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Variation of the anatomic characteristics of *Anthocleista grandiflora* wood as a function of tree age and trunk position

Frank Kofi DORWU [1], Kwaku ANTWI [1], Prosper MENSAH *[2],
Edgley Alves de Oliveira PAULA [3], Fernando RUSCH [2], Alexandre Santos PIMENTA [4],
Rafael Rodolfo de MELO [3]

[1] Akenten Appiah, Menka University of Skills Training and Entrepreneurial Development, Kumasi, Ghana.
[2] Council for Scientific and Industrial Research, Forestry Research Institute of Ghana, Wood Industry and Utilisation Division, Kumasi, Ghana.
[3] Department of Agronomic and Forestry Sciences, Federal University of the Semi-Arid Region, Mossoró, RN, Brazil.
[4] Specialized Unit in Agricultural Sciences, Federal University of Rio Grande do Norte, Macaíba, RN, Brazil.
*E-mail: pmensah@csir-forig.org.gh

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ABSTRACT: This paper presents significant findings on the variation in the anatomical properties of Anthocleista grandiflora wood, which could greatly influence its utilization in various products. Cubic-shaped heartwood and sapwood specimens were extracted at the base, middle, and top of boles from 38-, 43-, and 47-year-old trees. The variations in cell morphology and anatomical characteristics were meticulously assessed. The specimens were prepared into 3 mm x 10 mm fragments, macerated, and viewed under a microscope using Motic Image plus 2.0 ML software. The following parameters were determined: average values of fiber length, fiber diameter, lumen width, double fiber wall thickness, Runkel ratio, aspect ratio, coefficient of rigidity, and coefficient of flexibility of trees at the base, middle, and top. Notably, there were more vessels in sapwood than in heartwood, and the vessel areas increased with increasing vessel lengths. The results also revealed that in the heartwood region, the fraction of vessel lumen increases with tree age in the base, middle, and top sections. These findings are significant as they provide a comprehensive understanding of the anatomical properties of A. grandiflora wood, which is classified as wood from numerous vessels, a common characteristic of noble woods. The wood exhibited anatomical properties suitable for cellulose, paper, and fiber-based products, highlighting its potential in various industries.
Keywords: wood quality; fibers; morphological characterization; timber industry.

Variação das características anatômicas da madeira de *Anthocleista grandiflora* em função da idade e da posição no troco

RESUMO: Objetivou-se avaliar as propriedades anatômicas da madeira de *Anthocleista grandiflora* e as suas possíveis aplicações. Amostras do cerne e alburno foram extraídas na base, meio e topo de árvores com 38, 43 e 47 anos de idade. Em seguida, foram avaliadas variações na morfologia celular e nas características anatômicas, por meio de fragmentos de 3 mm x 10 mm, macerados e visualizados em microscópio utilizando o software Motic Image plus 2.0 ML. Foram avaliados: comprimento da fibra, diâmetro da fibra, largura do lúmen, espessura da parede dupla da fibra, razão de Runkel, razão de aspecto, coeficiente de rigidez e coeficiente de flexibilidade das árvores na base, meio e topo. Verificou-se mais vasos no alburno do que no cerne, e as áreas dos vasos aumentaram com o aumento de seu comprimento. Os resultados obtidos também indicaram que na região do cerne a fração do lúmen dos vasos aumenta com a idade árvores nas seções da base, intermediária e topo, sendo os valores de 14.76, 11.38 e 20.73 mm para 38 anos; 23.74, 22.13 e 23.09 mm para 43 anos; 28.62, 12.89 e 25.01 mm para 47 anos. A *A. grandiflora* foi classificada como madeira de numerosos vasos, característica comum para madeiras nobres. A madeira apresentou propriedades anatômicas adequadas para celulose, papel e produtos à base de fibras.
Palavras-chave: qualidade da madeira; fibras; caracterização morfológica; indústria madeireira.

1. INTRODUCTION

The variability in the anatomic ultra-structure of the wood and the extent of variation for the correct utilization of timber. The bole, an essential part of timber, comprises organs and structures whose variation significantly affects their proper growth and development. Thus, variations in wood anatomic structure could affect its quality for construction, furniture production, pulp and paper, and fiber-based products. Thus, Rajput et al. (2023) emphasized that the anatomical properties of wood, which can affect the density, type, and quality of pulp and paper produced, and the character of fiber-based products should not be overlooked, most especially concerning less-known (LKS) and lesser used timber species (LUS).

According to Chave et al. (2009), the amount and anatomical structure of wood determines the attributes of a tree's trunk, such as bio-mechanical support, the velocity of water and nutrient transport as well as storage capacity for water, nutrients, and chemical compounds such as carbohydrates and lipids, which generally occur in the heartwood and the sapwood. It is imperative, therefore, to know that variations in wood quality enhance timber valorization.

The inner layers of the trunk constitute the heartwood, which has no living cells and determines the hardness of the wood (DONALDSON, 2019). The presence of heartwood is the main factor determining wood quality for most end-users. Taylor et al. (2002) emphasized that in some species, heartwood may be distinguished from sapwood by a darker color, lower permeability, and increased decay resistance.

The International Association of Wood Anatomists (IAWA) defines sapwood as the wood portion in each tree containing living cells and reserve materials. The sapwood offers support, conduction, and storage functions in the living tree and determines the physiological properties of wood. These, however, depend mainly on the tree's anatomical characteristics. Hence, variation in the sapwood's anatomical structures affects the wood-water relationship and the tree's hydraulic conductivity.

