FIBRE SOURCING FOR THE NIGERIAN PULP MILLS: EVALUATION OF SUITABILITY INDICES OF SELECTED NIGERIAN RAINFOREST WOOD FIBRES

Nusirat A. Sadiku[1*] and Christiana M. Micheal[2]

[1]Department of Forest Resources Management, Faculty of Agriculture, University of Ilorin, P.M.B 1515. Ilorin, Kwara State, Ilorin, Kwara, Nigeria
[2]Department of Forest Products Production and Utilization, Faculty of Forest Resources Management, University of Ibadan, Oduduwa Road, 200132, Ibadan, Nigeria

Received: 2 November 2020, Revised: 1 June 2022, Accepted: 26 September 2022

FIBRE SOURCING FOR THE NIGERIAN PULP MILLS: EVALUATION OF SUITABILITY INDICES OF SELECTED NIGERIAN RAINFOREST WOOD FIBRES. To find a lasting solution to the problem of suitable fibre for pulp and papermaking in Nigeria, fibre suitability indices of nineteen wood species native to the rainforest zone of Nigeria were evaluated. Matured stems of the species were sourced and prepared for maceration. The fibre characteristics of the wood were carried out following ASTM D-1030-95 and ASTM D-1413-61. The fibres obtained were observed with the aid of a microscope and measurements of their morphology were done. A minimum of 25 fibres were measured for each species for accuracy. Selected morphological indices such as Runkel Ratio (RR), Flexibility Coefficient (FC), Slenderness Ratio (SR) as well as Rigidity Coefficient (RC) of the wood fibres were estimated. The results showed that the fibres lenght fall under short (1.05–1.36), medium-long (1.52–1.75), and long (2.0 mm) fibres criteria. All derived morphological indices showed significant variations from species to species. All fibres are not rigid and exhibited good SR with moderate rigidity and good felting power. They were all elastic; *R. heudolotii* and *P. macrocarpa* exhibited high elastic nature. They all have FC ≥ 50 and pass the RR ≤ 1, acceptable value for paper-making fibre except *P. biglobosa* and *M. excelsa*. The flexibility coefficients are in the range of 0.50 and 0.81. All the species pass the SR > 33 acceptable value for paper-making fibres. The species if harnessed as fibre blends in pulp and paper making furnish will help to solve the problem of inadequate long fibres for paper production in Nigerian pulp mills.

Keywords: Fibre length, fibre diameter, cell wall thickness, Runkel ratio, elastic fibre

KESESUAIAN SUMBER SERAT PABRIK PULP DI NIGERIA: EVALUASI INDEKS KESESUAIAN SERAT KAYU TERPILIH DARI HUTAN HUJAN NIGERIA. Dalam upaya menemukan solusi jangka panjang serat yang sesuai untuk pembuatan pulp dan kertas di Nigeria, dilakukan evaluasi indeks kesesuaian serat dari sembilan belas spesies kayu asli zona hutan hujan Nigeria. Bahan untuk maserasi disiapkan dan diambil dari batang matang tiap spesies terpilih. Karakteristik serat kayu dilakukan mengikuti ASTM D-1030-95 dan ASTM D-1413-61. Serat yang diperoleh diamati dengan bantuan mikroskop dan dilakukan pengukuran morfologi seratnya. Minimal 25 serat diukur untuk setiap spesies untuk akurasi. Indeks morfologi serat kayu yang diperkirakan yaitu Runkel Ratio (RR), Flexibility Coefficient (FC), Slenderness Ratio (SR) dan Rigidity Coefficient (RC). Hasil penelitian menunjukkan bahwa serat kayu yang dipelajari termasuk dalam kriteria serat pendek (1,05–1,36), sedang (1,52–1,75), dan panjang (2,0 mm). Semua indeks morfologi yang diturunkan menunjukkan variasi yang signifikan dari spesies ke spesies. Semua serat tidak kaku dan menunjukkan rasio kelangsiungan (SR) yang baik dengan kekakuan sedang dan kekuatan kempa yang baik. Semua serat kayu termasuk elastis; R. heudolotii dan P. macrocarpa menunjukkan sifat elastis yang tinggi. Semua memiliki koefisien fleksibilitas (FC) ≥ 50 dan Rungkel Ratio(RR) ≤ 1, nilai yang dapat diterima untuk serat pembuatan kertas kecuali P. biglobosa dan M. excelsa. Flexibility Coefficient (FC) berada pada kisaran 0,50 dan 0,81. Semua spesies melewati SR> 33, nilai yang dapat diterima untuk serat pembuatan kertas. Spesies-spesies tersebut jika dimanfaatkan sebagai campuran serat dalam pembuatan pulp dan kertas akan membantu memecahkan masalah serat panjang yang tidak memadai untuk produksi kertas di pabrik pulp Nigeria.

Kata kunci: Panjang serat, diameter serat, ketebalan dinding sel, runkel ratio, serat elastis

[*] Corresponding author: tundesalih@yahoo.com

 doi:10.20886/ijfr.2022.9.2.135-146

I. INTRODUCTION

Nigeria is one of the largest wood producers in Africa and a major exporter of timber resources (Obiora, Jonah, Ikenna, & Christian, 2019; FAO, 2004). The nation's forest industry, especially the paper sub-sector seems to be the worst-performing among all the industries (Nigerian Voice, 2010). The federal government established three paper mills in the 1970s which include; Nigerian Paper Mill in Jebba, Nigerian Newsprint Manufacturing Company, Oku Iboku, and Iwopin Pulp and Paper Company. According to reports, all three mills started well but could not sustain operation and eventually closed down in 1996 (Azeez, Andrew & Sithole, 2016; Udohitinah & Oluwadare, 2011). The cause of the failed investments has been attributed majorly to the inadequate supply of long-fibre for pulp and paper production (Oluwadare, 2007) due to the absence of long fibred raw materials in Nigerian forests. This then necessitated heavy dependence on imported pulp fibres. Although several species have been suggested to be used as a feasible solution to address the inadequate long fibre problem the suggestions were never implemented until all the mills finally closed down. Efforts to develop a sustainable pulp and paper industry have proved abortive because of the high dependence on imported long-fibre pulp (Ogunwusi, 2013). As far back as the 1980's, approximately US $ 85 million was required to import 85,000 tons of long fibre pulp required by the three integrated pulp and paper mills in Nigeria (Makinde, 2004; Egbewole, & Rotowa, 2017). Thus, Nigeria currently depends on the importation of writing, duplicating, printing, and kraft papers including newsprint (Ogunwusi & Onwualu, 2013).

