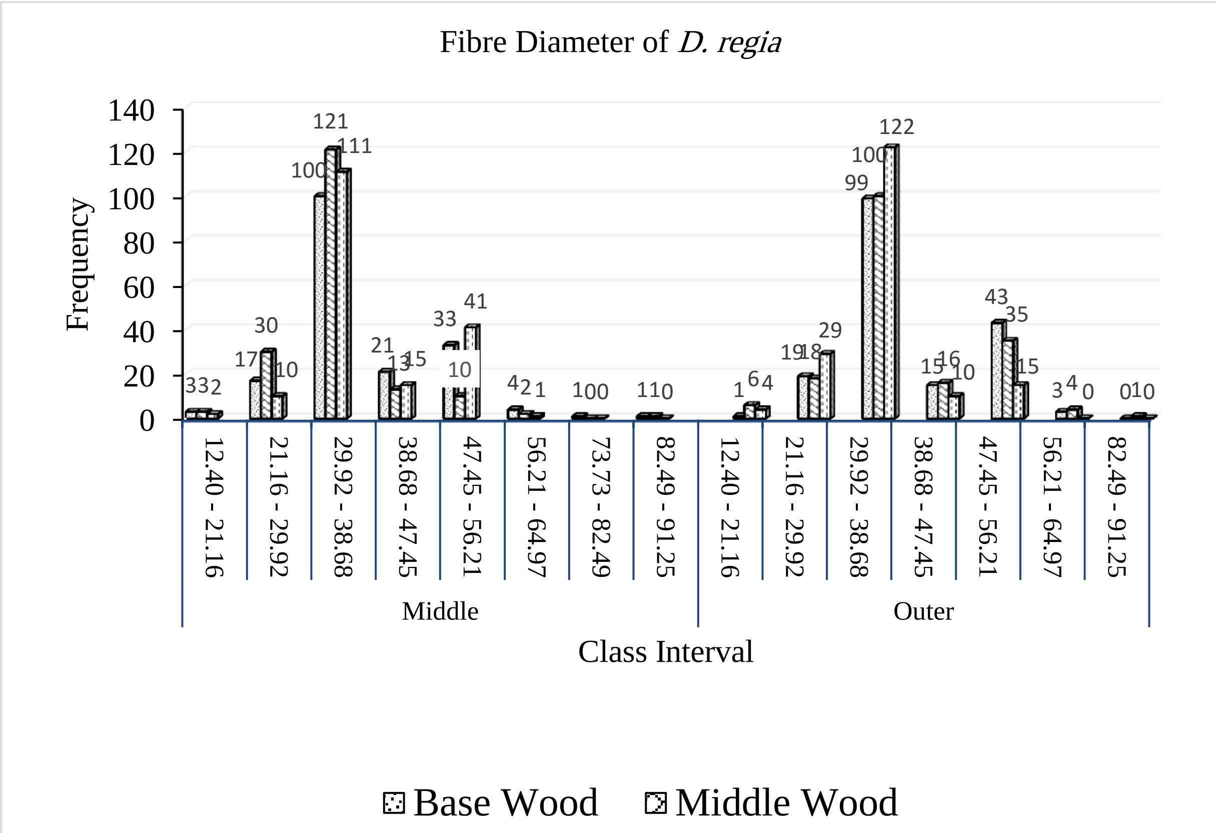

Figure 4: Histogram chart of *D. regia* Fibre Diameter distribution for Middle and Outerwood samples