The species *Antocleista grandiflora* Gilg is native to the African continent, being found mainly in the countries of South Africa, South Sudan, Cameroon, and Comoros (KEW SCIENCE, 2021). Belonging to the Gentianaceae family, this plant species shows excellent growth in humid tropical biome regions, and its height can vary between 5 and 25 meters (NOTTEN, 2014; KEW SCIENCE, 2021; ROTICH et al., 2022). According to Mudau et al. (2022), the roots and stems are extracted in fresh or dried states. They are widely used in folk medicine as raw material in manufacturing products for treating diabetes mellitus. According to Dorwu et al. (2024), *A. grandiflora* Gilg aged between 38 and 47 years has an average density in the heartwood region of 401.9 kg.cm-3 at the base, 389.2 kg.cm-3 in the middle and 378.3 kg .cm-3 at the top. The modulus of rupture is 51.0 MPa at the base, 43.3 MPa in the middle, and 37.0 MPa at the top. The modulus of elasticity is 6547 MPa at the base, 6217 MPa in the middle, and 5960 MPa at the top. The properties presented by the wood can be an interesting alternative for applications in different wood industry sectors.

Anthocleista grandiflora Gilg, a traditional and commercially popular tree for its medicinal uses, is often called the 'forest fever tree.' Generally, work has been done to assess the antimicrobial activities and phytochemical constituents (Bensandy et al., 2012). However, its suitability for timber utilization is not currently available in the literature. Mensah et al. (2021) and Ohemeng et al. (2023) noted that the ever-increasing demand for wood and wood products has been essential in sustainably utilizing Ghana's forest resources. Salleh et al. (2015) emphasized that limited wood resources in many countries create an interest in using underutilized wood and non-wood resources as raw materials to produce value-added products.

The overexploitation of timber resources having desirable fiber characteristics has been appreciated (APPIAH et al., 2009). Therefore, there is a need to research LKS and LUS to ascertain their suitability for the construction, furniture, pulp, and paper industries. Functional traits of timber species influence their survival, growth, and reproductive capacity (POORTER, 2008). Hence, water transport capacity and safety, besides being linked to the structure of bordered pit membranes (Li et al., 2020), are mainly defined by vessel size, vessel frequency, and vessel arrangement and play a key role in tree growth, especially in environments where water availability is determining tree growth.

The need to use new wood species in the industrial sector has motivated researchers to look for materials with good properties that meet the market's required quality criteria. In this context, the present study aims to characterize the anatomical properties of the species *Anthocleista grandiflora* and, based on tests, evaluate its potential for use in manufacturing products by the fiber and wood industries. Research on this species still needs to be conducted, and more information is necessary on several properties. Therefore, the knowledge presented in the research will majorly contribute to closing some information gaps in the literature.

2. MATERIAL AND METHODS

2.1. Tree selection and sawing

Matured trees of *Anthocleista grandiflora* Gilg, naturally grown and at ages of 38, 43, and 47 years old were extracted from Sefwi Asawinso Kitiwa off-reserved forest zone (GPS: 6.3062342, -2.282618), Sefwi Adiembra off-reserved forest zone (GPS: 6.250912, -2.209154) and (GPS: 6.252859, 2.207417) respectively, of Bibiani in the Western North Region of Ghana. One tree from each age group with a diameter at breast height diameter (DBH) ranging from 28.75 to 31.29 cm was felled for the study. The harvested trees were divided into three non-equal parts: base, middle, and top, with an average DBH of 30.02 cm. Three discs of 30 mm thick were cut from the base, middle, and top portions for the anatomical study.

2.2. Preparation of test specimens

Preparation and fiber dimensions of test specimens were done at the Anatomy Laboratory of CSIR-Forestry Research Institute of Ghana, Fumesua-Kumasi, following the procedures of Mensah et al. (2021) and Olaoye and Oluwadare (2020). Three discs were extracted from A. grandiflora boles in the sapwood and heartwood's base, mid, and top sections. Twenty samples of 20 mm cubes were prepared from the inner and outer wood to represent heartwood and sapwood, respectively.

2.3. Anatomical analyzes

Maceration of test specimens was done using the method described by Mensah et al. (2021). A light microscope platform, model National DC5-163, was employed for photo acquisition, equipped with Motic Image plus 2.0 ML software. The analyses of all photomicrographs were done with ImageJ software, including image captioning, anatomical examinations, and anatomic elements, which were performed using a Dell laptop (intel CORE vPRO i5). The nature and arrangement of various tissues were described based on the International Association of Wood Anatomists hardwood identification checklist (IAWA, 1989).

Anatomical measurements were done using the method used by Mensah et al. (2021). Fiber characteristics were measured per tree from the base, middle, and top. Captured images of fibers and loaded them in ImageJ software for measurements on 146 selected fibers from the three sections. The frequency of vessels was determined as Wan-Mohd-Nazri et al. (2012) did. The number of vessels per square millimeters was evaluated by counting all vessels individually (20 counts per specimen). The fraction of the vessel lumen was determined by multiplying the vessel area by the vessel number (VF= VA*VN). The size-to-number ratio was obtained by dividing the vessel area by the vessel number (S=VA/VN). The porosity classification proposed by IAWA (1989) was adopted, which establishes five different categories concerning the number of vessels per mm^2: very few – less than 5; few – between 5 and 20; moderately few – between 20 and 40; numerous – between 40 and 100; very numerous – more than 100.

3. RESULTS

The micrographs in Figure 1 show the qualitative analyses of the anatomical evaluation of A grandiflora wood. The transverse sections of trees with 38-year-olds illustrate solitary vessels in radial multiples of 4-6 vessels (Figure 1A). On the other hand, trees with 43- and 47-year-olds show isolated vessels in radial multiples of 2-3 vessels, some of which are occluded with tyloses (Figures 1D and 1G). In the tangential sections, the rays were multiseriate homocellular in all the trees. The radial sections show rays with visible crystals in trees with 38-year-olds (Figure 1C), as there are few in 43- and 47-year-olds (Figures 1F and 1I).