Nigerian forests are characterised by mixed tropical hardwood species whose fibre lengths are short. The morphology of the fibres is important index in evaluating the suitability of fibre for pulp and paper-making Dinwoodie (1965). A number of hardwood species have been studied by various researchers (Ogunwusi, 2002; Osadare, 2001; Ogunkunle & Oladele, 2008; Oluwadare, & Sotannde, 2007; Ogunjobi, Adetogun, & Omole, 2014) were reported to be suitable sources of fibre for paper making. Although the suitability rating by these authors was based only on the fibre lengths of the species. It is not that hardwoods are typically bad for paper production. Papers from hardwood pulps are generally lower in strength because of their shorter fibres than those of softwoods with longer fibres.

Long softwood fibres give essential strength, while short hardwood fibres are used in furnishes to provide good printability and stiffness to the end product. Analysis of the morphology of fibres and their derived indices are important factors in estimating the pulp quality of any fibre material (Dinwoodie, 1965). The morphology of the fibre and its derived indices correlates with most of the strength properties of pulp. Repetition A fibre with thinner cell walls will collapse more easily than a fibre with thicker cell walls. Collapsed fibres are more flexible and have a higher area available for bonding. Collapsed fibres create a network with much higher density and lower bulk. Thus, the paper will have a higher tensile strength, compression strength, burst strength, tensile stiffness, and elasticity. The flexibility of the fibres has a large influence on the tensile strength, density, porosity and light scattering of the paper. Fibre cell lumen size and cell wall thickness affect the rigidity and strength properties of the papers (Panshin & de Zeeuw 1980). Fibres with a large lumen and thin walls tend to flatten to ribbons during paper-making with enhanced inter-fibre bonding between fibres, consequently having good strength characteristics (Oluwadare, 1998; Osadare, 2001).

Suitable indices such as cell wall thickness, Runkel ratio, flexibility coefficient, slenderness ratio, and rigidity coefficient which determine the suitability of any fibrous material for pulp and paper making have not been well documented for the wood species under study. Most Nigerian woods are lacking in this aspect. To effectively use these species as raw materials in pulp and paper-making furnish, reliable knowledge of their suitability based on the derived indices is essential. In this study, the morphological indices of 18 hardwood species were analysed to determine if they could serve as fibre blended with long softwood fibre or recycled paper pulps. This intends as to increase the raw material base for the moribund Nigerian paper mills, whose major problem is inadequate fibre raw material.

II. MATERIALS AND METHOD

A. Wood Collection and Preparation

Eighteen different wood species were collected from sawmills in Akure, Ondo State. Akure falls within the rainforest zone of Nigeria. The wood Samples were first identified by the saw millers. The literature further substantiated the local identification to obtain their corresponding scientific names. A list of the species used in the study with their local names is provided in Table 1. All of the wood samples were taken from mature wood. Special care was taken to ensure that species were accurately identified using macroscopic and microscopic anatomical features such as colour, density, and press.

B. Methods

Fibre characterisation of the wood species

Fibre characterisation of the wood samples was carried out following ASTM D-1037-12 (2020) and ASTM D-1413-61 (2007). Small slivers having radial and tangential dimensions of 2 and 5 mm, respectively, from each of the wood species were macerated with acetic acid and hydrogen peroxide (1:1) and boiled in a water bath at a temperature of 100°C for 10 minutes following a procedure adopted by Ogbonnaya, Roy-Macauley, Nwalozie & Annerose (1997). Some macerated fibres were randomly selected and mounted on slides and then observed under a Reichert Microscope. The fibre length, fibre diameter and lumen width of unbroken fibres were measured using an eyepiece micrometer after calibrating with a stage micrometer. Some derived values such as the cell wall thickness, Slenderness Ratio, Flexibility coefficient, Runkle ratio, and Rigidity coefficient were computed from the measured fibre dimensions following the method of Sadiku, Oluyege, and Ajayi (2016) as shown below. Twenty-five fibres were measured from each representative sample slides.

Table 1: Wood species: Scientific names, family and local names

No.	Wood Species	Family	Local Names
1	*Parkia biglobosa* (Jacq.) R.Br. ex G. Don	Mimosaceae	Igba
2	*Milicia excelsa* (Welw.) C.C.Berg	Moraceae	Iroko
3	*Nauclea diderrichi* (De Wild. & T. Durand) Merr.	Rubiaceae	Opepe; MTN
4	*Azadiracta indica A. Juss.*	Meliaceae	Neem, Dongorayo
5	*Daniellia oliveri* (Rolfe) Hutch. & Dalziel	Fabaceae	Ogea, Iya
6	*Terminalia superba* Engl. & Diels	Combretaceae	White Afara, Limba, fraké
7	*Vitex doniana* Sweet	Verbenaceae	Black plum, Orii
8	*Chrysophyllum albidium* G.Don_Holl	Sapotaceae	Osandan
9	*Hevea brasiliensis* (Willd. ex A. Juss.) Müll. Arg.	Euphorbiaceae	Rubber tree, natural rubber, Pará rubber
10	*Ricinodendron heudelotii (Baill.) Pierre ex Heckel*	Euphorbiaceae	African oil-nut tree; Arumodo
11	*Irvingia gabonensis Baill. ex Lanen*	Irvingiaceae	Bush mango, Oro
12	*Blighia sapida K.D. Koenig*	Sapindacea	Isin
13	*Pterygota macrocarpa* K. Schum.	Sterculiaceae	Oporoporo
14	*Alstonia boonei* De Wild	Apocynaceae	Ahun, cheesewood
15	*Treculia africana* Decne	Moraceae	Breadfruit, Efo
16	*Albizia zygia (DC.) Macb*	Fabaceae	Ayunre
17	*Trichilia monaldepha* (Thonn.) J.J. de Wilde	Meliaceae	Trichilia; Ako rere; Rere
18	*Pycnanthus angolensis* (Welw.) Warb	Myristicaceae	African nutmeg; Akomu, Ilomba

