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ASSESSMENT OF ANATOMICAL PROPERTIES OF *DANIELLIA OLIVERI* FOR PULP AND PAPERMAKING

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Abstract:

Wood a versatile renewable natural resource has been the major raw material for pulp and papermaking. The ever-increasing demand for paper-based products globally makes it eminent for researchers to investigate other lesser-utilized wood species to supplement the traditional wood species used for pulp and papermaking. This paper assessed the suitability of Daniellia oliveri - a lesser-utilized wood species for pulp and papermaking. Three Daniellia oliveri trees were sampled and standard laboratory methods were used for the study. Mean fiber morphological values obtained for the heartwood sections were fiber length = 1294.11 - 1639.85μm; fiber diameter = 21.90-22.90μm; fiber lumen width = 11.21-13.28μm and double fiber wall thickness = 9.62-11.02μm and that of the derived fiber indices are Runkel ratio = 0.73-0.99, Slenderness ratio = 56.45-75.09, flexibility coefficient = 0.50-0.58, Luce's shape factor = 0.50-0.59 and solids factor = $455x10^3$-$572x10^3$μm^3. Mean values of the sapwood sections were: fiber length = 1339.25-1562.69μm; fiber diameter = 22.88-23.52μm; fiber lumen width = 12.52-13.94μm and double fiber wall thickness = 9.60-10.36μm and that of derived fiber indices including Runkel ratio = 0.70-0.83, Slenderness ratio = 56.99, flexibility coefficient = 0.55-0.59, Luce's shape factor = 0.49 and solids factor = $482x10^3$-$575x10^3$μm^3. These values were similar to those of Acacia species, Gmelina arborea, Eucalyptus species and Leucaena leucocephala. The results obtained in this study were appreciable for producing good quality flexible paper sheets of medium density, high tear index, high tensile and burst strengths with good double fold endurance.

Key words: *Anatomical properties, Daniellia oliveri, lesser-utilized species, Pulp, Paper making.*

INTRODUCTION

Wood is a versatile, recyclable and carbon neutral renewable natural resource used for various purposes around the world for over thousands of years (Afrifa and Adjei-Mensah 2021). The ever-increasing human population in recent times has a linear relationship with the rise in demand for pulp and paper products and virgin wood is the primary raw material for the pulp and paper industries (Afrifa and Adjei-Mensah 2021).

Emergence of technological advancement in modern times caused a significant decline in the demand for traditional printing and writing papers, notwithstanding, the demand for paper base products has continued to surge with significant regional disparities for several reasons including shift in consumer preference, economic trends and sustainability issues among others, as packaging papers (including health care, food and beverages, personal care etc.) continue to be the highest in demand (Farahaty 2020). The global pulp and paper market in 2023 was estimated to be USD 231 billion, but it is anticipated to reach approximately USD 303.98 billion by 2030, growing at a compound annual growth rate (CAGR) of 4% from 2024 to 2030 (Stellar Market Research 2023). The global consumption of pulp and paper products is projected to be 400 million tons annually with 7.2 billion trees harvested to meet this demand (Afrifa and Adjei-Mensah 2021, Tiseo 2021).

Wood species in Ghana are classified as: Premium, Commercial, Lesser-Utilized and Lesser-Known Species and continued to emphasis that lesser-utilized species (LUS) and lesser-known species (LKS)

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dominate the forest as premium and commercial species keep dwindling at a faster rate because both the international and local timber markets tend to favor the commercial and premium species over the lesser-known and lesser-utilized species (Oteng-Amoako 2006).

Daniellia oliveri, commonly known as African copaiba balsam tree, Accra copal, Gum copal or “Senya” as it is referred to in the local dialect by the Akan ethnic group in Ghana is a Lesser-Utilized Species (Oteng-Amoako 2006; International Tropical Timber Organization 2024). It is a species of least concern according to the International Union for Conservation of Nature (IUCN) (Arévalo 2020) and unrestricted according to the Conservation on International Trade in Endangered Species of Wild Fauna and Flora (CITES) although no data exist on its status and availability in the Ghanaian forests (Adutwum et al. 2019).

Daniellia oliveri was not widely used in Ghana due to lack of basic information and scientific knowledge about its wood properties and by extension was not accepted on the international timber market. The tree was traditionally restricted for use as fuel wood but recently, however, has gained popularity among wood users, its cost has increased and it’s among the top ten moving species on the local timber market in Ghana (Adutwum et al. 2019), but without its properties being taken into consideration, it poses treat to the end-user. The recent rise in popularity of *D. oliveri* among wood users is a major concern for its sustainable use and management as its wood properties are poorly known (Adutwum et al. 2019).