3.1. Vessel characteristics

Hence, its characterization will be an impetus for the utilization and valorization of *Anthocleista grandiflora* timber. The tree vessels' assessed properties varied considerably along the bole in the heartwood and the sapwood (Table 1). The results illustrate that, generally, the vessel areas increase with increasing vessel lengths.

Generally, the number of vessels for the 47- and 43-year-old trees was higher than the 38-year-old tree. From the interpretation of microscopic features of hardwood identification, the values obtained indicate that all tree's ages are numerous vessel wood (Table 1).

3.2. Fiber morphology

The anatomical characterization of the three *Anthocleista grandiflora* species acquired in this study indicates they are suitable raw materials for timber, fiber-based products, and pulp and paper production. The results indicated a significant difference in the means of fiber parameters measured from the heartwood and the sapwood along the trunk of the trees, as shown in Table 2. These indicate a variation in the fiber properties of A. grandiflora wood in both axial and radial positions. These variations play significant roles in the wood's physical and mechanical strength properties for different uses.

At the base, the results in Table 2 indicate a significant difference in the fiber length, lumen width, fiber double wall thickness, coefficient of rigidity, and coefficient of flexibility. However, there was no significant difference in fiber diameter, Runkel ratio, and aspect ratio of all trees' ages. In the middle, the results indicate a significant difference in fiber length, fiber diameter, fiber double wall thickness, Runkel ratio, and aspect ratio. However, there was no significant difference in the lumen width, coefficient of flexibility, and coefficient of rigidity. The fiber characteristics of *A. grandiflora* wood are at the top section of the trunks. The results indicate a significant difference in the fiber diameter, double wall thickness, Runkel ratio, and aspect ratio. At the same time, there was no significant difference in fiber length, lumen width, coefficient of flexibility, and coefficient of rigidity.

3.3. Fiber length

The values of fiber length (Figure 2) recorded for the heartwood of 38-year-old trees at the base, middle, and top are 1.80 mm, 1.68 mm, and 1.84 mm, with a mean of 1.77 mm. Meanwhile, 43-year-old trees recorded 1.66 mm, 1.93 mm, and 2.02 mm, with an average of 1.87 mm. In the sapwood sections, 38- and 43-year-old trees recorded fiber lengths of 2.00 mm, 1.90 mm, 2.02 mm with an average of 1.97mm, and 2.18 mm, 2.10 mm, 2.06 mm with an average of 2.11 mm for their base, middle, and top respectively (Table 2).

3.4. Fiber diameter

As recorded in Table 2, the fiber diameter results indicate that the 38-year-old trees recorded 35.39 μm, 30.85 μm, and 33.03 μm for the heartwood in the but, middle, and top, respectively. Sapwood recorded 37.00 μm, 31.16 μm, and 31.64 μm in the same directions; 43-year-old trees recorded 32.58 μm, 36.25 μm, 25.82 μm and 39.56 μm, 34.90 μm, 33.47 μm in the base, middle, and top of the heartwood and sapwood, whereas 47-year-old trees recorded 33.16 μm, 38.79 μm, 31.62 μm for the heartwood in the but, middle and top, and sapwood recorded 41.18 μm, 43.87 μm, 34.09 μm in the same directions, respectively. Thus, the average fiber diameter for all trees ages were 33.18, 33.76, and 37.12 μm, respectively. The results indicate an uneven pattern of fiber diameter from the base to the top and in the heartwood and the sapwood. However, the sapwood fiber diameters in the base are more extensive than the heartwood in both trees.

3.5. Lumen width

The results in Table 2 indicate that the heartwood of 38-year-old trees recorded lumen width varies from 26.88 to 24.14 μm for the sapwood at the top and from 19.53 to 18.82 μm for 43-year-old trees obtained. For 47-year-old trees, at the top, the values ranged from 19.77 to 17.97 μm. However, there were no significant differences in the values recorded by all tree ages for the heartwood and the sapwood at the middle and the top sections. The results indicate a reduction in the lumen width in the heartwood and the sapwood from the base to the top sections in both trees.

3.6. Double cell wall thickness

The 38-year-old *A. grandiflora* wood samples recorded double cell wall thickness sizes of 8.52 to 11.91 μm; 12.84 μm for the heartwood, and 10.86 to 11.95 μm, 13.50 μm for the sapwood from the base to the top. The heartwood of the 43-year-old was 13.05, 17.74, and 14.86 μm, and the sapwood was 20.74 μm, 13.34 μm, and 14.84 μm from the base to the top. The 47-year-old recorded double cell wall thickness of 15.67, 19.91 μm, 16.56 μm for the heartwood and 24.82, 29.25, and 24.07 μm for the sapwood from the base to the top.

3.7. Runkel ratio

The study results indicate that the Runkel ratio values recorded for 38-year-old trees are 0.66, 1.31, 1.74 for the heartwood and 1.13, 1.34, and 1.84 for the sapwood from the base to the top, respectively. The heartwood of 43-year-old trees obtained mean Runkel ratio values of 1.36, 1.95, 2.00 for the heartwood and 2.36, 1.26, 1.42 for the sapwood, whereas 47-year-old trees recorded 1.59, 2.01, 2.46, and 2.76, 2.54, 2.56 for the base, middle and top of the heartwood and sapwood, respectively. This implies that, on average, the Runkel ratio is high in the heartwood and sapwood of trees with 43- and 47-year-olds. Hence, the Runkel ratio of timber species increases with age. Generally, the Runkel ratio is used to determine the suitability of fibrous material for pulp and paper production. If a wood species has a Runkel ratio of more than 1, its fiber will be stiff, less flexible, and have poor bonding ability.