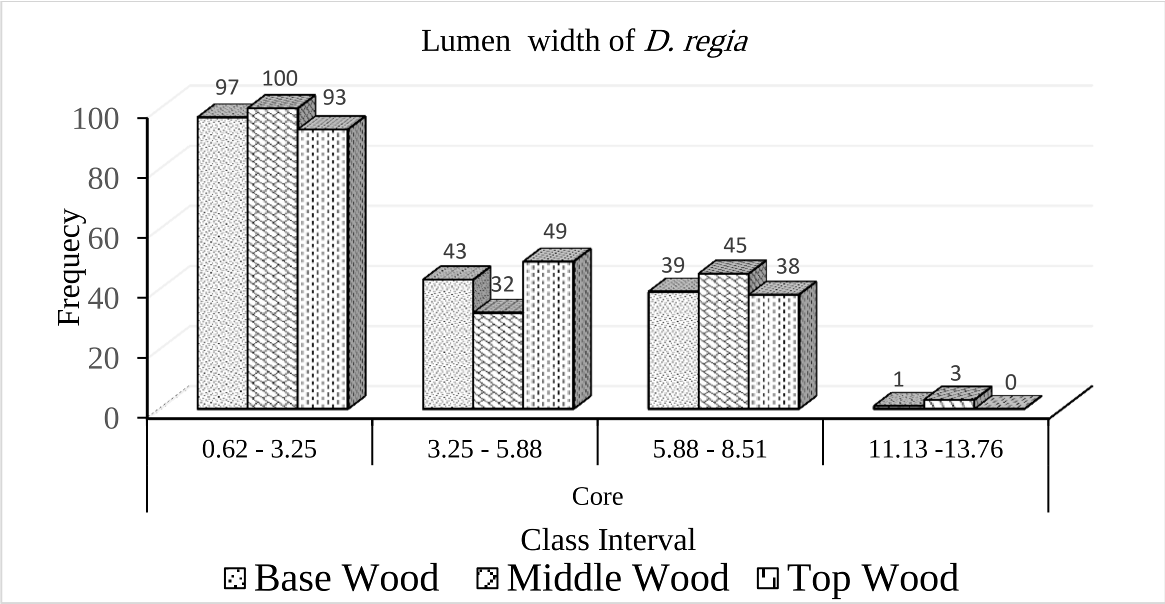

Figure 5: Histogram chart of *D. regia* Lumen width distribution for Corewood samples

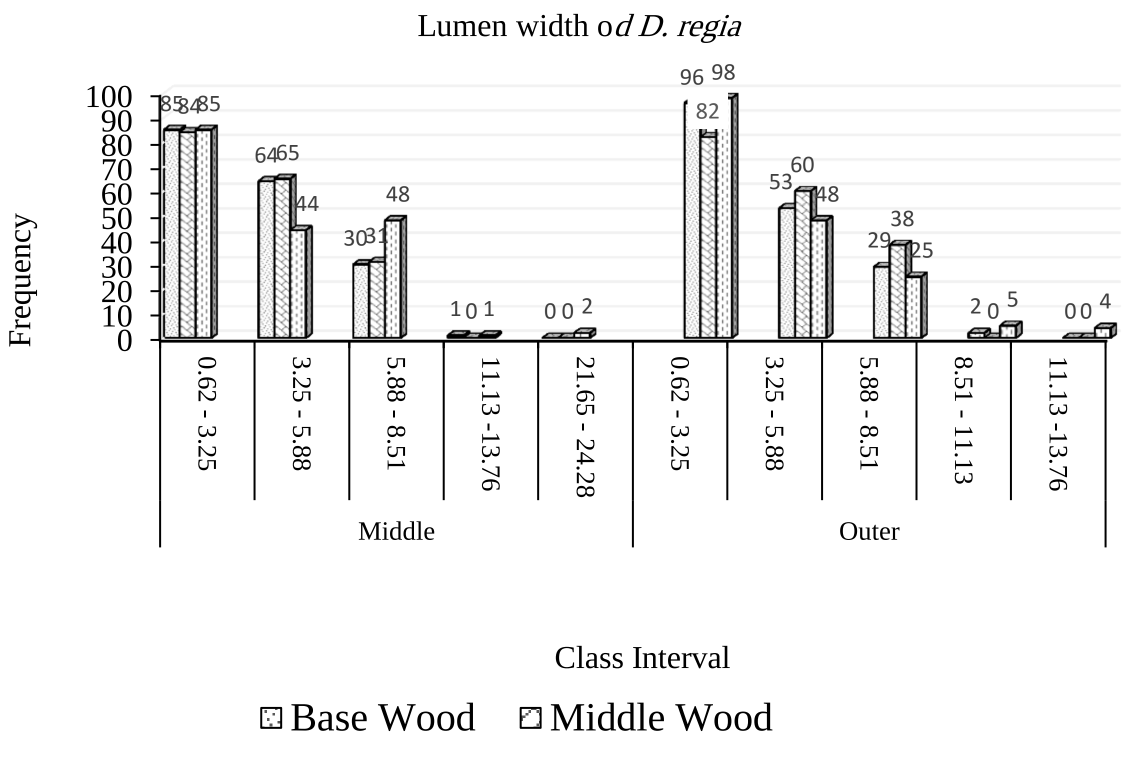

Figure 6: Histogram chart of *D. regia* Lumen width distribution for Middle and Outerwood samples