Daniellia oliveri is a greyish-white tropical deciduous hardwood with a dense spreading crown and a flattened top. Averagely, the tree can attain a height of 25 meters, whilst some trees can grow up to 45 meters high and attain a diameter of 1.5-2 m (Tropical Plants Database 2019; ITTO 2006). It is well-distributed in west, central and east Africa (Schmelzer and Louppe 2012). In Ghana, it is mostly found in the moist deciduous and drier types of deciduous forests (ITTO, 2006). *Daniellia oliveri* is a versatile tree that can grow in a variety of conditions and has many different uses. The tree is traditionally, harvested for its timber, gum, edible leaves, and medicinal properties (Schmelzer and Louppe 2012).

Investigating the pulp and papermaking potential of lesser-used tropical hardwood species like *D. oliveri* would assist the pulp and paper industries to maintain a steady and sustainable supply of raw materials in order to stay operational for long and to meet the current global demand for pulp and paper products.

Pulp and papermaking refer to the process of producing paper from raw materials such as wood, esparto-grass, straw, flax, hemp, jute, rags-cotton linen, other agricultural residues and recycled paper (Osei-Wusu and Danso-Boateng 2021). The paper manufacturing process involves pulp making and converting the pulp into paper (Puneet and Chhavi 202, Eugenio 2023). Pulp is a wet, soft mass of material (usually fibers) which is primarily obtained from wood and it is used for making paper and other cellulose base products. The manufacturing process involves getting raw materials ready, pulping, bleaching, preparing stock, producing paper, and reclaiming chemicals.

Wood anatomical properties influence the pulp and papermaking process. A good pulpwood should have certain desirable qualities including good growth traits, appreciable fiber biometry and derived fiber indices to ascertain its suitability for papermaking (Ofosu et al. 2020). The growth traits of pulpwood have a positive influence on the species’ anatomical properties (Dhaka and Prajapati 2022).

Wood anatomical properties vary between and within species at different geographical locations and within the same tree at different axial and radial stem portions (Jun et al. 2018; Jean et al. 2019; Guillermo 2022). These variations influence the fiber-to-fiber bonding, bulk density and strength properties of a paper product and the derived fiber indices aid in determining a wood species' potential for pulp and papermaking (Afrifa and Adjei-Mensah 2021; Ofosu et al. 2020).

The anatomical properties of wood such as fiber biometry and cell wall fraction determine the strength and quality of the paper produced (Riki et al. 2019). Fiber morphological properties such as long, slender, thin-walled fine fibers provide superior reinforcement strength to paper sheets. Wood anatomical studies aid scientists to identify unknown wood specimens, it helps to understand the adaptation of a tree species to different environmental conditions and also helps in identifying potential applications for specific wood specimens (Arévalo et al. 2020).

It is therefore, prudent to carry out research to investigate the properties of the wood to understand the type of paper (either writing, printing or packaging papers) to be produced from the different parts of the wood with its related qualities as *D. oliveri* can be a good alternative raw material to supplement the declining traditional raw material base for papermaking.

This study aims to explore the variations in the anatomical traits within *D. oliveri* trees with the goal of understanding the species’ inherent properties and to make critical decisions regarding the species' potential for pulp and papermaking.

OBJECTIVE

The objective of this research is to assess the anatomical variations in the axial and radial stem sections of *Daniellia oliveri* trunk wood for pulp and papermaking.

METHODS

Three *Daniellia oliveri* wood specimen estimated to be over 30 years old were harvested from open farm lands in the Atebubu-Amantin municipal. The municipal is located in Latitudes: 07^{o} 28^{1} 12^{11}N, 8^{o}0^{1}0^{11}N and Longitudes: 1^{0} 25^{1} 12^{11}W, 0^{0}45^{1}36^{11}W in the Bono East region of Ghana (Fig. 1). The town is found in the transition agro-ecological zone (FAO 2003) at an altitude of 80-231 m above sea level (Fig. 1).