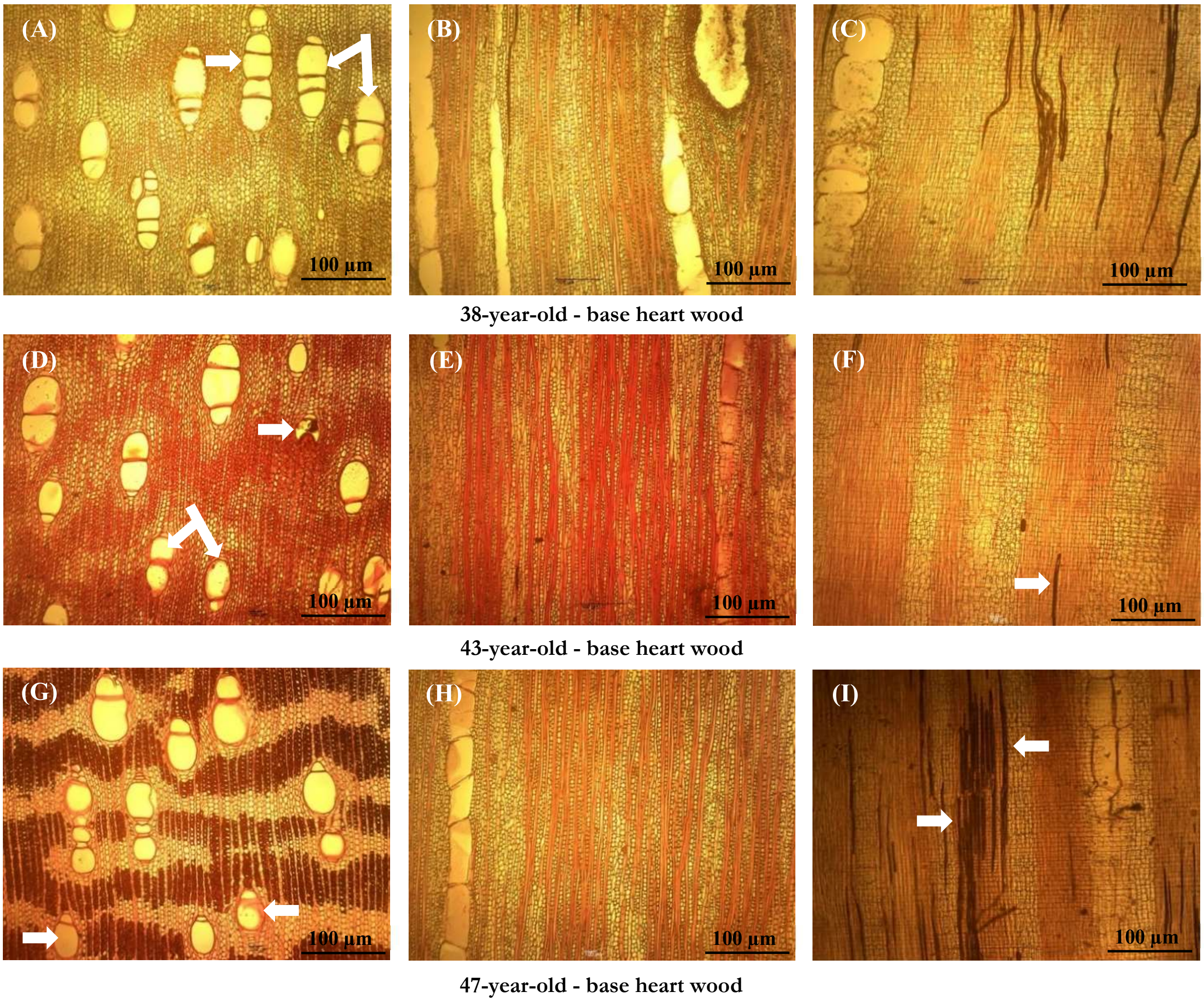


Figure 1. Micrographs describing anatomical features of *Anthocleista grandiflora* wood with 38, 43 and 47-year-old (10x magnification). (A) Transverse section showing solitary and radial multiples of 4-6 vessels, diffuse to diffuse-in-aggregates axial parenchyma; (B) Tangential section showing multiseriate homocellular rays; (C) Radial section showing ray cells containing some perismatic crystals (arrowed); (D) Transverse section showing solitary and radial multiples of 2-3 vessels with tyloses inclusions [arrowed], diffuse to diffuse-in-aggregates axial parenchyma; (E) Tangential section showing multiseriate homocellular rays; (F) Radial section showing ray cells containing few streaks of perismatic crystals (arrowed); (G) Transverse section showing solitary and radial multiples of 2-3 vessels with tyloses inclusions [arrowed], diffuse to diffuse-in-aggregates axial parenchyma; (H) Tangential section showing multiseriate homocellular rays; (I) Radial section showing ray cells containing visible streaks of perismatic crystals (arrowed).
Figura 1. Micrografias descrevendo características anatômicas de madeira de *Anthocleista grandiflora* aos 38, 43 e 47 anos (aumento de 10x). (A) Corte transversal mostrando múltiplos solitários e radiais de 4-6 vasos, parênquima axial difuso a difuso em agregados; (B) Corte tangencial mostrando raios homocelulares multiseriados; (C) Corte radial mostrando células dos raios contendo alguns cristais perismáticos (seta); (D) Corte transversal mostrando múltiplos solitários e radiais de 2-3 vasos com inclusões de tilos [seta], parênquima axial difuso a difuso em agregados; (E) Corte tangencial mostrando raios homocelulares multiseriados; (F) Corte radial mostrando células dos raios contendo poucas estrias de cristais perismáticos (seta); (G) Corte transversal mostrando múltiplos solitários e radiais de 2-3 vasos com inclusões de tilos [seta], parênquima axial difuso a difuso em agregados; (H) Corte tangencial mostrando raios homocelulares multiseriados; (I) Corte radial mostrando células dos raios contendo listras visíveis de cristais perismáticos (seta).