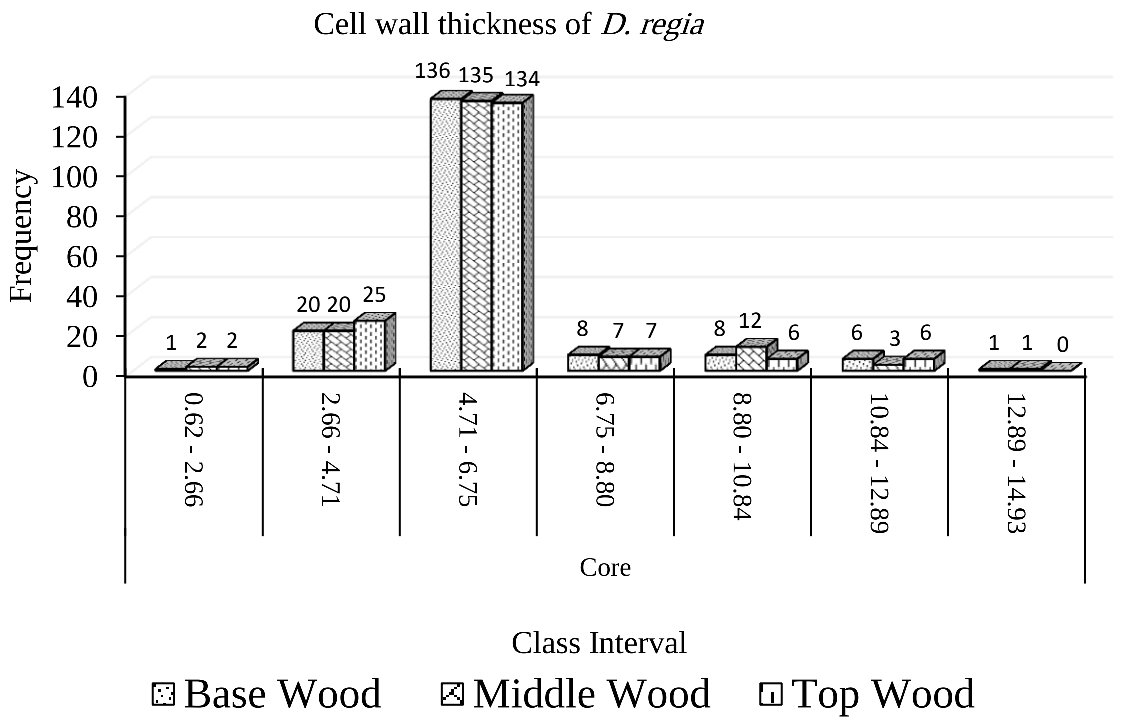

Figure 7: Histogram chart for *D. regia* cell wall thickness for Corewood samples

