宇 大 演 報
第 59 号（2023）論 文

Bull. Utsunomiya Univ. For.
No. 59 (2023) Article

Anatomical characteristics, derived-wood, chemical, and kraft pulp properties of *Acacia* species grown in Gabon

ガボンで生育した *Acacia* 種から得られた木材の組織学的性質，派生的木材性質，化学的性質およびクラフトパルプ特性

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ABSTRACT

To promote sustainable wood production based on plantation forestry using fast-growing tree species in Gabon, wood properties especially for anatomical characteristics, derived-wood properties related to pulp and paper quality, amounts of wood chemical components, and kraft pulp properties were investigated for *Acacia* sp. originated from plantation of *A. mangium* and *A. auricuriformis* in Gabon. Mean values of basic density, wood fiber length, wood fiber diameter, wood fiber wall thickness, vessel element length, vessel diameter, and vessel frequency were 0.50 g/cm^3, 0.98 mm, 17.5 μm, 2.7 μm, 0.26 mm, 138 μm, and 8 vessels/mm^2, respectively. Mean values were 0.45 for Runkel ratio, 0.69 for flexibility coefficient, 56.5 for slenderness ratio, 0.36 for Luce's shape factor, 0.15 for coefficient of rigidity, and 156 × 10^3 μm^3 for solid factor, respectively. Mean values of chemical and pulp properties, in heartwood were 6.0%, 16.4%, 7.2%, 0.4%, 23.5%, 74.9%, 59.5%, 54.8%, and 11.5 for hot-water extracts, 1% NaOH extracts, organic solvent extracts, ash, Klason lignin, holocellulose, α-cellulose, pulp yield, and kappa number, respectively. Obtained values of these characteristics in the present study were in the range of those reported in previous studies. Thus, it is considered that *Acacia* wood obtained from the plantation in Gabon can be used as raw material for pulp and paper production. In the present study, wood was classified into two types, core (up to 5 cm from pith) and outer wood in anatomical characteristics and derived-wood properties, and heartwood and sapwood in chemical and kraft pulp properties. As the results, these characteristics between core and outer wood, and heartwood and sapwood were almost the same, suggesting that effects of wood type (core or outer wood, and heartwood or sapwood) on pulp and paper quality might be limited on *Acacia* species grown in Gabon. Based on the results, it is concluded that raw materials of pulp and paper can be supplied from plantations of *Acacia* species in Gabon instead of natural forests.

Keywords: *Acacia mangium*, *Acacia auricuriformis*, core wood, outer wood, pulp and paper quality

要　旨

ガボンにおいて早生樹林業を基盤とした持続的な木材生産を促進するために，ガボンの *Acacia mangium* および *Acacia auricuriformis* の植林地の林縁において，天然で更新した *Acacia* 種から得られた木材の組織学的性質，派生的木材性質，化学的性質およびクラフトパルプ特性を調査した．容積密度，木部繊維長，木部繊維直径，木部繊維壁厚，道管要素長，道管直径および道管分布数の平均値は，0.50 g/cm^3，0.98 mm，17.5 μm，2.7 μm，0.26 mm，138 μm および 8 個 /mm^2 であった．また，派生的木材性質の平均値は，Runkel ratio で 0.45，flexibility coefficient で 0.69，slenderness ratio で 56.5, Luce's shape factor で 0.36, coefficient of rigidity で 0.15 および solid factor で 156 × 10^3 μm^3 であった．さらに，心材における木材化学成分量およびパルプ特性は，温水抽出物，1％アルカリ抽出物，有機溶媒抽出物，灰分，クラーソンリグニン，ホロセルロース，α －セルロース，パルプ収率およびカッパー価でそれぞれ 6.0%，16.4%，7.2%，0.4%，23.5%，74.9%，59.5%，54.8% および 11.5 であった．本研究で得られたこれらの平均値は，既往の文献で得られている値の範囲内であった．従って，ガボンで生育した *Acacia* 種も，紙・パルプの原料として十分に利用可能であると考えられる．また，本研究では，*Acacia* 種の木材を樹心部（髄から 5 cm まで）と辺縁部（髄から 5 cm 以降）に分割して組織学的性質および派生的木材性質を評価し，また，心材および辺材に分割して木材化学成分量およびクラフトパルプ特性を評価した．その結果，樹心部および辺縁部，もしくは心材および辺材の間で測定した性質の違いは