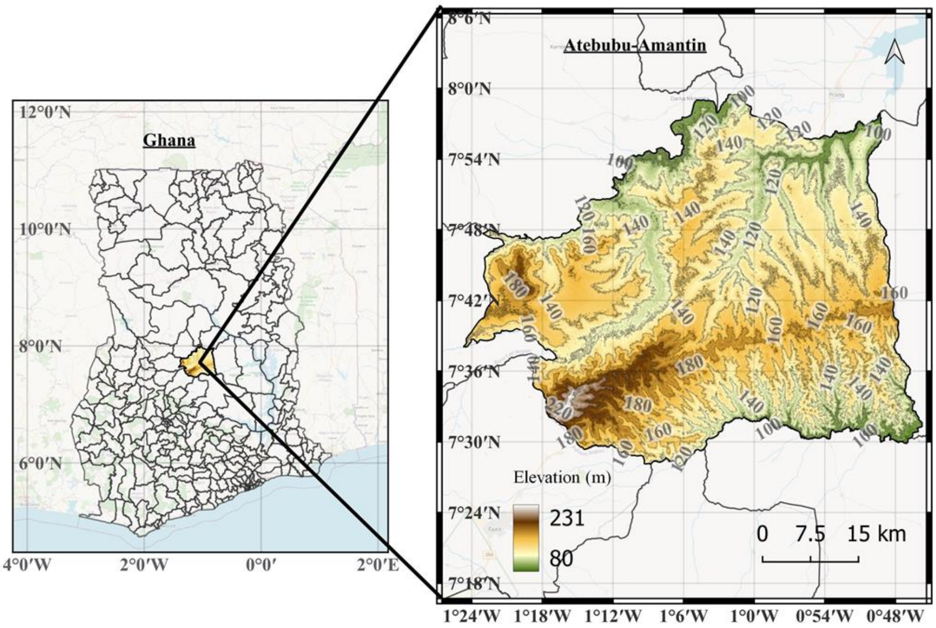


Fig. 1.
Topographic map of the study area.

The annual temperature of the area ranges from 22-34^{o}C, averaging at 28.2^{o}C with a mean annual rainfall of 1300mm (FAO 2003; Asare-Nuamah and Botchway 2018), and a minimal dry period of three to four months (usually late November to early March) characterized with rampant bush fires. The land is dominated by ferric luvisol soil type with a pH ranging from 3.5-6.7 (FAO 2003). This study area was chosen for data collection because of its abundance in *D. oliveri* trees.

Factorial totally randomized design experiment was employed for this study to establish a cause-and-effect link (Mitchual 2014) as a result of varying the wood specimen from different axial and radial stem sections of the trees to its anatomical properties and how these attributes affect the suitability of *D. oliveri* for pulp and papermaking.

The average length of the tree trunks were 11.3m and diameter of 86.2cm at breast height (dbh). The trees were logged at 60cm above ground level instead of the standard 1.3m diameter at breast height due to the unbuttressed nature of the tree species. Three discs of 10cm height were extracted from each of the tree trunks at the butt end, middle portion and top end of the clear bole and carefully labelled (Fig. 2).

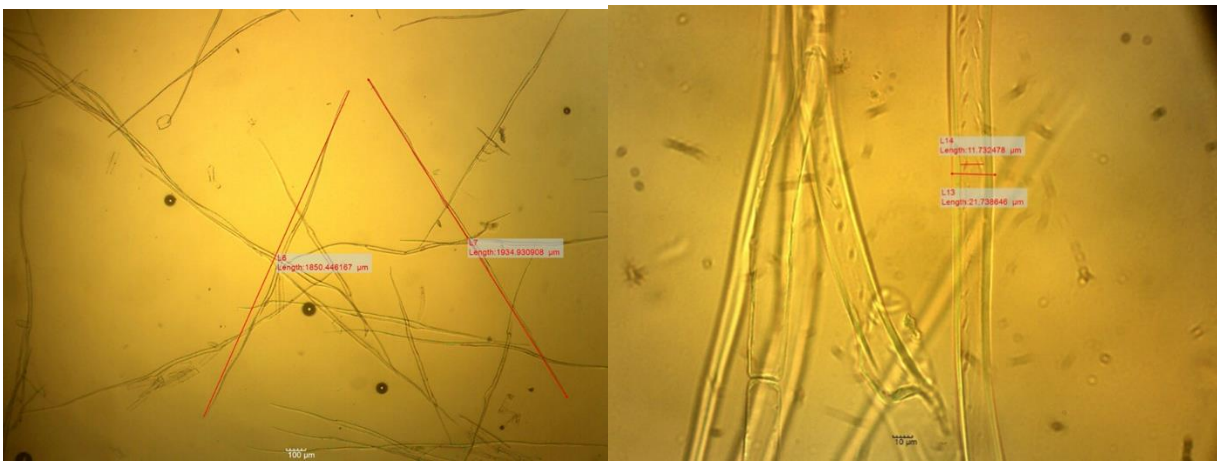
Fig. 2.
Daniellia oliveri wood discs.

The maceration procedure to determine the anatomical properties of *D. oliveri* was carried out at the Council for Scientific and Industrial Research, Forestry Research Institute of Ghana (CSIR-FORIG) Wood Anatomy Laboratory, Kumasi.