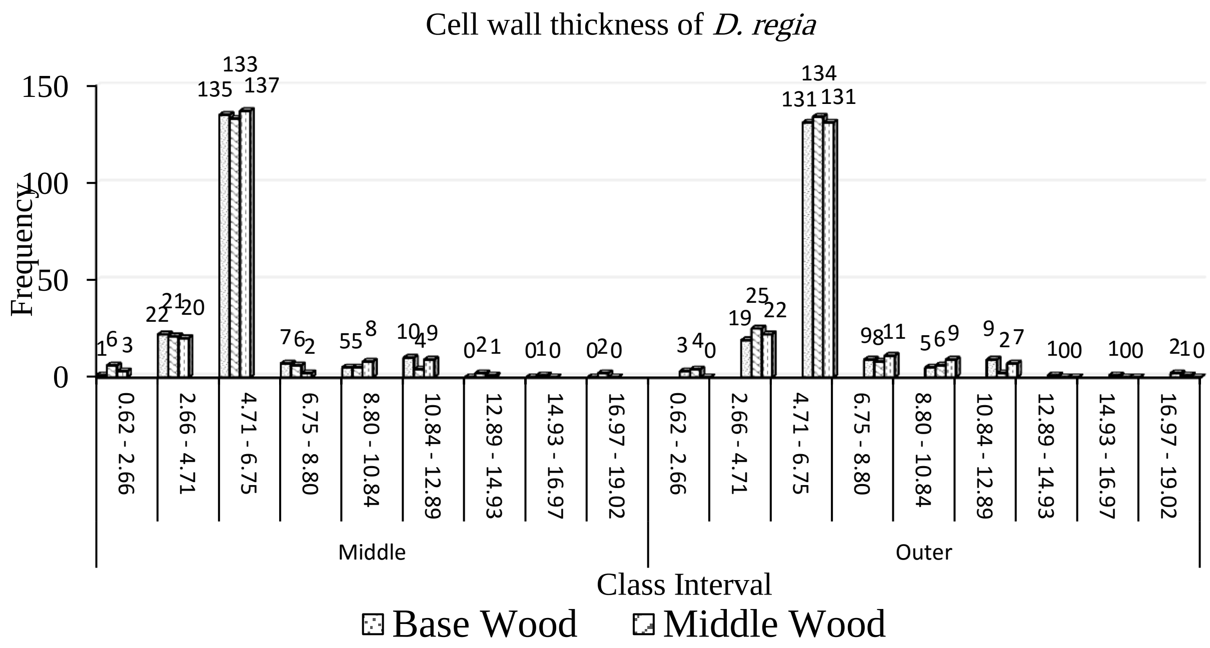

Figure 8: Histogram chart of *D. regia* cell wall thickness for Middle and Outerwood samples

5. Derived Morphological Indices

5.1 Runkel ratio (%)

The results of ANOVA in Table 6 shows that at 0.05 level of probability the effect of tree is not significant while they are significant both along the sampling height and across radial position. There is an inconsistent pattern of variation as the sampled trees increased from based to top and later decreased along the sampling and generally increased from corewood to outerwood (Table 7). Among trees, TN2 had the largest runkel ratio averaged 0.60±0.20% while TN1 had the least averaged 0.52±0.08% of the total stem (Table 5). The pooled mean of the runkel ratio stood at 0.55±0.17% for the sampled trees. The Runkel ratio (0.55%) was less than 0.76% in *Aningeria robusta* [17], 0.88 in *Gerdenia ternifolia* [19], 0.95 and 0.97 for *Rhizophora racemosa* and *Rhizophora harrisonii* accordingly, [29] and fall within 0.26 to 0.68 reported for other Ficus species [14], 0.70 for *Dacryodes edulis* [33] and 0.59 for *Leucaena leucocephala* [12]. Runkel ratio is an important trait for pulp and paper properties in terms of conformity and pulp yield [34]. The extent to which the ratio is less than 1 is an indication of suitability of the wood for paper making. Based on the values which compare favourably with known species, *D. regia* a lesser used specie (LUS) can be said to be an alternative source of wood for paper making.

5.2 Coefficient of Rigidity (%)

Table 5: Mean Runkel ratio and Coefficient of rigidity Along the Sampling Height and Radial Position

Derived Morphological	Species	Wood Type	Base	Middle	Top	Pooled Mean
Runkel ratio (%)						
	TN1	Corewood	0.61±0.04	0.44±0.01	0.40±0.02	0.48±0.10
		Middlewood	0.54±0.09	0.54±0.06	0.53±0.06	0.54±0.06
		Outerwood	0.49±0.05	0.53±0.07	0.58±0.07	0.53±0.07
		Mean	**0.55±0.07**	**0.50±0.06**	**0.50±0.09**	**0.52±0.08[a]**
	TN2	Corewood	0.51±0.02	0.52±0.05	0.47±0.01	0.50±0.03
		Middlewood	0.57±0.09	0.86±0.35	0.49±0.02	0.64±0.25
		Outerwood	0.69±0.15	0.79±0.33	0.52±0.04	0.67±0.22
		Mean	**0.59±0.12**	**0.72±0.29**	**0.49±0.03**	**0.60±0.20[a]**
	TN3	Corewood	0.47±0.07	0.44±0.02	0.48±0.04	0.46±0.04
		Middlewood	0.43±0.06	0.73±0.42	0.47±0.08	0.54±0.26
		Outerwood	0.46±0.01	0.63±0.36	0.65±0.07	0.58±0.20
		Mean	**0.45±0.05**	**0.60±0.30**	**0.53±0.10**	**0.53±0.19[a]**
Coefficient of Rigidity (%)						
	TN1	Corewood	17.73±0.28	15.08±0.50	13.69±0.43	15.50±1.81
		Middlewood	16.75±1.60	16.80±0.90	16.58±1.29	16.71±1.12
		Outerwood	16.10±1.03	16.51±0.94	18.09±1.98	16.90±1.52
		Mean	**16.86±1.19**	**16.13±1.06**	**16.12±2.28**	**16.37±1.58[ab]**
	TN2	Corewood	16.06±0.76	16.15±0.71	15.38±0.50	15.86±0.68
		Middlewood	17.47±1.60	19.57±3.71	16.03±0.54	17.69±2.55
		Outerwood	20.10±3.27	17.22±0.92	16.64±0.71	17.99±2.36
		Mean	**17.88±2.57**	**17.65±2.46**	**16.01±0.75**	**17.18±2.19[a]**
	TN3	Corewood	15.31±1.41	15.14±0.29	15.47±0.35	15.31±0.76
		Middlewood	14.61±1.36	16.90±1.26	18.50±4.90	16.67±3.12
		Outerwood	15.28±0.09	15.01±1.95	17.06±3.54	15.79±2.24
		Mean	**15.07±1.04**	**15.68±1.48**	**17.01±3.30**	**15.92±2.25[b]**