認められなかった．このことは，ガボンで生育した *Acacia* 種において，木材のタイプ（樹心･辺縁部，心･辺材）は紙･パルプ特性に大きな影響を与えないことを示唆している．以上のことから，ガボンにおける紙・パルプ原料は，天然林からの木材に代わって，植林地から得られる *Acacia* 種が利用可能であることが明らかとなった．
キーワード：*Acacia mangium*, *Acacia auricuriformis*, 樹心部，辺縁部，紙パルプ特性

1. Introduction

Fast-growing tree plantation has been developed in tropical and subtropical countries to fulfil the demands for raw materials in the wood, pulp and paper industries. The implementation of fast-growing species plantation is also expected to have a great effect on mitigating increasing atmospheric carbon dioxide (CO_2) by acting as a massive sink (Kojima et al. 2009). The most obvious advantage of fast-growing tree species is their rapid growth. Compared with longer-rotation plantations, fast-growing tree plantations can produce one and a half to two times more wood per hectare per year and reach maturity two to three times faster (Cossalter and Pye-Smith 2003). Many studies have indicated that fast-growing tree species have the potentials for further utilization for wood products due to their rapid growth rate, availability, renewable nature, high productivity, and multiple uses (Alamsyah et al. 2007; He et al. 2016; Istikowati et al. 2016; Grzegorzewska et al. 2020).

Wood from commercial plantations with fast-growing trees is mainly utilized as raw materials for pulp and paper (Cossalter and Pye-smith 2003; Malinen et al. 2006; Alamsyah et al. 2007; Nugroho et al. 2012; Istikowati et al. 2016). To increase efficiency in production of pulp and paper, pulping properties as well as wood properties in relation to pulp and paper quality have been investigated for the fast-growing tree species (Santos et al. 2006, 2012; Yahya et al. 2010; Takeuchi et al. 2016; Prasetyo et al. 2017, 2019). Anatomical characteristics of wood are the most important properties affecting the properties and quality of pulp and paper production (Table 1, Ona et al. 2001; Wimmer et al. 2002; Ohshima et al. 2011). Paper with stronger properties can be produced from longer wood fibers (Zobel and van Buijtenen 1989; Ona et al. 2001; Wimmer et al. 2002). In addition, wood fiber wall thickness is closely related to pulp yield, sheet density, and paper strength (Ona et al. 2001). For evaluation of pulp and paper properties, derived-wood properties can be calculated based on anatomical characteristics (Table 1, Runkel 1949; Tamolang and Wangaard 1961; Barefoot et al. 1964; Luce 1970; Malan and Gerischer 1987; Ona et al. 2001). Ona et al. (2001) reported that quality of pulp and paper such as pulp yield, sheet density, burst factor, and other pulp and paper properties were significantly correlated with derived-wood properties such as the Runkel ratio, the flexibility ratio, the slenderness ratio, Luce's shape factor, coefficient of rigidity, and the solid factor. Besides anatomical characteristics, the chemical properties of wood also affect the properties of pulp and paper. Chemical properties of wood are one of the important factors determining the quality of pulp and paper, especially for pulping process, pulp yield, kappa number, and quality of the final product (Table 1, Little et al. 2003; Ramírez et al. 2009; Istikowati et al. 2016). Wood with lower lignin and extractive contents results in higher pulp yield and pulp strength and it is preferable for pulp and paper (Little et al. 2003; Ramirez et al. 2009; Istikowati et al. 2016). Therefore, it is important to study the anatomical characteristics, derived-wood properties, and chemical properties of wood in relation to pulp and paper quality.

Gabon is a country located on the equator in west coast of central Africa. Climatic conditions as Köppen climate classification are tropical rainforest climate (Af) and tropical savanna climate with dry-winter characteristics (Aw):

Table 1 Anatomical characteristics, derived-wood properties, and chemical properties of wood in relation to pulp and paper quality.