Maceration was done in accordance with the Franklin's method (Franklin 1927). Wood slivers parallel to the grain about the size of match sticks were extracted from each sample disc using chisel and hammer. A portion of the slivers from each sample was kept in different heat-resistant test tube and carefully labelled according to the axial and radial stem portions of the trees (Fig. 3). The samples were flooded with 1:1 mixture of glacial acetic acid and 20% hydrogen peroxide and incubated at 60^{o}C in an electric oven for 6 days (Fig. 3). The macerates were transferred into clean vials and washed with distilled water to get rid of residual chemicals and to bring the reaction to a halt.

Fig. 3.
Macerated D. oliveri wood specimen for fiber analysis.

Few drops of glycerol was put on the macerates in petri dishes and carefully teased out to separate the individual wood components. A drop of the teased macerate was fetched onto a slid and covered with a cover slip. The slides were mounted on Micron USB2 electronic microscope and images of fibers to be measured were then captured with Image J software (Fig. 4). Fifty straight wood fibers each were measured from each sample for fiber length, fiber diameter, fiber lumen width and fiber wall thickness was calculated by subtracting the lumen width from the fiber diameter in accordance with IAWA (1989) standard. The fiber lengths were measured at a magnification of x4 whiles the fiber diameter and lumen width were measured at a magnification of x40.



(a) (b)

Fig. 4.
Microscopic measurement of D. oliveri (a) fiber length (b) fiber diameter and lumen width.

The following fiber derivatives; Runkel Ratio, Luce's Shape Factor, Flexibility Coefficient, Slenderness Ratio and Solids Factor were calculated following Runkel (1949); Luce (1970), Afrifa *et al.* (2020) and Afrifa and Adjei-Mensah (2021) by substituting the recorded fiber dimensions into equations 1 to 5.

$$\text{Runkel Ratio} = \frac{\text{Double Cell Wall Thickness}}{\text{Lumen Width}} \tag{1}$$

$$\text{Luce's Shape Factor} = \frac{\text{Fiber Diameter}^2 - \text{Lumen Width}^2}{\text{Fiber Diameter}^2 + \text{Lumen Width}^2} \tag{2}$$

$$\text{Flexibility Coefficient} = \frac{\text{Lumen Width}}{\text{Fiber Diameter}} \tag{3}$$

$$\text{Slenderness Ratio} = \frac{\text{Fiber Length}}{\text{Fiber Diameter}} \tag{4}$$

$$\text{Solids Factor} = (\text{Fiber Diameter}^2 - \text{Lumen Width}^2) \times \text{Fiber length } [\mu m^3] \tag{5}$$

Analysis of Variance (ANOVA) statistical tool was used for testing the variations in the anatomical properties of *D. oliveri* using Origin Pro. version 20 software, with each variation tested at 95% confidence level ($p<0.05$) to establish any significant difference existing in the properties studied.

RESULTS AND DISCUSSION

Fiber Biometry

Fiber Length

The relationship between fiber length and the strength of paper has been studied extensively and it has been found that longer fibers generally have a positive effect on the strength properties of paper (Liang 2010; Larsson et al. 2018; Taslima et al. 2021). Papers made from longer fibers display higher tensile strength and fracture toughness (Carlson and Lindström 2005). Tear strength of paper sheet also increase with fiber length within a certain range (Petri 1996). Although longer fibers contribute to improved strength properties of paper, however, the effect of fiber length on paper strength may also be influenced by other factors such as fiber-to-fiber bonding (Taslima et al. 2021).

Table 1

Means and Test of Significance of Fiber Biometry and Derived Indices of D. oliveri