*Means± Standard error of mean of 3 replicate samples. TN 1, 2 and 3 = Tree number 1, 2 and 3.

Coefficient of rigidity in *D. regia* showed that the wood follow a particular pattern as it decreased from the base with a pooled mean of 16.60±2.05% to 16.38±2.317% at the top along the axial position and similarly, increased from 15.56±1.18% at the corewood to 17.02±2.85% at the middlewood and decreased to 16.89±2.19% at the outerwood across the radial position (Table 7). TN2 had the highest coefficient of rigidity of 17.18±2.19% and the least with 15.92±2.25% at TN3 (Table 5). Coefficient of rigidity expresses the fraction of the cell-wall thickness in the fibre diameter. It is a major index that governs flexibility and coarseness of the fibre. The coefficient of rigidity (16.95%) found in this study is lower than 18.84% in *Ficus exasperata* reported by Anguruwa [16], 22.73 and 22.25% in *Gliricidia sepium* and *Senna semia* respectively by Riki [35]. *D. regia* will more suitable as a raw material for pulp and paper making because fibres with low rigidity coefficient give higher degree of conformability within the sheet, which result in sheet of lower bulk or higher density [36]. The implication of this is that paper from such fibres will have physical strength properties with high brightness and low porosity and could be said to be appropriate for printing, writing, packing and wrapping purposes.

Table 6: Anova results of Derived Morphological Indices of the selected species

Sources of Variation	DF	RR (%)	CR (%)	SR (%)	FR (%)	FF	SF
Species (S)	2	0.091^{ns}	0.041*	0.001*	0.099^{ns}	2.876^{ns}	0.205^{ns}
Sampling Height (SH)	2	0. 043*	0.903^{ns}	0.001*	0.304^{ns}	0.678^{ns}	0.172^{ns}
Radial Position (RP)	2	0. 022*	0.007*	0.001*	0.315^{ns}	11.36^{ns}	0.459^{ns}
S*SH	4	0.084^{ns}	0.026*	0.001*	0.916^{ns}	0.888^{ns}	0. 153^{ns}
S*RP	4	0.823^{ns}	0.690^{ns}	0.001*	0.468^{ns}	3.702^{ns}	0. 629^{ns}
SH*RP	4	0. 102^{ns}	0.113^{ns}	0.001*	0.033*	1.127^{ns}	0.702^{ns}
S*SH*RP	8	0.717^{ns}	0.186^{ns}	0.001*	0.255^{ns}	1.522^{ns}	0.772^{ns}
Error	54						
Total	80						

*p-values > 0.05 are not significant. S= Slenderness, FR = Flexibility ratio, RR= Runkel ratio, CR= Coefficient of rigidity, FF= F-Factor, SF= Solid factor

Table 7: Effect of Variation in Tree species, Sampling Heights and Radial position on the Derived Morphological Indices of the selected species

Sources	RR (%)	CR (%)	SR (%)	FR (%)	FF	SF
Sampling Height						
Base	0.53 ± 0.10^{ab}	16.60 ± 2.05^{a}	36.82 ± 5.23^{a}	68.16 ± 3.15^{a}	241.86 ± 41.31^{a}	$1140939.13 \pm179127.09^{a}$
Middle	0.61 ± 0.25^{a}	16.49 ± 1.91^{a}	36.53 ± 6.77^{a}	67.78 ± 2.64^{a}	236.27 ± 43.42^{a}	$2008101.84\pm 3522770.07^{a}$
Top	0.51 ± 0.81^{b}	16.38 ± 2.31^{a}	34.73 ± 5.95^{b}	69.42 ± 6.15^{a}	230.87 ± 42.85^{a}	$1022184.56\pm 205834.15^{a}$
Radial Position						
Corewood	0.48 ± 0.06^{a}	15.56 ± 1.18^{a}	31.30 ± 4.06^{a}	69.42 ± 6.15^{a}	210.87 ± 27.69^{a}	$1040813.68\pm 106563.65^{a}$
Middlewood	0.57 ± 0.2^{b}	17.02 ± 2.37^{b}	36.75 ± 4.67^{b}	68.64 ± 5.98^{a}	244.68 ± 44.41^{a}	$1380337.09\pm 1650454.66^{a}$
Outerwood	0.59 ± 0.18^{c}	16.89 ± 2.19^{b}	40.04 ± 5.70^{c}	67.53 ± 3.56^{a}	253.45 ± 41.25^{a}	$1750074.74\pm 3176366.07^{a}$
Pooled Mean	**0.55±0.17**	**16.95±2.07**	**36.03±6.01**	**68.45±4.28**	**236.33±42.24**	**1390408.51± 2062269.39**