	Property	Effects of wood properties on pulp and paper quality	References
Wood property	Basic density	Pulp yield and tearing strength (positively), tensile and bursting strength (negatively)	Wimmer et al. (2002) Ramírez et al. (2009)
Anatomical characteristics	Wood fiber length	Pulp yield and tearing strength (positively)	Wimmer et al. (2002)
	Wood fiber wall thickness	Pulp yield, sheet density, and paper strength (positively)	Ona et al. (2001)
	Vessel element length	Printability (negatively)	Ohshima et al. (2011)
	Vessel diameter	Pulp yield and tearing strength (positively)	Ona et al. (2001)
Derived-wood properties	Runkel ratio	Pulp yield (positively) and digestibility (negatively)	Runkel (1949), Ona et al. (2001)
	Flexibility coefficient	Tearing and tensile strength (positively)	Malan and Gerischer (1987)
	Slenderness ratio	Tearing strength (positively)	Malan and Gerischer (1987)
	Luce's shape factor	Resistance to beating (positively)	Luce (1970)
	Coefficient of rigidity	Bursting and tensile strength (negatively)	Tamolang and Wangaard (1961)
	Solid factor	Sheet density (negatively)	Barefoot et al. (1964)
Chemical properties	Extracts	Pulp yield (negatively)	Little et al. (2003)
	Lignin	Pulp yield (negatively) and tensile strength (positively)	Ramírez et al. (2009), Istikowati et al. (2016)
	Cellulose	Pulp yield (positively)	Ramírez et al. (2009)

mean annual temperature and precipitation in capital city, Libreville are 26.9 ℃ and 2510 mm, respectively (Ninomiya Shoten Publishing 2021). The country is rich in forest resources: 91% of total land area of the country is forest (23,531,000 ha) (FAO 2020). Of the total forest area of the country, only 0.13% (30,000 ha) of the forests is plantation. Using the forest resources from huge natural forests, timber is one of the main export products of the country (Ninomiya Shoten Publishing 2021). Thus, wood resources obtained especially from natural forests are very important for economy of the country. To conserve the ecological conditions and biodiversity, forest resources should be obtained from not only natural forests but also plantations with intensive management systems for sustainably obtaining the forest resources. Fortunately, the country is located in tropical regions, suggesting that plantation with fast-growing trees can be established in the country as well as other tropical countries such as tropical Asian countries, south American countries, and others.

To promote sustainable wood production based on plantation forestry using fast-growing tree species in Gabon, wood properties especially for anatomical characteristics, derived-wood properties related to pulp and paper quality, amounts of wood chemical components, and kraft pulp properties were investigated for *Acacia* species originated from a plantation of *A. mangium* and *A. auricuriformis* in Gabon.

2 Materials and methods

2.1 Materials

Two trees (tree no. 1 and tree no. 2) of *Acacia* sp. were used in the present study. These trees originated from seedlings were grown in surrounding area of an *A. mangium* and *A. auriculiformis* plantation (Figure 1). Species of used trees were not identified, but it might be *A. mangium*, *A. auriculiformis* or their hybrids. The age was unknown due to lack of annual rings. Stem diameter at 1.3 m above the ground and tree height were 17.5 cm and 11.5 m in tree no. 1, and 21.4 cm and 13.0 m in tree no. 2, respectively. After harvesting the trees, one log (10 cm in length) and two disks (3 cm in thickness) were collected from around 1.3 m above the ground in each tree for the following experiments (Figure 1).

2.2 Basic density

Wedge-shape specimens (30° in center angle) were collected from the disks for determining basic density (Figure 1). The specimens were cut again at 1-cm intervals from pith. Before determining the volume in wet condition, specimens were soaked into tap water for about one week. Basic density was calculated by dividing the oven-dry weight at 105 ℃ by wet volume measured by water displacement.

2.3 Anatomical characteristics

Pith-to-bark radial strips were prepared from the disks (Figure 1). The strips were again cut into specimens and small sticks at 1-cm intervals from the pith. The small specimens were used for preparing transverse sections, while the small sticks were used for measuring cell length.

Transverse sections (20 μm in thickness) were prepared by a sliding microtome (REM-710, Yamato Koki, Saitama, Japan). The sections were stained with safranin, and