3.6. Aspect ratio

The results in Table 2 show that the 38-year-old *A. grandiflora* recorded aspect ratios of 52.78, 63.99, and 62.15 for the heartwood in the base, middle, and top and obtained 54.93, 54.81, and 61.86 for the sapwood in the same sections, the 43-year-old recorded aspect ratio of 51.25, 58.57 and 78.73 for the heartwood at the base, middle and the top sections, and 55.74, 55.59 and 61.88 for the sapwood in the three sections. In contrast, 47-year-olds recorded an aspect ratio of 55.49, 60.56, and 62.62 for the heartwood in the base, middle, and top and obtained 60.47, 66.79, and 66.88 for the sapwood in the same sections.

Table 1. Vessel measurement of the base, middle and top section of trees with 38-, 43-, and 47-year-old *A. grandiflora* wood.
Tabela 1. Dimensões dos vasos localizados na base, meio e topo das árvores de *A. grandiflora*, aos 38, 43 e 47 anos de idade.

Section	Parameters measured	38-year-old		43-year-old		47-year-old	
		Heartwood	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood
Base	Vessel área (µm)	434.21 (86.30)	501.81 (47.31)	484.49 (45.86)	534.90 (76.26)	511.07 (38.77)	551.36 (47.33)
	Vessel length (µm)	205.91 (39.26)	250.02 (42.90)	222.23 (38.87)	238.99 (21.47)	251.74 (27.61)	279.85 (81.13)
	Vessel number	34.00 (0.74)	54.00 (1.02)	49.00 (0.67)	63.00 (1.08)	56.00 (0.06)	72.00 (1.09)
	Vessel lumen fraction (mm)	14.76 (0.22)	27.10 (2.45)	23.74 (2.71)	33.70 (4.41)	28.62 (0.82)	39.70 (5.90)
	Size to number ratio	12.77 (0.37)	9.29 (0.44)	9.90 (0.33)	8.49 (0.63)	9.13 (0.23)	7.67 (0.76)
Middle	Vessel área (µm)	392.57 (79.73)	541.17 (77.49)	503.03 (51.30)	524.02 (55.03)	401.62 (42.51)	631.79 (38.15)
	Vessel length (µm)	186.92 (34.83)	246.33 (46.44)	237.02 (31.89)	240.18 (32.16)	241.11 (29.81)	252.90 (22.76)
	Vessel number	29.00 (0.43)	48.00 (0.45)	44.00 (0.72)	54.00 (1.06)	47.00 (0.65)	61.00 (1.11)
	Vessel lumen fraction (mm)	11.38 (0.47)	25.98 (2.61)	22.13 (0.56)	28.30 (1.08)	12.89 (0.51)	38.54 (4.04)
	Size to number ratio	13.54 (0.38)	11.27 (0.49)	11.43 (0.47)	9.7 (0.21)	8.55 (0.30)	10.36 (0.46)
Top	Vessel área (µm)	471.17 (44.85)	554.91 (84.44)	481.11 (54.55)	611.00 (51.69)	522.88 (47.19)	613.00 (47.35)
	Vessel length (µm)	208.58 (29.31)	260.31 (39.89)	215.08 (37.07)	237.81 (31.72)	244.55 (29.36)	288.79 (27.33)
	Vessel number	43.00 (0.43)	44.00 (0.54)	48.00 (0.56)	57.00 (0.88)	48.00 (0.32)	59.00 (0.65)
	Vessel lumen fraction (mm)	20.73 (1.23)	23.86 (3.58)	23.09 (1.38)	24.83 (3.63)	25.01 (3.36)	36.17 (4.27)
	Size to number ratio	10.71 (0.88)	12.91 (0.97)	10.02 (0.47)	10.72 (0.46)	10.89 (0.34)	10.39 (0.51)

Standard deviation in parenthesis.

Table 2. Fibers dimensions of wood at base, middle and top of 38-, 43-, and 47-year-old *A. grandiflora* trees.
Tabela 2. Dimensão das fibras localizadas na base, meio e topo das árvores de *A. grandiflora*, aos 38, 43 e 47 anos de idade.