S= Slenderness ratio, FR = Flexibility ratio, RR= Runkel ratio, CR= Coefficient of rigidity, FF= F-Factor, SF= Solid factor.*Means± Standard error of mean of 3 replicate samples. Values with the same alphabet in each column are not significantly different at α = 0.05

5.3 Slenderness Ratio (%)

The pooled mean values in Table 7 showed specific pattern of variation in slenderness ratio along the sampling height as it decreased from 36.82±5.23% at the base to 34.73±5.95% at the top and increased from the corewood (31.30±4.06%) to the outerwood (40.04±5.70%) radially. On average, slenderness ratio was 36.03%. TN2 (38.19±6.69) recorded the highest value of slenderness ratio and the least was found in TN3 (32.44±4.11) in Table 8. Analysis of variance shows that sampling height, radial position and sampled trees significantly influenced slenderness ratio ($P < 0.05$) in Table 6. Slenderness ratio, a measure of tearing property of pulp in paper making is determined from fibre length and fibre diameter [18]. Slenderness ratio is also referred to as felting power is a measure of tear properties of pulp in paper production. The trend in radial plane agrees with the work of Noah and his colleagues [19] and Ogunleye and his colleagues [18] in other hardwood but contrary along the longitudinal plane. *Delonix regia* had a lower value of 36.03% which is less than 55.06% for *Aningeria robusta* [17], 47.0 in *Gerdenia ternifolia* [19] and 42 obtained in *Leucaena leucocephala* [12]. The value is higher than 35.85% *Ricinodedron Heudelotii.* Nevertheless, low slenderness ratio means production of weak paper. Slenderness ratio is produced by shorter and thicker fibres which in turn reduced tearing resistance drastically.

5.4 Flexibility Ratio (%)

As shown in Table 7, the mean of flexibility ratio show no trend of variation along the longitudinal plane as it increased from 68.16±3.15% at the base to 69.42±6.15% at the top with a slight decreased in the middle. On the other hand, radial plane show a particular pattern as it increased from the corewood (69.42±6.15%) to the outerwood (67.53±3.56%). 69.80±6.06% was recorded in TN3 as the highest and 67.49±2.91% in TN2 as the least. However, average flexibility ratio was 68.45% (Table 8). The ANOVA presented in Table 6 showed that flexibility ratio was not significantly influenced by sampled trees, sampling height and radial plane. Flexibility ratio is the ratio of lumen diameter to fibre diameter. It is one of the important factors which determine the suitability of pulp for paper making. Amidon [37] described flexibility as the key to the development of burst and tensile strength as well as the development of the paper properties that affects printing and determines the degree of fibre bonding in paper sheet. The fibre having flexibility ratio of 68.45%/0.68 fall between 0.50-0.75 as considered elastic fibres [38-40]. The value is higher than 0.53 and 0.50 for *Rhizophora racemosa* and *Rhizophora harrisonii* accordingly [29] and within the range of 0.63- 0.79 for some Nigerian Ficus species [41, 14], it is also, higher than the 0.24, 0.16 and 0.12 reported by Ezeibekwe and his colleagues [42]. So, the mean flexibility ratio (68.45) of *D. regia* qualified it to be a good source of raw material for pulp and paper as it compared very well with some reported species for pulp manufacturing.