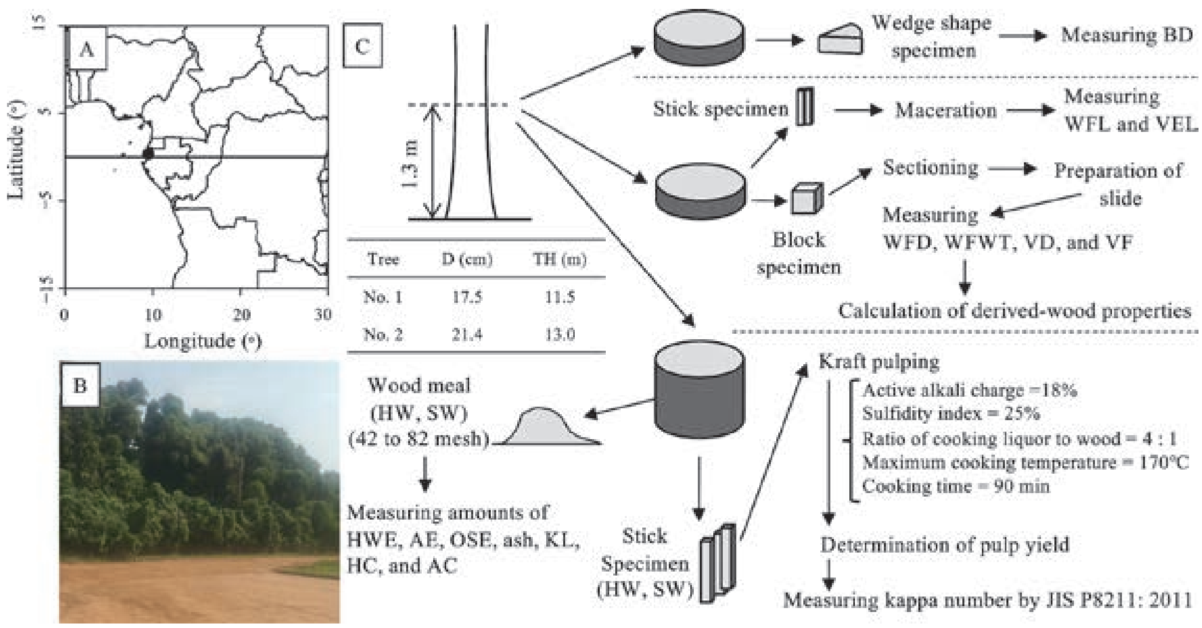

Figure 1 Map (A) and a photograph (B) of sampling site, and experimental procedures (C) in the present study.

Note: D, stem diameter at 1.3 m above the ground; TH, tree height; BD, basic density; WFL, wood fiber length; VEL, vessel element length; WFD, wood fiber diameter; WFWT, wood fiber wall thickness; VD, vessel diameter; VF, vessel frequency; HWE, hot-water extracts; AE, alkaline extracts (1% NaOH extracts); OSE, organic solvent extracts (ethanol-toluene extracts); KL, Klason lignin; HC, holocellulose; AC, α-cellulose; HW, heartwood; SW, sapwood; JIS, Japanese Industrial Standards. A closed circle and a solid line in map (A) indicate the sampling site (0°18'N, 9°30'E) and equator, respectively.

then were dehydrated by graded ethanol. The dehydrated sections were dipped into xylene. After that, the sections were mounted with biolite. Digital images of the transverse sections were captured by a digital camera (DS-2210, Sato syoji, shouji Kawasaki, Japan) equipped with a microscope (CX41, Olympus, Tokyo, Japan) to measure wood fiber morphology (diameter and wall thickness) and vessel morphology (diameter and frequency). Morphology of wood fibers and vessels was determined by the methods described in Takeuchi et al. (2016).

2.4 Derived-wood properties

Runkel ratio, flexibility coefficient, slenderness ratio, Luce's shape factor, coefficient of rigidity, and solid factor were calculated as derived-wood properties. The formula of these derived-wood properties are listed in Table 2 (Runkel 1949; Tamolang and Wangaard 1961; Barefoot et al. 1964; Luce 1970; Malan and Gerischer 1987).

2.5 Wood chemical components

The amounts of the following wood chemical components were determined: hot-water extracts, alkaline extracts (1% NaOH extracts), organic solvent extracts (ethanol-toluene extracts), ash, Klason lignin, and holocellulose. For determining the chemical components, wood meals (42 to 82 mesh) of heartwood and sapwood were prepared from the samples (Figure 1). These wood chemical components were determined by the methods described in previous report (Istikowati et al. 2016).

2.6 Kraft pulp properties

Kraft pulp was prepared according to the method of Istikowati et al. (2016). Wood sticks (ca. 1 (T) × 1 (R) × 20 (L) mm) of heartwood and sapwood were prepared from the disk (Figure 1). Five gram (oven-dry weight) of wood sticks was put in the an autoclave (40 mL) with cooking liquor (16% active alkali charge and 25% sulfidity index, weight basis mixture ratio: 4 : 1 = cooking liquor : wood sticks). The autoclave with cooking liquor and wood sticks was heated at 170 ℃ for 90 min by an oil bath (OB-BS, ADVANTEC, Tokyo, Japan). After cooking, cooked pulp was defibrinated by a pestle and a motar. The cooked pulp was filtrated thought a glass filter (1G3) and then washed with 2L of distilled water. Washed kraft pulp was dried at 105 ℃ and weighted to determine the pulp yield. In addition, kappa number was also determined according to Japanese Industrial Standards (JIS P8211: 2011).