Fiber Dimensions and Indices	Radial Sections	Axial Sections		
		Butt	**Middle**	**Top**
Fiber Length (μm)	Heartwood	$1473.46\pm39.2^{ab*}$	$1294.11\pm203.4^{ac*}$	$1639.85\pm15.7^{bc*}$
	Sapwood	$1339.25\pm117.5^{ab*}$	$1562.69\pm32.1^{ac*}$	$1493.59\pm119.8^{bc*}$
Fiber Diameter (μm)	Heartwood	$22.23\pm0.5^{b*}$	22.90 ± 0.6	$21.90\pm1.1^{b*}$
	Sapwood	$23.52\pm0.6^{*}$	22.93 ± 0.1	$22.88\pm1.9^{*}$
Lumen Diameter (μm)	Heartwood	$11.21\pm0.6^{a*}$	13.28 ± 0.3^{ac}	$11.44\pm0.7^{c*}$
	Sapwood	$13.94\pm1.4^{ab*}$	12.57 ± 0.4^{a}	$12.52\pm1.3^{b*}$
Double Fiber Wall Thickness (μm)	Heartwood	$11.02\pm0.5^{b*}$	10.38 ± 0.4^{c}	9.62 ± 0.99^{bc}
	Sapwood	$10.36\pm0.6^{b*}$	10.36 ± 0.3^{c}	9.60 ± 1.3^{bc}
Runkel Ratio	Heartwood	$0.99\pm0.09^{a*}$	$0.73\pm0.08^{ac*}$	$0.91\pm0.03^{c*}$
	Sapwood	$0.70\pm0.16^{ab*}$	$0.83\pm0.05^{a*}$	$0.83\pm0.04^{b*}$
Slenderness Ratio	Heartwood	$66.34\pm3.0^{ab*}$	$56.45\pm8.5^{ac*}$	$75.09\pm4.1^{bc*}$
	Sapwood	$56.99\pm5.3^{ab*}$	$68.15\pm1.6^{a*}$	$65.33\pm2.6^{b*}$
Flexibility Coefficient	Heartwood	$0.50\pm0.02^{a*}$	$0.58\pm0.03^{ac*}$	$0.52\pm0.01^{c*}$
	Sapwood	$0.59\pm0.06^{ab*}$	$0.55\pm0.01^{a*}$	$0.55\pm0.01^{b*}$
Luce's Shape Factor	Heartwood	$0.59\pm0.03^{a*}$	$0.50\pm0.08^{ac*}$	$0.58\pm0.03^{c*}$
	Sapwood	$0.49\pm0.16^{ab*}$	$0.54\pm0.05^{a*}$	$0.55\pm0.04^{b*}$
Solids Factor (μm^3)	Heartwood	$542\pm1410^{3a*}$	$455\pm10\times10^{3ac*}$	$572\pm46\times10^{3c*}$
	Sapwood	$482\pm86\times10^{3ab*}$	$575\pm19\times10^{3a*}$	$556\pm121\times10^{3b*}$

± = Standard deviation; means in a roll with similar letters are significantly different (p<0.05).
**= means in column with significant difference*

The mean fiber length of the heartwood of *D. oliveri* studied ranged from 1294.11 to 1639.85μm and that of the sapwood ranged from 1339.25μm to 1562.69μm (Table 1). Tukey's multiple comparison post hoc test showed significance differences among all the fiber lengths of the heartwood and sapwood sections of the trees in both the axial and radial stem portions (Table 1).

The fiber lengths of *D. oliveri* observed in this study are within the range of hardwood fibers ≤900μm ≥1600μm (IAWA 1989) and it is comparable to the length of some fibers used for papermaking such as *Leucaena leucocephala* wood*,* 1.15mm (Oluwadare and Sotannde 2023), *Acacia decurrence* 1.37mm (William 2022) and *Gmelina arborea,* 1.29mm (Róger et al. 2016) *Eucalyptus,* 1392.622 and *Casuarina equisetifolia*, 1521.022 (Vishnu and Revathi 2019) but longer than that of *Acacia mangium* Wild, 1,101μm/1.101mm (Marsoem et al. 2012) and *Eucalyptus globulus,* 0.85mm (Santos et al. 2008) which are all very important hardwood species for pulp and paper production. Therefore, wood fibers from every part of the tree trunk would be suitable for producing good quality papers. The fiber lengths studied did not show any association with increasing tree height or transition from sapwood to heartwood. The inconsistencies in fiber length values observed in the axial and radial stem portions could be attributed to the tree age, tree species, influence of climatic and edaphic conditions (Angelo et al. 2022; Warlen et al. 2022).

Fiber Diameter

Wood fiber diameter plays a crucial role in determining the quality of a paper. Product quality such as paper formation, porosity, tensile strength, tear resistance and absorbency are all influenced by the fiber diameter (Ronak et al. 2022). The fiber diameter and wall thickness vary depending on the wood species, density and age of the tree (Ridwan et al. 2020).

The mean fiber diameter of the heartwood of *D. oliveri* ranged from 21.90 to 22.90μm and that of the sapwood ranged from 22.88 to 23.52μm (Table 1). Only the butt end and the top portion of the heartwood fiber diameters showed a significant difference from the Tukey's multiple comparison post hoc test (Table1). The diameter of the sapwood fibers revealed inverse proportionality to the height of the tree as the fiber diameters decreased with tree height.The analysis of variance (ANOVA) revealed a strong significant difference ($p<0.01$) between the heartwood and sapwood sections in the butt end and top end (Table 1). The fiber diameter range of *D. oliveri* obtained in this study are within the range of fiber diameters preferred for papermaking, that is 20-40 μm (Ofosu et al. 2019; Afrifa and Adjei-Mensah 2021).