Section	Parameters measured	38-year-old		43-year-old		47-year-old	
		Heartwood	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood
Base	Fiber length (mm)	1.80 (0.13)	2.00 (0.25)	1.66 (0.13)	2.18 (0.14)	1.84 (0.20)	2.49 (0.21)
	Fiber diameter (µm)	35.39 (6.50)	37.00 (5.49)	32.58 (2.83)	39.56 (3.85)	33.16 (1.54)	41.18 (2.63)
	Lumen width (µm)	26.88 (4.60)	24.14 (5.11)	19.53 (2.11)	18.82 (3.92)	19.77 (1.08)	17.97 (2.33)
	Fiber wall thickness (µm)	8.52 (4.19)	10.86 (3.39)	13.05 (2.49)	20.74 (4.31)	15.67 (3.34)	24.82 (3.37)
	Runkel ratio	0.66 (0.36)	1.13 (0.45)	1.36 (0.33)	2.36 (0.90)	1.59 (0.06)	2.76 (0.45)
	Aspect ratio	52.78 (11.34)	54.93 (10.40)	51.25 (6.11)	55.74 (6.79)	55.49 (3.82)	60.47 (5.12)
	Coefficient of rigidity	0.46 (0.24)	0.70 (0.17)	0.80 (0.12)	1.05 (0.19)	0.47 (0.11)	0.61 (0.14)
	Coefficient of flexibility	0.78 (0.12)	0.65 (0.09)	0.60 (0.06)	0.48 (0.10)	0.60 (0.12)	0.44 (0.20)
Middle	Fiber length (mm)	1.68 (0.19)	1.90 (0.18)	1.93 (0.13)	2.10 (0.14)	1.96 (0.12)	2.93 (0.13)
	Fiber diameter (µm)	30.85 (6.32)	31.16 (6.31)	36.25 (3.08)	34.90 (3.29)	38.79 (2.06)	43.87 (2.55)
	Lumen width (µm)	18.94 (4.35)	19.61 (4.67)	18.51 (2.05)	21.55 (2.52)	19.77 (2.33)	23.01 (1.32)
	Fiber wall thickness (µm)	11.91 (4.39)	11.95 (4.69)	17.74 (3.11)	13.34 (2.36)	19.91 (2.10)	29.25 (2.17)
	Runkle ratio	1.31 (0.52)	1.34 (0.80)	1.95 (0.47)	1.26 (0.28)	2.01 (0.34)	2.54 (0.15)
	Aspect ratio	63.99 (15.22)	54.81 (10.30)	58.57 (7.85)	55.59 (6.00)	60.53 (5.14)	66.79 (4.22)
	Coefficient of rigidity	0.76 (0.22)	0.75 (0.24)	0.97 (0.12)	0.76 (0.10)	0.46 (0.33)	0.33 (0.13)
	Coefficient of flexibility	0.62 (0.11)	0.63 (0.12)	0.51 (0.06)	0.62 (0.51)	0.51 (0.23)	0.53 (0.47)
Top	Fiber length (mm)	1.84 (0.12)	2.02 (0.21)	1.98 (0.21)	2.06 (0.09)	1.98 (0.18)	2.28 (0.77)
	Fiber diameter (µm)	33.03 (4.38)	31.64 (4.10)	25.82 (4.24)	33.47 (2.80)	31.62 (2.14)	34.09 (3.02)
	Lumen width (µm)	18.16 (4.82)	16.81 (3.81)	12.98 (2.26)	19.98 (3.28)	13.45 (1.55)	18.79 (2.11)
	Fiber wall thickness (µm)	12.84 (2.73)	13.50 (2.93)	14.86 (4.00)	14.84 (6.87)	16.56 (2.00)	24.07 (4.13)
	Runkle ratio	1.74 (0.69)	1.84 (0.87)	2.00 (0.42)	1.42 (0.53)	2.46 (0.34)	2.56 (0.31)
	Aspect ratio	62.15 (10.67)	61.86 (16.70)	78.73 (15.16)	61.88 (5.69)	62.62 (11.23)	66.88 (6.26)
	Coefficient of rigidity	0.89 (0.20)	0.90 (0.27)	0.99 (0.11)	0.81 (0.15)	0.46 (0.27)	0.44 (0.13)
	Coefficient of flexibility	0.55 (0.10)	0.55 (0.14)	0.51 (0.05)	0.60 (0.07)	0.43 (0.03)	0.55 (0.04)

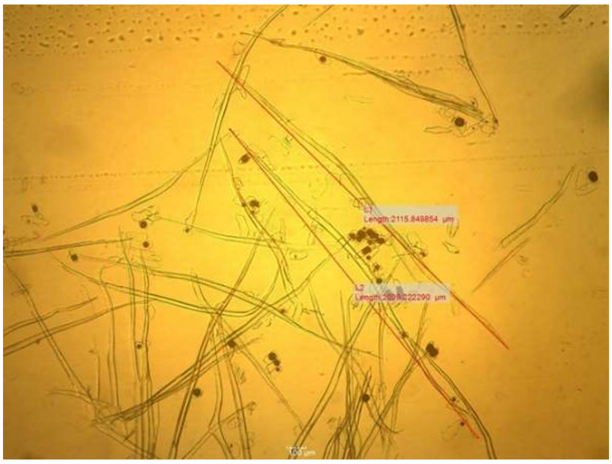
Standard deviation in parenthesis.

3.8. Coefficient of rigidity

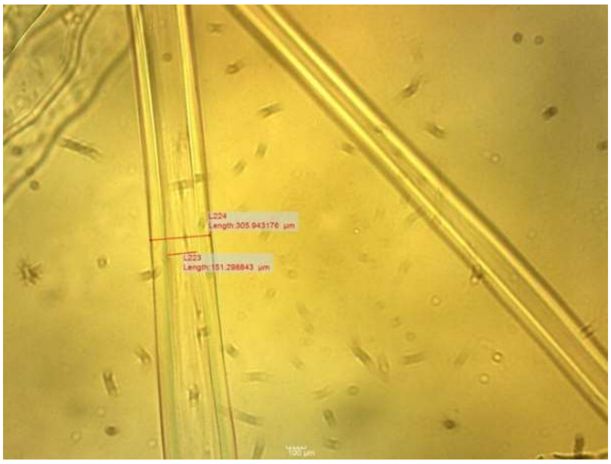
The rigidity coefficient of *A. grandiflora* fibers was 0.46, 0.76, and 0.89 for the heartwoods in the base, middle, and top of 38-years-old trees, and 0.70, 0.75, and 0.90 for the sapwood in the three respective sections, 43-years-old trees obtained 0.80, 0.97, 0.99 and 1.05, 0.76, 0.81 for the bases, middles, and tops in heartwood and sapwood, respectively. At the same time, 47-year-old trees were 0.47, 0.46, and 0.46 for the heartwoods in the base, middle, and top of 38-year-old trees, and 0.61, 0.33, and 0.44 for the sapwood in the three respective sections.