Table 8: Mean Slenderness and Flexibility ratio along the Sampling Height and Radial Position of the selected species

Derived Morphological	**Tree**	**Wood Type**	**Base**	**Middle**	**Top**	**Pooled Mean**
Slenderness ratio (%)						
	TN1	Corewood	35.54±0.97	29.10±0.99	29.16±2.43	31.27±3.50
		Middlewood	41.35±3.20	40.64±0.62	37.16±1.34	39.72±2.62
		Outerwood	38.04±0.15	43.92±3.07	42.20±1.23	41.39±3.10
		Mean	**38.31±3.03**	**37.89±6.94**	**36.17±5.90**	**37.46±5.4[a]**
	TN2	Corewood	33.25±2.70	38.55±2.14	29.16±2.33	33.66±4.58
		Middlewood	36.71±3.60	42.82±4.76	29.99±2.40	36.51±6.42
		Outerwood	47.33±4.69	42.79±2.14	43.12±2.66	44.42±3.64
		Mean	**39.10±7.13**	**41.39±3.53**	**34.09±7.11**	**38.19±6.69[b]**
	TN3	Corewood	32.16±1.98	26.69±2.03	28.18±0.51	28.99±2.85
		Middlewood	31.87±0.65	35.30±0.19	34.86±2.60	34.01±2.11
		Outerwood	35.17±1.87	28.96±0.89	38.80±3.25	34.31±4.72
		Mean	**33.06±2.11**	**30.32±4.02**	**33.92±5.13**	**32.44±4.11[b]**
Flexibility ratio (%)						
	TN1	Corewood	64.55±0.57	70.96±1.56	72.63±0.86	69.38±3.81
		Middlewood	68.60±0.44	66.41±1.80	69.12±2.59	68.04±2.02
		Outerwood	67.80±2.07	66.98±1.89	65.52±1.78	66.77±1.94
		Mean	**66.98±2.16**	**68.11±2.63**	**69.09±3.48**	**68.06±2.84[a]**
	TN2	Corewood	67.88±1.52	67.70±1.43	70.45±0.99	68.68±1.76
		Middlewood	65.06±3.19	66.16±2.10	67.95±1.07	66.39±2.35
		Outerwood	69.94±6.52	65.55±1.84	66.72±1.43	67.41±3.98
		Mean	**67.63±4.27**	**66.47±1.84**	**68.37±1.94**	**67.49±2.91[a]**
	TN3	Corewood	69.37±2.82	70.12±1.01	69.06±0.07	69.51±1.60
		Middlewood	70.77±2.72	66.21±2.52	77.44±16.03	71.47±9.57
		Outerwood	69.43±0.20	69.98±3.90	65.88±7.07	68.43±4.47
		Mean	**60.97±13.44**	**68.77±3.06**	**70.79±10.18**	**69.80±6.06[a]**

*Means± Standard error of mean of 3 replicate samples. TN 1, 2 and 3 = Tree number 1, 2 and 3.

Values with the same alphabet in each column are not significantly different at α = 0.05

5.5 F-Factor

The average F-factor in the sampled trees is 236.33±42.24. There is a regular pattern of variation along the longitudinal plane as it decreased from 241.86±41.31 at the base to 230.87 ±42.85 at the top and increased from 210.87±27.69 at the corewood to 253.45±41.25 at the outerwood (Table 7). Among sampled tree, TN1 and TN3 had 244.48±26.58 and 223.42 for the highest and the least ±42.03 respectively (Table 9). Analysis of variance carried out at 5% level of significance shows no any mark effect between axial and radial planes among the sampled trees (Table 6). Similar trends both along and across the sampled trees have been reported by Riki [35] in *Gliricidia sepium and Senna seamia*. The F-factor (236.33) of this study fall within values recorded for other hardwood species such as 240.6, 140.40, 235.9 and 206.8 for *Pine nigra*, *Fagus orienntalis*, *Populus euramericana* and *Populus tremula* respectively according to Akgul and Tozluogu [43]. The F-factor obtained indicates that flexibility of papers from *D. regia* can be recommended for paper making.

5.6 Solid Factor

Table 9: Mean F-Factor and Solid Factor along the Sampling Height and Radial Position of the selected species