C. Analysis

Variations in the fibre morphology and derived values were evaluated by analysis of variance at p ≤ 0.05. Duncan Multiple Range Test was used to compare mean values for the different species. The evaluated fibre morphology and derived values were then ranked based on the suitability of each species.

$$Cell\ Wall\ Thickness = \left(\frac{Fibre\ Diameter\ - Lumen\ Width}{2}\right) \quad \text{.........(1)}$$

$$Slenderness\ Ratio = \left(\frac{Fibre\ Lenght}{Fibre\ Diameter}\right) \quad \text{.........(2)}$$

$$Flexibility\ Coefficient\ = \left(\frac{Lumen\ Diameter}{Fibre\ Diameter}\right) \quad \text{.........(3)}$$

$$Runkel\ Ratio\ = 2x\left(\frac{Cell\ Wall\ Thickness}{Lumen\ Diameter}\right) \quad \text{.........(4)}$$

$$Rigidity\ Coefficient = 2x\left(\frac{Cell\ Wall\ Thickness}{Fibre\ Diameter}\right) \quad \text{.........(5)}$$

$$F\ factor = 100\ x\ \frac{Fibre\ Lenght}{Cell\ Wall\ Thickness} \quad \text{.........(6)}$$

III. RESULT AND DISCUSSION

A. Fibre Morphology

The mean values of the Fibre Length (FL), Fibre Diameter (FD), Lumen Width (LW) and Cell Wall Thickness (CWT) is presented in Table 2. The fibre length, diameter, lumen width and Cell Wall Thickness varied significantly from species to species. The fibre length varied from 1.05 mm to 2.48 mm. *N. diderichii* had the longest fibre of 2.48 mm followed closely by *R. heudollotii* (1.7 mm), while *A. indica* had the shortest fibre length (0.8 mm) and was closely followed by *P. macrocarpa* (1.05 mm). The fibre diameter varied from 15.22 µm to 51.68 µm. *R. heudolotii* had the largest (51.68 µm) fibre diameter, while *M. excelsa* had the smallest (15.22 µm) (Table 2). The wood species lumen width (LW) varied from 8.89 µm to 43.82 µm. *R. heudolotii* had the largest lumen width of 43.82 µm, while the smallest (8.89 µm) was recorded for *M. excelsa*. Cell wall thickness also varied from 2.61 µm to 6.92 µm. *P. macrocarpa* had the thinnest (2.61µm) fibre cell wall while *N. diderichii* had the thickest fibre wall of 6.48 µm based on the Duncan multiple range test (Table 3).

Generally, the influence of species was profound on the fibre properties of the wood species according to ANOVA result (Table 2). There were significant statistical variations in the fibre morphologies of the wood species (Table 2). However, the fibre length of *M. excelsa*, *A. boonei*, *T. africana* and *A. zygia* are statistically similar. *T. monaldeph* and *T. superba*; *P. angolensis* and *C. albidium* had similar fibre lengths, respectively (Table 3). The fibre diameters were statistically similar for *B. sapida*, *C. albidium*, *H. brasiliensis*, *A. indica* and *P. biglobosa*; *P. macrocarpa* and *I. gabonensis*; *A. zygia,* and *A. boonei* are statistically similar in their fibre lengths (Table 3). Lumen width were statistically similar for *P. macrocarpa*, *T. africana* and *T. monaldeph*; *P. biglobosa* and *M. excelsa*; *D. oliveri*, *A. indica*, *C. albidium* and *H. brasiliensis*; *A. zygia*, *T. superba* and *A. boonei* were statistically similar (Table 3). Cell wall thickness too were similar for *C. albidium*, *H. brasiliensis*, *A. indica* and *P. angolensis*;

Table 2. Analysis of variance for the fibre morphology and derived morphological indices

Source of variation	Property	SS	df	MS	P-values
Species	FL (mm)	20.455	19	1.077	21.600 **
	FD (µm)	13936.343	19	733.492	20.590 **
	LW (µm)	129911.823	19	683.780	20.761 **
	CWT (µm)	203.408	19	10.706	6.214 **
	SR	0.222	19	0.012	6.806 **
	FC	1.636	19	0.086	9.793 **
	RR	11.775	19	0.620	4.661 **
	RC	2.693	19	0.142	9.972 **

Note: * = Significant at (p≤ 0.05) probability level

P. biglobosa and *T. monaldeph*; *M. excelsa* and *T. africana*; *I. gabonensis* and *T. superba*; *A. boonei* and *A. zygia* were statistically similar in their cell wall thickness (Table 3).

The wood fibres in this study fall into short (1.05–1.36), medium-long (1.52–1.75), and long (2.0 mm) fibres (Table 3). This finding further substantiates the report of Illvessalo-Pfaffli (1995) that fibre length and width of both woody and non-woody plants vary depending on the species and the plant part from which the fibre is derived. Hurther (2001) also reported that the average length of fibres in hardwoods is about 1 mm and in coniferous wood is about 3 mm. Similar observations by Kpikpi (1992) and Uju and Ugowoke (1997) reported of less than 1.60 mm fibre lengths in some Nigerian hardwood species. All the fibre length of the species falls in the same range as those reported for Guinea savannah species except *N. diderrichi* which had 2.48 mm (Sadiku & Abdukareem, 2019). *R. heudolotii* had a larger fibre diameter, *T. monaldepha*, *R. heudolotii*, *P. angolensis*, *T. africana*, *P. macrocarpa,* and *V. doniana* had extremely wider lumen than the reported Guinea savannah woods. However, their cell wall thickness falls in the same range.

The fibre morphological properties are important quality parameters for pulp and paper properties. They are mostly correlated with the physical and mechanical properties of paper. Fibre length is one of the major factors controlling the strength properties of paper (Riki et al., 2019). The fibre length affects the tensile strength, breaking strain and fracture toughness of dry paper and is important for wet web strength (Retulainen et al., 1998). Also, fibre length has been discovered to influence paper sheet formation and its uniformity.