3.9. Coefficient of flexibility

The values of the coefficient of flexibility recorded for the heartwood of all trees ages at the base, middle, and top are 0.78, 0.62, and 0.55 with an average of 0.65; 43-year-old recorded 0.60, 0.51, and 0.51 with an average of 0.54 and 47-year-old recorded 0.60, 0.51, 0.43 with an average of 0.51. In comparison, their sapwood sections recorded 0.65, 0.63, 0.55 (average of 0.61); 0.48, 0.62, 0.60 (average of 0.57); 0.44, 0.53, 0.55 (average of 0.51).



Measuring the fiber length



Measuring lumen width and fiber wall thickness

Figure 2. Measuring fiber properties of *Anthocleista grandiflora* wood under a microscope.
Figure 2. Medição das fibras da madeira de *Anthocleista grandiflora* em microscópio.

4. DISCUSSION

4.1. Vessels characteristics

The results show more vessels in the sapwood region. The older species (47-year-old) had more vessels in the base section, 72.00 ± 1.09. Vessels in sapwood are the conduits through which most water in the transpiration stream of angiosperms must pass during its ascent to the canopy. The area of these vessels grows as their length increases (Jacobsen et al., 2012; Olson et al., 2014; and Liu et al., 2018). The sapwood determines the physiological properties of wood, while the heartwood determines the hardness of wood. Similar results were obtained by Jokanović et al. (2015) and Ren et al. (2023).

The study's results illustrate an apparent variation in the vessel composition of A. grandiflora, which could influence the sap conductivity of the three trees, as Poorter et al. (2008) and Zanne et al. (2010) observed. The values recorded for trees with all ages at the base, middle, and top sections indicate that vessel lumen fraction increases with the tree's age. The 47-year-old species had the highest lumen fraction values, 28.62 ± 0.82 mm in the heartwood region and 39.70 ± 5.90 mm in the sapwood. Both values were obtained from the base section. The high vessel lumen fraction in the sap along the bole indicates a lower mechanical strength property in the sapwood. Zanne et al. (2010) emphasized that variation in mean vessel size is a more potent driver of conductivity than variation in vessel size and that the contribution to hydraulic resistivity is approximately equal to vessel lumens and end walls (Bouda et al., 2019; Zanne et al. 2010).

In studies by Mensah et al. (2021) for *Theobroma cacao*, the number of vessels increased with the tree's age. Ogasa et al. (2010) stated that vessel diameter and distribution affect water conduction efficiency. Hence, with the average vessel distribution of 40, 49, and 57 vessels mm^{-2} for 38-, 43-, and 47-year-olds, respectively, it could be expected that *A. grandiflora* would have a high water uptake. Tyloses restrict pathogen movement. Hence, forming tyloses in A. grandiflora may contribute to its durability. Pouzoulet et al. (2014) emphasized that tylose formation was correlated with increased resistance to Dutch elm disease in elm trees.

It is worth noting that the exact characteristics of heartwood can vary depending on the tree species, growth conditions, and environmental factors (Pinto et al., 2004). Despite these variations, the heartwood is generally recognized for its enhanced strength, durability, and beauty, making it a valuable material in woodworking and construction (Antwi-Boasiako et al., 2019). In the utilization of hardwood in various applications, understanding the characteristics of both sapwood and heartwood is essential to make informed decisions about the suitability of the wood for a particular purpose.

Monteoliva et al. (2005) report that variations in wood density and fiber dimensions are present in trees in the radial and longitudinal direction and within the annual rings. These variations may be due to genetic, physiological, or silvicultural treatments (Ma et al., 2021; Roque and Fo, 2007).

The sapwood has longer fibers than the heartwood (Atac and Eroğlu, 2013; Bahmani et al., 2020). The research analysis showed that the greatest fiber length is in the sapwood region, the middle section of the 47-year-old – the value was 2.93 ± 0.13 mm. Comparatively, *A. grandiflora* has a higher average fiber length than other timbers such as *Sorbus terminalis* (1.57 mm), reported by Bahmani et al. (2020); *Terminalia ivorensis* (1.20 mm) and *Triplochiton scleroxylon* (1.30 mm), reported by Awaku (1994); and *Hevea brasiliensis* (1.18 mm), reported by Amorim et al. (2021). Thus, according to IAWA (1989), A. grandiflora is classified as medium-length fiber wood. Migneault et al. (2008) emphasized that fiber length significantly influences fiber-based products, such as fiberboard strength properties. These authors again affirmed that fiber length determines whether the quality of raw material is suitable for specific use in the paper industry or not because of its impacts on paper characteristics, such as strength, optical properties, and surface quality. Species with higher fiber lengths are preferred in fiberboard, pulp, and paper production for better mechanical interconnectivity to enhance high resistance and better static bending properties. Hence, Monteoliva et al. (2002) confirmed that fibers longer than 1.00 mm (as recorded by *A. grandiflora* in this study) are preferred for pulp and paper manufacturing.