The fiber diameter of *D. oliveri* recorded in this study is similar to *Leucaena leucocephala* wood (23.66μm) (Oluwadare and Sotannde 2023) and *Casuarina equisetifolia* (22.770) (Vishnu and Revathi 2019) but smaller than that of *Acacia decurrence* wood (39.60μm) (William 2022), *G. arborea* wood (30.67μm) (Róger et al. 2016) and *Melia dubia* (29.949) but larger than *Eucalyptus (*18.919) (Vishnu and Revathi 2019). According to Afrifa and Adjei-Mensah (2021), wood species with smaller fiber widths produce papers with good density, hence the smaller fiber widths of *D. oliveri* recorded from all portions of the trees in this study suggests that every portion of the tree will be suitable for producing good quality papers.

Fiber Lumen Width

Lumen width is an important fiber characteristic in pulp and papermaking because it impacts the rigidity and strength of paper (Syed et al. 2016). Fibers with large lumen and thin cell-walls give a positive effect as they are flexible and tend to easily collapse to form non-porous tightly bonded paper sheets with good strength properties (Syed et al. 2016). In contrast, less flexible thick-walled fibers do not burst easily resulting in the production of less bounded and bulkier paper sheets.

The mean lumen width of the heartwood of *D. oliveri* fibers ranged from 11.21 to 13.28μm and the sapwood mean values ranged from 12.52 to13.94 (Table 1). Only comparison of the butt-end to the top-portion revealed no significant differences, all the other axial stem portions of the heartwood showed significant differences (Table 1). In the comparison of the axial sapwood portions however, only the middle and top portions showed no significant difference. In the radial sections also, comparison of the heartwood and sapwood of the middle sections showed no significant difference whiles all the other sections showed significant differences.

The lumen width of *D. oliveri* from this study is larger than that of *Acacia decurrence*, 9.68μm (William 2022), *Eucalyptus spp,* 7.898μm and *Casuarina equisetifolia*, 6.565μm (Vishnu and Revathi 2019) but smaller than that of *Leucaena leucocephala* wood, 16.34μm (Oluwadare and Sotannde 2023) *G. arborea,* 22.64μm (Róger et al. 2016) and *Melia dubia*, 23.594μm (Vishnu and Revathi 2019). The lumen width values recorded from this study suggests that, every part of *D. oliveri* stem wood would be suitable for producing good quality papers because its values fall within the range of lumen width of hardwood species used for pulp and paper production.

Fiber Wall Thickness

The mean double fiber wall thickness of the heartwood of *D. oliveri* ranged from 9.62 to 11.02μm and that of the sapwood ranged from 9.60 to 10.36 (Table 1). Statistical analysis of the heartwood and sapwood sections showed no significant differences between the butt-ends and middle-portions. However, a significant difference occurred between the butt-ends and the top-ends as well as between the middle-portions and the top-ends (Table 1). Radially, only the butt-end sapwood and heartwood sections showed significant difference whilst comparison of all the other radial sections showed no significant differences.Comparison of the double fiber walled thickness of *D. oliveri* in this study to other species whose values were reported as single fiber wall thickness revealed similar values to *Eucalyptus*, 5.510 but lower values in *G. arborea,* 4.02µm (Róger et al. 2016), *Acacia decurrence*, 1.93µm (William 2022), *Leucaena leucocephala* wood, 3.63µm (Oluwadare and Sotannde 2023) and *Melia dubia*, 3.177, and larger value in *Casuarina equisetifolia*, 8.103 (Vishnu and Revathi 2019).

According to IAWA (1989), fibers are classified as very thin-walled when fiber lumen is three or more times wider than the double wall thickness, thin-to thick-walled fiber when the lumen is less than three times the double wall thickness and clearly open, and very thick-walled fiber when the lumen is almost completely closed.In view of this classification, *D. oliveri* fibers in this study can be classified as thin-to thick-walled fibers. The large lumen width plus thin-thick-walled fibers of *D. oliveri* would lead to moderate beating of pulp with enough water penetration to flatten the fibers to ribbon (Ofosu et al. 2019; Afrifa and Adjei-Mensah 2021). Implying that, papers produced from *D. oliveri* fibers would possess relatively appreciable density, good burst strength and good tear and tensile indices.

Fiber Derived Indices

Derived fiber indices are important in determining the suitability of a lignocellulose material for pulp and papermaking. The derived fiber indices include Runkel’s ratio, slenderness ratio, flexibility coefficient, Luce’s shape factor and solids factor were calculated from the fiber biometry and discussed below.