Fibre length is associated with a number of bonding sites available on an individual fibre. It also affects certain characteristics of pulp and paper, such as tear resistance, tensile power and folding power (Fatriani and Banjarbaru, 2017).Generally, both long and short fibres are needed for good papers. Most of the fibres of the species in this study are short except for *N. diderichii* having long fibres. A long fibred

Table 3. Effect of species on the fibre morphological characteristics of the wood species

No.	Wood species	FL (mm)	FD (µm)	LW (µm)	CWT (µm)
1.	*M. excels*	1.34[cde]	15.22[a]	8.89[a]	3.81[b]
2.	*D. oliveri*	1.64[gh]	24.13[bcd]	13.34[abc]	5.40[cdefg]
3.	*N. diderichii*	2.48[i]	30.48[efg]	17.53[cf]	6.48[h]
4.	*A. boonei*	1.35[cde]	22.48[bc]	14.35[abcd]	4.07[bc]
5.	*B. sapida*	1.21[bcd]	19.55[ab]	11.05[ab]	4.26[bcd]
6.	*V. doniana*	1.41[def]	31.88[g]	20.32[ef]	5.78[efgh]
7.	*C. albidium*	1.10[b]	21.21[ab]	12.19[abc]	4.51[bcde]
8.	*H. brasiliensis*	1.14[bc]	21.21[ab]	12.19[abc]	4.51[bcde]
9.	P. macrocarpa	1.58[fgh]	28.19[cdefg]	22.99[f]	2.61[a]
10.	*A. indica*	0.84[a]	21.21[ab]	12.19[abc]	4.51[bcde]
11.	*T. africana*	1.33[cde]	31 21[fg]	23.24[f]	3.90[b]
12.	*I. gabonensis*	1.60[fjh]	28.07[cdefg]	16.89[bcde]	5.59[defg]
13.	*P. angolensis*	1.05[b]	29.08[defg]	20.06[def]	4.64[bcde]
14.	*R. heudolotii*	1.71[h]	51.68[i]	43.82[h]	3.94[b]
15.	*A. zygia*	1.35[cde]	22.48[bc]	14.36[abcd]	4.07[bc]
16.	*P. biglobosa*	1.38[def]	20.57[ab]	10.41[a]	5.08[bcdef]
17.	*T. monaldeph*	1.47[efg]	32.64[g]	23.11[f]	4.77[bcdef]
18.	*T. superba*	1.47[efg]	25.53[bcdef]	14.48[abcd]	5.53[defg]

Note: Means with the same letter vertically are not significantly different at ($p \leq 0.05$)

material can have more fibre joints and create a stronger network than a shorter fibre (Riki et al., 2019). Although shorter fibres decrease tensile stiffness. However, the shortening of fibres will improve the formation if well beaten. Therefore, the beating of the wood species in this study will increase the fibres surface and flexibility, which will aid good paper formation.

B. Derived Fibre Morphological Indices of the Wood Species

Some indices are usually calculated to determine the suitability of any fibrous material for pulp and paper production. According to Veveris et al. (2004), the Slenderness Ratio also termed Felting Power, if less than 70 for any fibrous material is not valuable for quality pulp and paper production. Low slenderness ratio means reduced tear strength. Fibre flexibility dictates the burst and tensile strength as well as the development of the paper properties that affects printing. High elastic fibres with high flexibility can collapse easily and flatten to produce good surface area contact while elastic fibres collapsed partially to give relative contact and fibre bonding (Riki et al., 2019).

Good quality papers are produced when the Runkel Ratio is less than one. Fibres with higher Runkel Ratio are stiffer, less flexible and form bulkier paper of low bonded areas than fibres with lower Runkel Ratio (Veveris et al., 2004). The higher the Coefficient of Rigidity the lower the tensile power of the paper, conversely the lower the coefficient of rigidity the higher the tensile power of paper. The mean values of the Slenderness Ratio (SR), Flexibility Coefficient (FC), Runkel Ratio (RR) and Rigidity Coefficient (RC) are presented in Table 4. ANOVA result (Table 2) showed that there were significant variations in all the derived values among the 18 wood species (Table 4).

Generally, the most slender fibre is *R. heudolotii* while the most flexible fibre is that of *P. macrocarpa* judging from the FC value of 0.81 (Table 4). *M. excelsa* had the highest RR of 1.5 while *R. heudolotii* had the lowest RR of 0.1. However, some of the wood species showed similarities in their derived values. Generally, the most suitable wood for pulp and paper production based on Runkel Ratio is *R. heudolotii* due to the lowest RR value of 0.1 (Table 4). *R.*

Table 4. Effect of species on the derived morphological indices of the wood species

No.	Wood species	SR	FC	RR	RC	F-factor
1.	*M. excels*	0.9^{bc}	0.57^{abc}	1.51^{i}	0.51^{g}	0.35^{bc}
2.	*D. oliveri*	0.5^{d}	0.54^{ab}	0.88^{fghi}	0.46^{efg}	0.30^{b}
3.	*N. diderichii*	0.6^{d}	0.56^{abc}	0.82^{efghi}	0.44^{defg}	0.38^{bc}
4.	*A. boonei*	0.6^{abc}	0.64^{cdefg}	0.61^{bcdefg}	0.36^{bcdef}	0.33^{bc}
5.	*B. sapida*	0.7^{abc}	0.57^{abd}	0.82^{efghi}	0.43^{cdefg}	0.28^{ab}
6.	*Vitex doniana*	0.5^{ab}	0.63^{bcdef}	0.63^{cdefgh}	0.38^{bcdef}	0.24^{a}
7.	*C. albidium*	0.5^{ab}	0.58^{abcd}	0.42^{abcd}	0.70^{h}	0.24^{a}
8.	*H. brasiliensis*	0.6^{ab}	0.58^{abcd}	0.75^{cdefgh}	0.42^{cdefg}	0.25^{a}
9.	*P. macrocarpa*	0.96^{c}	0.81^{hi}	0.25^{ab}	0.19^{a}	0.61^{d}
10.	*A. indica*	0.5^{ab}	0.57^{abc}	0.79^{defghi}	0.43^{adefg}	0.19^{a}
11.	*T. africana*	0.4^{a}	0.74^{gh}	0.38^{abc}	0.26^{ab}	0.34^{bc}
12.	*I. gabonensis*	0.6^{ab}	0.60^{abcde}	0.69^{cdefgh}	0.40^{bcdefg}	0.29^{b}
13.	*P. angolensis*	0.4^{a}	0.71^{fg}	0.52^{abcdef}	0.32^{bcd}	0.23^{a}
14.	*R. heudolotii*	0.3^{a}	0.84^{i}	0.10^{a}	0.16^{a}	0.43^{c}
15.	*A. zygia*	0.6^{abc}	0.64^{cdefg}	0.61^{bcdefg}	0.36^{bcde}	0.33^{bc}
16.	*P. biglobosa*	0.7^{abc}	0.50^{a}	1.01^{hi}	0.50^{fg}	0.27^{ab}
17.	*T. monaldeph*	0.5^{ab}	0.67^{defg}	0.54^{abcdef}	0.33^{bcd}	0.31^{b}
18.	*T. superba*	0.6^{ab}	0.57^{abc}	0.81^{defghi}	0.43^{cdefg}	0.27^{ab}