Table 2 Formula of derived-wood properties calculated in the present study.

Derived-wood property	Formula	Reference
Runkel ratio	(2 × WFWT) / WFLD	Runkel (1949)
Flexibility coefficient	WFLD / WFD	Malan and Gerischer (1987)
Slenderness ratio	WFL / WFD	Malan and Gerischer (1987)
Luce's shape factor	$(WFD^2 - WFLD^2) / (WFD^2 + WFLD^2)$	Luce (1970)
Coefficient of rigidity	WFWT / WFD	Tamolang and Wangaard (1961)
Solid factor	$(WFD^2 - WFLD^2) \times WFL$	Barefoot et al. (1964)

Note: WFWT, wood fiber wall thickness; WFLD, wood fiber lumen diameter; WFD, wood fiber diameter; WFL, wood fiber length.

2.7 Statistical analysis

All statistical analysis were conducted by R version 4.0.2 (R Core Team 2020). Boundary between core and outer wood was determined by increasing ratio of wood fiber increment (Honjo et al. 2005). Wood fiber increment was defined as a subtracted value of wood fiber length from vessel element length at each radial position in individual tree. The following logarithmic formula (1) was developed for radial variation of wood fiber increment:

$$WFI = a \bullet \ln(RD) + b \quad (1)$$

where *WFI* is wood fiber increment, and *RD* is radial distance from pith (1-mm intervals from pith). Using the estimated values of wood fiber increment, increase ratio of wood fiber increment was determined by the following formula (2):

$$IR = a \bullet RD^b \quad (2)$$

where *IR* is increasing ratio, and *RD* is radial distance from pith (1 mm interval from pith).

To evaluate the effect of wood type (heartwood or sapwood) on chemical and pulp properties, the following linear mixed-effects model (3) was developed by using lmer function in lme4 package (Bates et al. 2015):

$$y_{ij} = \mu + WT_j + e_{ij} \quad (3)$$

where y_{ij} is the observation value in the ith replicate of the jth wood type, μ is the grand mean of all observation, WT_j is the random effect of the *j*th wood type, and e_{ij} is the residual. Variance component ratios were also calculated by the obtained variance components.

3 Results

3.1 Anatomical characteristics

Table 3 shows the mean values of basic density, anatomical characteristics, and derived-wood properties. The mean values of basic density, wood fiber length, wood fiber diameter, wood fiber wall thickness, vessel element length, vessel diameter, and vessel frequency was 0.50 g/cm^3, 0.98 mm, 17.5 μm, 2.7 μm, 0.26 mm, 138 μm, and 8 vessels/mm^2, respectively. Basic density gradually increased up to 4 cm from pith and then showed almost stable values (Figure 2). Figure 3 shows radial variations of anatomical characteristics. Wood fiber length, vessel element length,

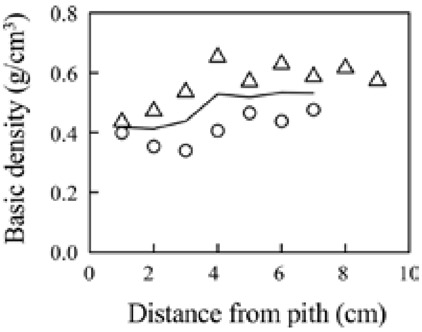

Figure 2 Radial variation of basic density.

Note: Circles, triangles, and solid line indicate data of tree no. 1 and no. 2, and mean values of two trees, respectively.

Table 3 Statistical values of basic density, anatomical characteristics, and derived-wood properties.

Property	Tree No. 1 (n = 7)		Tree No. 2 (n = 10)		Mean / total (n = 17)	
	Mean	SD	Mean	SD	Mean	SD
BD (g/cm³)*1	0.41	0.05	0.56	0.07	0.50	0.10
WFL (mm)	1.01	0.18	0.96	0.09	0.98	0.14
WFD (μm)	18.7	1.2	16.7	0.7	17.5	1.4
WFWT (μm)	2.6	0.2	2.8	0.2	2.7	0.2
VEL (mm)	0.28	0.05	0.24	0.02	0.26	0.04
VD (μm)	143	33	135	9	138	22
VF (vessels/mm²)	8	6	8	2	8	4
RR	0.39	0.07	0.50	0.03	0.45	0.07
FC	0.72	0.04	0.67	0.01	0.69	0.04
SR	54.6	13.2	57.8	7.7	56.5	10.1
LSF	0.32	0.05	0.38	0.02	0.36	0.05
CR	0.14	0.02	0.17	0.01	0.15	0.02
SF (× 10^3 μm³)	167	22	148	9	156	18