Derived Morphological	**Species**	**Wood Type**	**Base**	**Middle**	**Top**	**Pooled Mean**
F-Factor						
	TN1	Core	210.71±14.68	208.53±15.92	237.67±21.93	218.97±20.86
		Middle	267.19±7.60	253.83±16.27	248.88±28.38	256.64±18.69
		Outer	245.18±19.34	277.79±3.62	250.61±18.41	257.82±20.33
		Mean	**241.03±27.83**	**246.68±32.52**	**245.72±21.05**	**244.48±26.58[a]**
	TN2	Core	225.70±29.56	208.80±61.63	202.61±10.18	212.37±36.07
		Middle	215.47±19.02	268.15±61.87	198.54±12.38	227.39±45.55
		Outer	316.93±76.06	262.96±19.94	267.73±20.38	283.54±48.98
		Mean	**253.70±65.13**	**246.64±53.08**	**222.96±36.04**	**241.10±52.45[a]**
	TN3	Core	225.12±18.28	185.42±24.48	193.26±6.58	201.27±23.99
		Middle	228.76±19.28	249.28±46.05	271.97±99.63	250.01±58.78
		Outer	238.62±9.22	211.76±16.77	206.56±10.60	218.98±18.48
		Mean	**230.84±15.31**	**215.49±39.02**	**223.93±62.06**	**223.42±42.03[a]**
Solid Factor						
	TN1	Core	885162.27 ±58743.12	1109458.47 ±38858.40	1123758.15 ±93925.92	1114506.04 ±59109.95
		Middle	1248462.4 ±36229.25	1019990.46 ±154118574.50	1248885.00 ±38300.62	1110655.40 ±123717.64
		Outer	1024741.7± 58061.19	1326024.90 ±123896.32	1207689.96 ±154536.98	1186152.21 ±167126.78
		Mean	**1066044.7 ±58404.62**	**1151824.61 ±162173.90**	**1193444.30 ±107668.26**	**1137104.55 ±125022.23[a]**
	TN2	Core	885162.28 ±98377.59	1095825.15 ±40581.89	950849.60 ±19085.01	977279.01 ±107871.54
		Middle	1248462.48 ±93614.10	1185943.01 ±226303.54	996046.44 ±61434.39	1143483.98 ±169994.64
		Outer	1218789.69± 133802.65	924256.96± 169502.73	1004468.95 ±65583.70	1049171.87 ±173561.22
		Mean	**1117471.48 ±199017.77**	**1068675.04 ±183445.90**	**983788.33 ±52282.90**	**1056644.95 ±162944.76[a]**
	TN3	Core	1085874.17 ±109320.18	1013777.09 ±152723.98	992316.76 ±39452.01	1030656.00 ±104925.85
		Middle	1139843.38 ±83820.31	3774405.94 ±5014015.23	746366.40 ±470222.81	1886871.91 ±2893996.71
		Outer	1492185.91 ±93489.18	6623234.58 ±9515386.95	929279.96 ±61587.85	3014900.15 ±5479232.24

	Mean	**1239301.15 ±208440.97**	**3803805.87 ±5901434.51**	**889321.04 ±262402.51**	**1977476.02 ±3536045.34[a]**

*Means± Standard error of mean of 3 replicate samples. TN 1, 2 and 3 = Tree number 1, 2 and 3. Values with the same alphabet in each column are not significantly different at α = 0.05

The LSD at 5% level of probability shows that there is no significant variation along the longitudinal plane, across the radial position and the sampled trees ($p<0.05$) as presented in Table 6. There was an inconsistent trends along the sampling height as increased from 1140939.13±179127.09 at the base to 2008101.84±3522770.07 at the middle and later decreased to 1022184.56±205834.15 at the top while uniform pattern of variation was observed across the plane as the increased from the corewood (1040813.68±106563.65) to outerwood (1750074.74±3176366.07) in Table 7. The highest solid factor was found TN3 (1977476.02) and the least in TN2 (1056644.95) in Table 9. The average solid factor *D. regia* wood (1390408.51) recorded in this study is lower than 2655651.12 in Senna seamia [35] and much higher than 14.2×10^{-3} reported in *Ricinodendron heudelotii* by Ogunyele and his colleagues [18] which could be due to age and environmental factors. Similar pattern across the radial direction was reported in *Glicidia sepium* [35]. Solids factor was found to be related to paper sheet density and could be significantly correlated to breaking length of paper [44].

6. Conclusion and Recommendations

Based on the results of this study, *Delonix regia* a lesser used species (LUS) can be said to be an alternative source of wood for pulp and paper making. It compared favourably with *Gmelina arborea, Pinus caribaea, and Tectona grandis* which are known to be the prime source of pulpwood in Nigeria. The basic information on the its appreciable fiber characteristics for a typical hardwood specie, coupled with a good runkel ratio of less than 1 and high flexibility ratio, *D. regia* is satisfactorily pulpable and can therefore be used in pulp and paper production. Blending of its pulp with fibrous stock from other wood species like *Gmelina* and *Pinus caribaea* is recommended in a bid to enhance the desired finished paper properties. Plantation establishment of *D. regia* should also be encouraged.

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