Runkel Ratio

Runkel’s ratio is a measure of the rigidity of a fiber and it is obtained by dividing the double fiber wall thickness by the lumen width. Several authors have proposed different values of Runkel’s ratio values suitable for pulp and papermaking. Thus, less than 1 (Dadswell and Wardrop 1959); less than or equal to 1 (Okereke 1962) and a range of 0.25-1.5 (Singh et al. 1991). Runkel’s ratio less than 1 are most suitable for papermaking, because the fiber walls are presented as thin, flexible and form paper with large bonding (Okereke 1962). Runkel’s ratio equal to 1 is less preferable although it is suitable for paper production. The fiber properties with this Runkel’s ratio are hard and stiff, leading to poor bonding ability and therefore reduced paper quality (Syed et al. 2016). This value can be improved by using a suitable screening technique at a high cost. Runkel’s ratio greater than 1, corresponds to rigid fiber characteristics.

The mean Runkel’s ratio of the heartwood of *D. oliveri* ranged from 0.73 to 0.99 and that of the sapwood ranged from 0.70 to 0.83 (Table 1). Statistically no significant differences existed between the butt-end and the top-end of the heartwood while comparison of all the other heartwood stem portions revealed significant differences (Table 1). A strong significant difference ($p<0.01$) existed between the butt-end and the middle portion as well as between the butt-end and the top-end but no significant differences exist between the middle and the top-end of the sapwood sections (Table 1). Radially, there was significant difference in Runkel’s Ratio values between all the heartwood and sapwood sections of *D. oliveri*. Irrespective of some significant differences, all the Runkel’s Ratio values recorded in this study were less than 1.

The Runkel ratio values of *D. oliveri* observed in this study were higher than that of *Leucaena leucocephala* wood, 0.44µm (Oluwadare and Sotannde 2023) *Acacia decurrence*, 0.39 (William 2022) and *Melia dubia,* 0.269 but lower than *Eucalyptus spp,* 1.396 and *Casuarina equisetifolia,* 2.468 (Vishnu and Revathi 2019). The Runkel’s ratio values obtained in this study indicates that *D. oliveri* stem wood can be used to produce papers of good quality with large bonding.

Slenderness Ratio

The desired Slenderness Ratio of fibers for pulp and papermaking for hardwoods range from 40 to 60 and that of softwoods range from 70 to 90 (Sangumbe et al. 2018; Ofosu et al. 2019). Slenderness ratios greater than 33 are also deemed good for pulp and paper production (Syed et al. 2016; Ofosu et al. 2019). Fibers with higher slenderness ratios produce papers with higher tear index (Syed et al. 2016). The mean value of the slenderness ratio of the heartwood of *D. oliveri* ranged from 56.45 to 75.09 (Table 1). Statistically, a strong significant difference existed among all the axial heartwood stem portions. The mean sapwood values of the slenderness ratio ranged from 56.99 to 68.15 (Table 1). There was significant difference ($p<0.01$) in comparison of the sapwoods of the butt end to the middle and between the butt end and the top portion but no significant difference existed between the middle and the top portions (Table 1). Radially, the slenderness ratios of all the sapwood sections were significantly different ($p<0.05$) from the heartwood sections.

Most of the slenderness ratio values observed in this study were slightly greater than the range proposed for hard wood species. These variations could be related to the tree species, tree age, climatic and ecological conditions (Angelo et al. 2022; Warlen et al. 2022). The slenderness ratio values of *D. oliveri* recorded in this study were higher than that of *Acacia decurrence*, 35.38μm (William 2022) and *Melia dubia* 33.779 but comparable to *Casuarina equisetifolia* 66.799 and *Eucalyptus* 73.609 (Vishnu and Revathi 2019). Although the various sections showed some significant differences, all the values recorded were very appreciable for pulp and papermaking. Consequently, samples from all sections of *D. oliveri* stem wood would be suitable for producing papers with good fiber-to-fiber bonding, higher bursting strength, good double-folding endurance, and high tear and tensile indices.