Note: Means with the same letter vertically are not significantly different at ($p \leq 0.05$)

heudolotii had the least rigid fibres judging from the RC value of 0.16, while *C. albidium* was the most rigid (Table 4). The F-factor too showed significant statistical variations among the 20(? not 18?) species, with *P. macrocarpa* having the highest F-factor of 0.61 (61) while *A. indica* had the lowest of 0.19 (19). Fibre morphology, all the derived morphological indices showed significant variations from species to species.

According to Dinwoodie (1965), the basis for establishing the suitability of raw material for pulp and paper making is that the Runkel Ratio must be less than one. All the species had RR less than 1 except *M. excelsa* and *P. biglobosa*. This indicates that the two species are unsuitable for pulping considering their Runkel Ratio as they are relatively higher than the standard (Xu, Wang, Zhang, Fu & Wu, 2006) (Table 4). A higher Runkel ratio gives lower burst, tear and tensile indexes (Bektas, Tutus & Eroglu, 1999). Fibre with a high Runkel ratio value is stiff, less flexible and forms bulkier paper of low bounded area than the lower ratio fibre. Therefore, it is expected that *P. biglobosa* and *M. excelsa* produce poor paper. The RR values reported in this work are similar to other Nigeria timbers reported in previous works (Ezeibekwe, Okeke, Unamba & Ohaeri, 2009; Awaku, 1994; Ogunkunle, 2010; Oluwadare and Sotannde, 2007; Ajuziogu, Nzekwe & Chukwuma, 2010; Sadiku and Abdukareem, 2019).

The fibre flexibility (elasticity coefficient, or Istas coefficient) of the species are 0.50–0.81. Depending on the elasticity rate, fibres were grouped into four Istas followings, Heremans & Roekelboom (1954) and Bektas et al. (1999) grouping. According to this grouping, all the species are not rigid. They were all elastic with *R. heudolotii* and *P. macrocarpa* exhibiting high elastic nature. All the wood species have their flexibility/elasticity coefficient ≥ 50 and are therefore included in the elastic fibre group (Table 7). Rigid fibres do not have efficient elasticity and are not suitable for paper production except for cardboard production (Akgül and Tozluoğlu, 2009). It is expected that pulp made from all the wood species would have a greater inter-fibre bond and hence greater tensile strength, which favours those properties that affect printing (Ogunjobi et al., 2014). This range is almost similar to Brindha, Vinodhini & Alarmelumangai (2012), where 0.60 (60%) was reported as well as similar for some and higher than some Nigerian Guinea Savannah Timbers (Sadiku and Abdukareem, 2019). Considering the FC > 0.55 (55%) acceptable value for paper-making fibre (Bektas et al., 1999), all the species would be suitable. However, a flexibility ratio between 50 and 70 implies that the fibres can easily be flat and give good paper with high-strength properties (Brindha et al., 2012).

Fibre slenderness significantly influenced the pulp sheets breaking length, bursting, tearing and stretching (Ogunjobi et al., 2014). All the species had good Slenderness Ratio as they all pass the SR > 33 acceptable value for paper-making fibre according to Xu et al., (2006). However, Bektas et al. (1999) show that if Slenderness Ratio is lower than 70, it is invaluable for quality pulp and paper production (Bektas et al., 1999). But, if the Slenderness ratio is higher than 70, it can be utilized for pulp and paper production. Generally resistance to tearing increases with increasing fibre slenderness. Paper made from all the species is expected to have increased tear strength suitable for wrapping and packaging purposes (Sankia et al., 1997).

The Rigidity Coefficient (RC) of the fibres varied from 0.16 to 0.7. The RC might be associated with fibre cell wall thickness and fibre diameter used to obtain the equation for RC. These fibres are less rigid compared to those of Guinea savannah species (Sadiku & Abdukareem, 2019). This value is in the range of those reported for *Eucalyptus tereticornis* (0.63) and *Eucalyptus camadulensis* (0.53) and *Eucalyptus grandis* (0.33) (Dutt & Tyagi, 2011) which are conventional paper-making fibres as well as juvenile beech (25.85%) and black pine (13.30%) woods. As the fibre rigidity increases, the physical resistance properties of paper weaken (Akgül & Tozluoğlu, 2009). As hard wood generates thick wall fibres, their Rigidity

Coefficients are mostly higher (Hus, Tank & Goksal, 1975). The RC in this study is higher than those reported by the various researchers, which may be due to the ages of the trees from which the woods of these species were cut. Therefore, observed species shows higher RC and they may not be used conveniently for producing high quality writing and printing papers, compared with these of low RC which will be less stiff, more flexible and form lower bulk and well bonded paper. Increasing fibre rigidity results in a decrease in fibre bonding, which results in stiffer, less flexible and form bulkier paper with a lower bonded area, coarse surfaced and containing a large amount of void volume (Dutt & Tyagi, 2011).

F-factor is the fibre length ratio to the fibres cell wall thickness. According to Akgül and Tozluoğlu (2009), the higher the F-factor, the better the fibre is for paper-making. The F-factors reported in this study are extremely lower than those reported for both soft and hardwoods. 140.38 and 240.55 were reported for beech and black pine juvenile woods (Akgül & Tozluoğlu (2009); 25.92 and 206.78 for two Populus species (Kar, 2005) which are hardwood species and 606.66 and 410.34 were reported for *Pinus brutia* and *Cedrus libani* which are softwood species respectively (Erdin, 1985). The F-factor was low for all the species under study as the F-factors did not exceed 0.61 or 61%. The lower values compared to those reported for hardwoods by other researchers may be attributed to the short length of the fibres and the higher cell wall thickness of the fibres.