The diameter of the fiber is another factor that varies with age and the positions in which the samples were taken. The analyses showed that at 47-year-old, the middle section presented the highest value for fiber diameter in the sapwood region (43.87 ± 2.55 μm). The increase in fiber diameter was reported to be associated with the many molecular and physiological changes that occur in the vascular cambium and the increase in wood cell walls during the tree-growing processes (Plomion et al., 2001). Comparatively, the average fiber diameter of *A. grandiflora* is higher than *Theobroma cacao* wood (22.51 μm), as reported by Mensah et al. (2021); *Gmelina arborea* (23.00 μm) Roque et al. (2007); *Paraserianthes falcataria* (18.30 μm) Ishiguri et al. (2009). Hence, the results indicate that A. grandiflora is suitable for construction, furniture works, fiber-based products, and pulp and paper production.

The reduction in lumen diameter from heartwood to sapwood and from base to top was observed by Mensah et al. (2021) and Izekor and Fuwape (2011), who attributed the difference in lumen width with increasing age of the tree to an increase in cell size and physiological development of the wood as the tree grows in girth. Adamopoulos et al. (2010) and Rodriguez-Zaccaro et al. (2019) attributed this phenomenon to an increase in fiber length initially associated with increasing cambium age. Thus, *A. grandiflora* is suitable for utilization as timber as this property compares favorably with other species in the industry.

The highest fiber wall thickness value was indicated for the 47-year-old species, middle section, sapwood region (29.25 ± 2.17 μm). Double cell wall thickness increases with age, which could be attributed to the increasing age of the cambium as the tree grows in girth (Molina et al., 2016). Saravanan et al. (2013) again attributed the increase in double cell wall thickness of *Gmelina arborea* to changes in cell size associated with annual and periodic growth cycles and the increasing age of the cambium.

The study values were higher than that of Ailanthus altissima, as recorded by Samariha et al. (2011), and *Theobroma cacao* stem wood, as reported by Mensah et al. (2021). San et al. (2016) emphasized that cell wall thickness directly affects the strength properties of cell walls. The thicker the cell wall, the more flexible the fibers in the pulp refining process (Hemmasi et al. 2011). Woods with thicker cell walls would be more robust, heavier, and stiffer than wood with thin-walled elements. Some anatomical features like fiber wall thickness affect the bending strength properties of the timber species (Xie et al., 2016).

Fibers from heartwood samples taken from the base of the 38-year-old showed the lowest Runkel value, 0.66 ± 0.36. Whereas fibers with a low Runkel ratio (<1) produce good-quality pulp and paper (Ganesh et al., 2023). Riki et al. (2019) reported that materials with a Runkel value of less than one would be suitable for papermaking because they collapse (become ribbon-like) and provide a large surface area for bonding. At 38-year-old, a value lower than 1,0 was observed for the Runkel index in the heartwood region. It will not be suitable for pulp and paper production but for fiber-based product production, which does not necessarily pay much attention to the Runkel ratio properties of lignocellulose materials, as does the aspect ratio. The timber obtained is suitable for construction and furniture fitments.

Previous studies have indicated that the mechanical properties of fiberboards positively correlate with the aspect ratio (particle geometry) of the biomass materials. This is because of its greater surface area regarding contact between particles (Bax and Mussig 2008; Juliana et al. 2014; Mitchual et al. 2020). Wood particles with a higher aspect ratio enhance stress transfer from the polymer matrix to the particles, improving the composite mechanical properties. The aspect ratio influences the mechanical properties of wood when producing fiberboard. Juliana et al. (2014) confirm that higher bending strength properties are obtained from longer particles because of their greater surface area regarding particle-particle interactions. Mensah et al. (2021) indicated that *Theobroma cacao* stem wood with an aspect ratio of 59.31 and 64.81 for 14- and 26-year-olds could exhibit high mechanical properties in fiberboards produced with it. Khan et al. (2020) indicated that the processing method's influence on the composite panels' stiffness and strength depends strongly on the aspect ratio of the wood particles.

According to the rigidity ratio, there are four groups of fibers Kiaei (2012): (i) High elastic fibers with an elasticity coefficient greater than 0.75. (ii) Elastic fibers having an elasticity ratio between 0.50-0.75: (iii) Rigid fibers having an elasticity ratio between 0.30-0.50: (iv) Highly rigid fibers having an elasticity ratio less than 0.30. This classification included the rigidity coefficients of 38-, 43- and 47-year-old A. grandiflora fibers in the high elastic fibers group. It was observed that, generally, this characteristic decreases with age.

For the coefficient of flexibility, the results were similarly recorded for *Dacryodes edulis* (0.57) by Ajuziogu et al. (2010), *Daniellia olivera* (0.51) by Idu and Ijeomah (2000), and *Leucaena leucocephala* (0.63) by Oluwadare and Ashimiyu (2007). The coefficient of flexibility property is significant in producing pulp and paper. The recorded figures imply that A. grandiflora is a suitable alternative timber species for pulp and paper as it is compared very well with those reported species used for pulp and paper manufacturing.

5. CONCLUSIONS

The *A. grandiflora* wood at the 38-, 43- and 47-year-old exhibited, in the base, middle and top regions, anatomical variations characteristically in the vessels area, vessels length, vessels number, fraction of the vessels lumen, and in the proportion pot size/number. The fibers also showed variations in length, diameter, lumen width, wall thickness, Runkel ratio, aspect ratio, stiffness, and flexibility coefficient for all trunk regions and in all ages of trees studied. However, these variations do not significantly affect its suitability for construction, furniture, fiber-based products, and other industrial applications.

The morphological micrographs present patterns for vessels, fibers, and parenchyma, providing bases for wood identification and explaining wood behavior; hence, they do not distinguish it from congeners.

Due to properties such as aspect ratio, fiber length, Runkel ratio, and other suitable anatomical characteristics, the wood species evaluated can be a viable alternative for use in industries based on fibers, agglomerates, cellulose, and paper.

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