Flexibility Coefficient

Flexibility coefficient influences the extent to which fibers bond in paper and by extension determines the strength properties of paper sheet. The flexibility coefficient of hardwood fibers ranges from 0.5-0.7 (50-70%) and that of softwood is 0.7 (70%) (Vishnu and Revathi 2019). The mean flexibility ratio values of the heartwood of *D. oliveri* recorded in this study ranged from 0.50 to 0.58 (50-58%) and that of the sapwood ranged from 0.55-0.59 (55-59%) (Table 1). Statistical comparison of all the axial stem portions of sapwood and heartwood showed significant differences with exception to the middle portion to top-end sapwood and butt-end to top-end heartwood (Table 1). Radially, all the sapwood sections were significantly different ($p<0.05$) from the heartwood sections. The flexibility coefficient recorded in this study was higher than that of *Eucalyptus* 41.744% and *Casuarina equisetifolia* 28.832% but lower than *Melia dubia* 78.781% (Vishnu and Revathi 2019). All the values recorded in this study were within the range of elastic fibers (0.5-0.70) indicating that *D. oliveri* has elastic fibers to provide good inter-fiber bonding properties so it can be used to produce paper sheets with higher tensile index.

Luce’s Shape Factor

Luce’s Shape Factor is an index derived from fiber diameter and lumen diameter for estimating the resistance of pulp to beating (Ofosu et al. 2019; Afrifah and Adjei-Mensah 2021). It has a positive relationship with the paper sheet density and influences the breaking length of paper sheet significantly (Vishnu and Revathi 2019). Fibers with lower values exhibit less resistance to beating during pulping and papermaking and will produce papers of good strength properties. Therefore, fibers with lower Luce’s shape factor values are more ideal for pulp and papermaking.

The mean Luce’s shape factor values recorded for the heartwood of *D. oliveri* in this study ranged from 0.50 to 0.59 and that of the sapwood ranged from 0.49 to 0.55 (Table 1). The mean values recorded for the axial sapwood sections were directly proportional to the height of the tree. Tukey’s multiple comparison post hoc test in revealed significant differences ($p<0.05$) in most parts of the axial stem sections except comparison of the butt-end to top-end of the heartwood and the middle-portion to top-end of the sapwood which did not show any significant differences ($p>0.05$).Radially, the Luce’s Shape Factor values of all the sapwood sections were significantly different ($p<0.05$) from all the heartwood sections.

Most of the Luce’s shape factor values recorded for *D. oliveri* were slightly greater than 0.5, indicating moderate uniformly shaped fibers. The slightly higher Luce’s Shape Factor values of *D. oliveri* fibers also suggests that, the fibers will slightly resist beating in the pulping process which would impact the strength, flexibility, conformity, energy requirements, resistance to bending and breaking length of the paper sheet. This implies that, fibers from the butt end and top end of the heartwood as well as those from the middle-portion and top-end of the sapwood sections of *D. oliveri* stem wood would have moderate conformability and good bonding properties suggesting that papers produced from such fibers would be moderately flexible and quite strong.

However, the butt-end of the sapwood section and the middle-portion of the heartwood which recorded 0.49and 0.5 respectively are considered very ideal for producing writing and printing papers. Luce’s shape factor values from this study were lower than *Casuarina equisetifolia* 0.847, *Eucalyptus* 0.703 and *Detarium sengalense* 0.73 but higher than *Melia dubia* 0.234, *Gmelina arborea* 0.29 and *Ficus mucuso* 0.25 but comparable to *Afzelia africana* 0.47 (Vishnu and Revathi 2019).

Solids Factor

The mean Solids factor of the heartwood of *D. oliveri* ranged from $455\times10^3\mu m^3$ to $572\times10^3\mu m^3$ and that of the sapwood ranged from 482×10^3 to $575\times10^3\mu m^3$ (Table 1). Statistically, there was no significant difference between the butt end and top portions of the heartwood as well as the middle and top portions of the sapwood ($p>0.05$) while comparison of all the other axial stem portions showed significant differences ($p<0.05$) (Table 1). The mean solids factor values in the radial stem portions showed that the heartwood sections were significantly different ($p<0.05$) from the sapwood sections.

The solids factor values recorded in this study were higher compared to that of a 14-year-old *E. camaldulensis* ($46\times10^3 \mu m^3$) and *E. globulus* ($91.2\times10^3 \mu m^3$) (Ona et al. (2001), suggesting that, papers of good density, less absorbent, strong and durable can be produced from *D. oliveri* fibers.

CONCLUSION

Data compiled from this study revealed that *Daniellia oliveri* stem wood has longer, larger diameter, larger lumen width and slightly thicker-walled fibers. Its Runkel ratio, slenderness ratio, flexibility coefficient, Luce's shape factor and solids factor values were all appreciable, good for producing quality flexible paper sheets with low density, high burst strength, high tear and tensile indices and good double fold endurance suitable for printing and writing papers. The observed fiber properties of *D. oliveri* stem wood were comparable to *Acacia spp, Eucalyptus spp*, *Gmelina. arborea* and *Leucaena leucocephala* which are among the important wood species traditionally used for papermaking.

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