C. Classification of the Fibres and the Suitability Rating of the Wood Species for Pulp and Paper Production

The classification was done following Metcalfe and Chalk (1983) and Anonymous (1984). They classified fibres below 1.60 mm as short while those above 1.60 mm in length as long. Judging from the fibre morphology, we classified the fibres into four classes: <1.00mm as extremely short fibres; 1.00–1.49 mm short fibres; 1.50–1.99 mm medium long and > 2.00 mm long fibres (Table 5).

D. Classification of Suitability of the Wood Species for Pulp and Paper's Production based on their Derived Morphological Indices

The flexibility coefficient, otherwise known as elasticity coefficient, or Istas coefficient, is a function of the elasticity of the wood fibres. Depending on the elasticity rate, fibres are grouped into four following Istas et al. (1954) and Bektas et al. (1999) grouping (Table 4.17). The wood species were thus grouped following the classification as outlined in Table 7. All the wood fibres are elastic with *R. heudolotii* and *P. macrocarpa* have highly elastic fibres.

Similarly, the Runkel Ratio is the most important and primary parameter needed to find the suitability of any raw material for pulp and paper. The standard for this ratio is one (1). Any RR values greater than 1 is termed poor (does not favour pulp strength properties). Favour pulp strength properties are usually obtained when the value is below the standard value. All the wood fibres are excellent pulp and paper materials judging from their RR values. Two species; *M. excelsa* and *P. biglobosa* had RR values that were greater than 1 (Table 4.12)

F-factor shows the flexibility of fibres. The highest F-factor was observed for *P. macrocarpa* while the least was for *A. indica*. (Table 4). The high F-factor values for *P. macrocarpa* and *R. heudolotii* place these species well in the ranking at the upper limit among the selected hardwood species. The rigidity coefficient put *C. albidium* to be less suitable due to its highest rigidity (0.70) while *R. heudolotii* was most suitable considering the Rigidity Coefficient. In terms of slenderness ratio, *P. macrocarpa* had the best rating while *R. heudolotii* was the poorest considering the Slenderness Ratio.

Table 5. Fibre length classification of the wood species

No.	Wood species	Fibre length (mm)	Fibre Class
1.	*M. excelsa*	1.34[cde]	Short
2.	*D. oliveri*	1.64[gh]	Medium long
3.	*N. diderichii*	2.48[i]	Long
4.	*A. boonei*	1.35[cde]	Short
5.	*B. sapida*	1.21[bcd]	Short
6.	*Vitex doniana*	1.41[def]	Short
7.	*C. albidium*	1.10[b]	Short
8.	*H. brasiliensis*	1.14[bc]	Short
9.	*P. macrocarpa*	1.58[fgh]	Medium long
10.	*A. indica*	0.84[a]	Extremely short
11.	*T. africana*	1.33[cde]	Short
12.	*I. gabonensis*	1.60[fjh]	Medium long
13.	*P. angolensis*	1.05[b]	Short
14.	*R. heudolotii*	1.71[h]	Medium long
15.	*A. zygia*	1.35[cde]	Short
16.	*P. biglobosa*	1.38[def]	Short
17.	*T. monaldeph*	1.47[efg]	Short
18.	*T. superba*	1.47[efg]	Short

Note: Means with the same letter vertically are not significantly different at ($p \leq 0.05$)

Table 6. Elasticity coefficients of the wood fibres

Types of Fibres	Elasticity Coefficient
High elastic fibres	> 75
Elastic fibres	50 – 75
Rigid fibres	30 – 50
High rigid fibres	< 30

Sources: Istas et al. (1954) and Bektas et al. (1999)

Table 7: Fibre flexibility and suitability rating of the wood species

No.	Wood species	SR	FC	RR	RC	F-factor	Suitability rating
1.	*M. excels*	Slender	Elastic	Poor	Poor	Flexible	Poor
2.	*D. oliveri*	Slender	Elastic	Good	Good	Flexible	Good
3.	*N. diderichii*	Slender	Elastic	Good	Good	Flexible	Good
4.	*A. boonei*	Slender	Elastic	Good	Good	Flexible	Good
5.	*B. sapida*	Slender	Elastic	Good	Good	Flexible	Good
6.	*Vitex doniana*	Slender	Elastic	Good	Good	Flexible	Good
7.	*C. albidium*	Slender	Elastic	Good	Poor	Flexible	Good
8.	*H. brasiliensis*	Slender	Elastic	Good	Good	Flexible	Good
9.	*P. macrocarpa*	Slender	Highly elastic	Good	Good	Flexible	Good
10.	*A. indica*	Slender	Elastic	Good	Good	Flexible	Good
11.	*T. africana*	Slender	Elastic	Good	Good	Flexible	Good
12.	*I. gabonensis*	Slender	Elastic	Good	Good	Flexible	Good
13.	*P. angolensis*	Slender	Elastic	Good	Good	Flexible	Good
14.	*R. heudolotii*	Poor	Highly elastic	Good	Good	Flexible	Good

No.	Wood species	SR	FC	RR	RC	F-factor	Suitability rating
15.	*A. zygia*	Slender	Elastic	Good	Good	Flexible	Good
16.	*P. biglobosa*	Slender	Elastic	Poor	Poor	Flexible	Poor
17.	*T. monaldeph*	Slender	Elastic	Good	Good	Flexible	Good
18.	*T. superba*	Slender	Elastic	Good	Good	Flexible	Good

Note: Means with the same letter vertically are not significantly different at ($p\leq 0.05$)

IV. CONCLUSION

There were significant variations in all the measured fibre properties and derived values. Each of the 18 wood species either falls into short (1.05–1.36), medium long (1.52–1.75) or long (2.0 mm) fibre categories. All the fibres were elastic. All the wood is suitable for paper-making based on > 33 SR acceptable value for paper-making fibres. However, *P. biglobosa* and *M. excelsa* are not suitable considering their RR, which are greater than 1. *C. albidium* is unsuitable due to its highest rigidity, while *R. heudolotii* was most suitable considering its low Rigidity Coefficient. Regarding Slenderness Ratio, *P. macrocarpa* had the best rating while *R. heudolotii* had the poorest.

ACKNOWLEDGEMENT

We would like to acknowledge Mr. Adeniyi of the Wood Anatomy Unit of the Forest Products Development Unit of the Forestry Research Institute, Ibadan, Nigeria, for the microscopic sectioning of the wood samples. Also Danladi Damilola Areola for helping calculate the fibre morphological indices.

REFERENCES

Ajuziogu, G.C., Nzekwe, U. & Chukwuma, H. I. (2010). Assessment of suitability of fibres of four nigerian fruit trees for paper-making. *Bio-Research*, *8*(2):679-681.

Akachukwu, A.E. (2001) Study of Reaction among some wood features in hardwood species. *Journal of Tropical Forest Resources*, *5,*72-78.

Akgül, M. & Tozluoğlu, A. (2009). Some chemical and morphological properties of juvenile woods from beech (*Fagus orientalis* L.) and Pine (*Pinus nigra* A.) Plantations. *Trends in Applied Sciences Research*, *4*(2), 116-125.

American Society for Testing and Materials (2007). ASTM D1413-61- Preparation of decayed wood for microscopical examination, ASTM International, West Conshohocken, PA, 2007.

American Society for Testing and Materials. ASTM (2020): Standard Test Methods for Evaluating Properties of Wood-Based Fibre and Particle Panel Materials. ASTM D1037-12, West Conshohocken, PA.

Anonymous. (1984). Chemical analysis of Nigerian grown timbers. Annual Report of the Forestry Research Institute of Nigeria. Jan. - Dec., p.108-109.

Awaku, F.A. (1994). Anatomical properties of afina (*Strombosia glaucescens*, var *lucida* J. Leonard). *Ghana Journal of Forestry*, *1*:30-33.

Azeez, M.A., Andrew, J.E. & Sithole, B.B. (2016). A preliminary investigation of Nigerian *Gmelina arborea* and bambusa vulgaris for pulp and paper production. *Maderas Ciencia Y Tecnología*, 18, 65–78.

Bektas, I. Tutus, A. & Eroglu, H. (1999). A study of the suitability of calabrian pine (*Pinus burtia*, Jen) for pulp and paper manufacture. *Turkish Journal of Agriculture and Forestry*, *23*(3),589-597.

Brindha, D., Vinodhini, S. & Alarmelumangai, K. (2012). Fiber dimension and chemical contents of fiber from *Passiflora foetida*, l. and their suitability in paper production. *Science Research Reporter*, *2*(3),210-219.

Dinwoodie, J.M. (1965). The relationship between fibre morphology and paper properties: A review of literature. *Tappi*, *48*(8), 440-447.

Dutt, D. & Tyagi, C.H. (2011). Comparison of various Eucalyptus species for theirmorphological, chemical, pulp and paper making characteristics. *Indian Journal of Chemical Technology*. *1*(2), 145-151.

Egbewole, Z.T. & Rotowa, O.J. (2017). Effects of declining paper industry on Nigeria economy and the way forward. *American Journal of Agriculture and Forestry*, 5 (6), 181-187. doi://10.11648/j.ajaf.20170506.11.

Erdin N. (1985). Researh on anatomic structure of toros cedar (*Cedrus libani* A. Ric) and its specific weight. Istanbul University: New York Press Technicians Printing House.

Ezeibekwe, I.O., Okeke, S.E., Unamba, C.I. & Ohaeri, J.C. (2009). An investigation into the potentials of dactyladenia bacteri; *Dialum guineense*; and anthonotama crophylia for paper pulp production. *Report and Opinion, 1*(4), 18-25.

Fatriani and Banjarbaru (2017). Fiber dimension and derivatives value of sugar palm frond in various positions. *Agriculture, Forestry and Fisheries*, *6*(2), 66-68. doi://10.11648/j.aff.20170602.13.

Food and Agricultural Organization (FAO) (2004). Trends and current status of the contribution of the forestry sector to national economies. 2004. Retrieved from: http://www.fao.org/docrep/007/ad493e/ad493e00.htm#TopOfPage.

Fengel, D. & Wegener, G. (1989). Wood chemistry, ultrastructure, reactions. 2nd Edition. Berlin: Walter de Gruyter.

Hurter, R.W. (2001). Agricultural fibers for paper pulp. *Outlook on Agriculture*, *8*(3), 96-103.

Hus, S., Tank T. & Goksal E (1975). Considering eucalyptus (*E. camaldulensis* Dehnh) wood which grow in Turkey (in Tarsus-Karabacak) morphological and opportunities for evaluating semi-chemical cellulose in paper industry. USA: Tubitak Publications.

Illvessalo-Pfaffli, M.S. (1995). Fibre atlas. Identification of papermaking fibres. Berlin: Springer – Verlag

Istas, J.R., Heremans, R. & Roekelboom, E.L. (1954). General Characteristics of Belgian congo hardwoods in relation to their use in the pulp industry: A Detailed study of some species. *Serie Technique*, *43*. Gembloux: INEAC.

Kar, S. (2005). Investigating *Populus uramericana*, *Populus nigra* and *Populus tremula* woods micrographically. Unpublished BSc. Thesis, Zonguldak Karaelmas University, Zonguldak, Turkey.

Kpikpi, W.M. (1992). Wood structure and paper-making potentials of *Ricinodendron heudelotti* and *Albizia zygia* in relation to *Gmelina arborea*. *Nigerian Journal of Botany*, *5*(0), 41-50.

Makinde, M.A. (2004). Keynote address at the national symposium of technical association of pulp and paper industry in Nigeria. In Proceedings of National Symposium on Rehabilitation of the Forestry, Pulp, Paper and Board Industries for the Revival of National Economy. March, 2004.

Mcdougall, G.J., Morrison, I.M., Stewart, D., Weyers, J.D.B. & Hillman, J.R. (1993). Plant fibers-botany, chemistry and processing for industrial use. *Journal of the Science of Food and Agriculture*, *62*(1), 1-20.

Metcalfe, C.R. & Chalk, L. (1983). Anatomy of the dicotyledons 2, 2. *Nordic Journal of Botany*, *4*(5),668-668.

Obiora, B.E., Jonah, C.A., Ikenna, C.E. & Christian, N.M. (2019). Sustainable production and consumption of paper and paper products in Nigeria: A review. *Resources*, *8*(53), 1-23. doi://10.3390/resources8010053.

Ogbonnaya, C.I., Roy-Macauley, H., Nwalozie M.C. & Annerose, D.J.M. (1997). Physical and histochemical properties of kenaf (*Hibiscus cannabinus* L.) grown under water deficit on a sandy soil. *Industrial Crops Product*, *7*, 9-18.

Ogunkunle, A.T.J. (2010). A quantitative modelling of pulp and paper making suitability of Nigerian wood species. *Advances in Natural and Applied Sciences*, *4*(1), 14-21.

Ogunkunle, A.T.J. & Oladele, F.A. (2008). Structural dimensions and paper making potentials of the wood in some Nigerian species of *Ficus L.* (Moraceae). *Advances in Natural and Applied Sciences*, *2*(3), 103-111.

Ogunjobi, K.M., Adetogun A.C. & Omole A.O. (2014). Assessment of variation in the fibre characteristics of the wood of *Vitex doniana* sweet and its suitability for paper production. *Journal of Research in Forestry Wildlife and Environmental*, *6*(1),39-51.

Ogunwusi, A.A. (2002). Wood properties of *Sterculia setigera* forming in the savanna belt of Nigeria. *Nigerian Journal of Forestry*, *32*(1), 50-55.

Ogunwusi, A.A (2013). Towards optimising pulp and paper production capacities in Nigeria. *An International Journal of Science and Technology, Bahir Dar, Ethiopia*, *2* (1), 27-44.

Ogunwusi, A.A. & Onwualu, A.P. (2013). Impact of privatization of primary pulp and paper mills on performance of the pulp and paper sector in Nigeria. *Development Country Study*, *3*, 109–119.

Ohshima, J., Yokota, S., Yoshizawa, N. & Ona, T. (2005). Examination of within-tree variations and the heights representing whole-tree values of derived wood properties for quasi-non- destructive breeding of *Eucalyptus* *camaldulensis* and *Eucalyptus globulus* as quality pulpwood. *Journal of Wood Science*, *51*(2),102-111.

Oluwadare, A.O. 1998. Evaluation of the fibre and chemical properties of some selected Nigerian wood and no-wood species for pulp production. *Journal of Tropical Forest Resources*,*14*, 110-119.

Oluwadare, A.O. (2007). Wood properties and selection for rotation length in Carribean pine (Pinus caribaea Morelet) grown in Afaka, Nigeria. *American-European Journal of Agriculture Environment and Science*, *2*(4), 359-363.

Oluwadare, A.O. & Sotannde, O.A. (2007). The relationship between fibre characteristics and pulp-sheet properties of *Leucaena leucocephala* (Lam.) De Wit. Middle-East. *Journal of Scientific Research*, *2*(2), 63-68.

Osadare, A.O. (2001). Basic wood and pulp properties of Nigerian-grown caribbean pine (*Pinus caribaea* Morelet) and their relationship with tree growth indices. Unpublished Ph.D. thesis, University of Ibadan, Ibadan, Nigeria.

Panshin, J. & de Zeeuw, C. (1980). Textbook of wood technology. 4th edition Mc. Grawhill: New York, p.772.

The Nigerian Voice (2010). N400BN Loss to paper import. Retrieved from: https://www.thenigerianvoice.com/news/30327/n400bn-loss-to-paper-imports.html.

Retulainen, E., Niskanen, K. & Nilsen, N. (1998). Fiber and bonds. Chapter 2 in Paper Physics (ed. Kaarlo Niskanen), Book 16 in *Papermaking Science and Technology*, Fapet Oy, Jyväskylä, Finland, pp 54-87.

Riki, J. T. B., Sotannde, O. A. & Oluwadare, A. O. (2019). Anatomical and chemical properties of wood and their practical implications In Pulp and Paper Production: A review. *Journal of Research in Forestry, Wildlife & Environment*, *11*(3), 358- 368.

Sadiku, N.A., Oluyege, A.O. & Ajayi, B. (2016). Fibre dimension and chemical characterisation of naturally grown *Bambusa vulgaris* for pulp and paper production. *Journal Bamboo and Rattan*, *15*(1-4), 33-43.

Sadiku, N.A. & Abdukareem, K.A. (2019). Fibre morphological variations of some Nigerian guinea savannah timber species. Maderas. *Ciencia y tecnología*, *21*(2): 239 – 248. 0717-3644. doi://10.4067/S0718-221X2019005000211.

Saikia, S.N., Goswami, T. & Ali, F. (1997). Evaluation of pulp and paper making characteristics of certain fast growing plants. *Wood Science and Technology*, *31*(6), 467-475.

Sankia, D.G., Gaswani, T. & Sankia, C.N. (1997). Wild banana as a source of fibre for paper and cordage industries. *Journal of Scientific and Industrial Research*, *56(7)*, 408-413.

Udohitinah, J.S. & Oluwadare, A.O. (2011). Pulping properties of kraft pulp of Nigerian-grown kenaf (*Hibiscus Cannabinus* L.). *Bioresources*, *6*, 751–761.

Uju, C.C. & Ugwoke, C.E. (1997). Studies on the dimensions and suitability of wood fibres of selected tree species of the family Moraceae in papermaking. *Nigerian Journal of Botany*, *10*,7-13.

Ververis, C., Georghiou, K., Christodoulakis, N., Santas, P. & Santas, R. (2004). Fiber dimensions, lignin and cellulose content of various plant materials and their suitability for paper production. *Industrial Crops Products*, *19*, 245-254.

Volkomer, P.J. (1969). Wood raw materials for pulp and paper in tropical countries. FAO International Review of Forestry and Forest Products. *Unasylva*, *23*(3).

Xu, C. Y., Wang, H.X., Zhang, X.Y., Fu, S.Y. & Wu, J.E. (2006). Lignocellulose selectivity degradation of white rot fungi in bamboo. *Journal Microbiol*, *26*, 14-18.