Note: n, number of radial position; SD, standard deviation; BD, basic density; WFL, wood fiber length; WFD, wood fiber diameter; WFWT, wood fiber wall thickness; VEL, vessel element length; VD, vessel diameter; VF, vessel frequency; RR, Runkel ratio; FC, flexibility coefficient; SR, slenderness ratio; LSF, Luce's shape factor; CR, coefficient of rigidity; SF, solid factor; *1, number of radial position was 7 and 9 in tree no. 1 and 2, respectively.

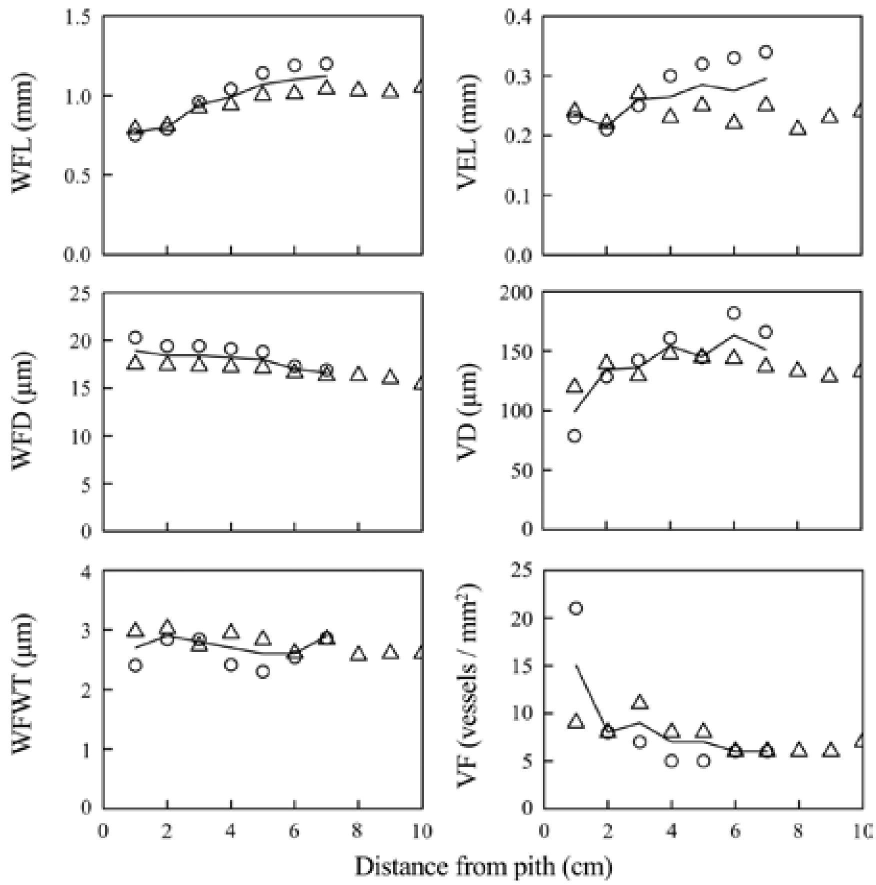

Figure 3 Radial variations of anatomical characteristics.

Note: WFL, wood fiber length; VEL, vessel element length; WFD, wood fiber diameter; VD, vessel diameter; WFWT, wood fiber wall thickness; VF, vessel frequency. Circles, triangles, and solid line indicate data of tree no. 1 and no. 2, and mean values of two trees, respectively.

and vessel diameter gradually increased from pith to bark, whereas wood fiber diameter gradually decreased from pith to bark. In wood fiber wall thickness, almost stable value was found from pith to bark. Vessel frequency rapidly decreased up to 2 cm from pith and then showed almost constant values around 5 to 10 vessels/mm^2 (Figure 3).

Figure 4 shows the radial variations of derived-wood properties. Although slenderness ratio and solid factor increased and flexibility coefficient gradually decreased from pith to bark, no consistent trend from pith to bark were found in other derived-wood properties. As the results, mean values were 0.45 for Runkel ratio, 0.69 for flexibility coefficient, 56.5 for slenderness ratio, 0.36 for Luce's shape factor, 0.15 for coefficient of rigidity, and 156 × 10^3 μm^3 for solid factor, respectively (Table 3).

Correlation coefficients between basic density and

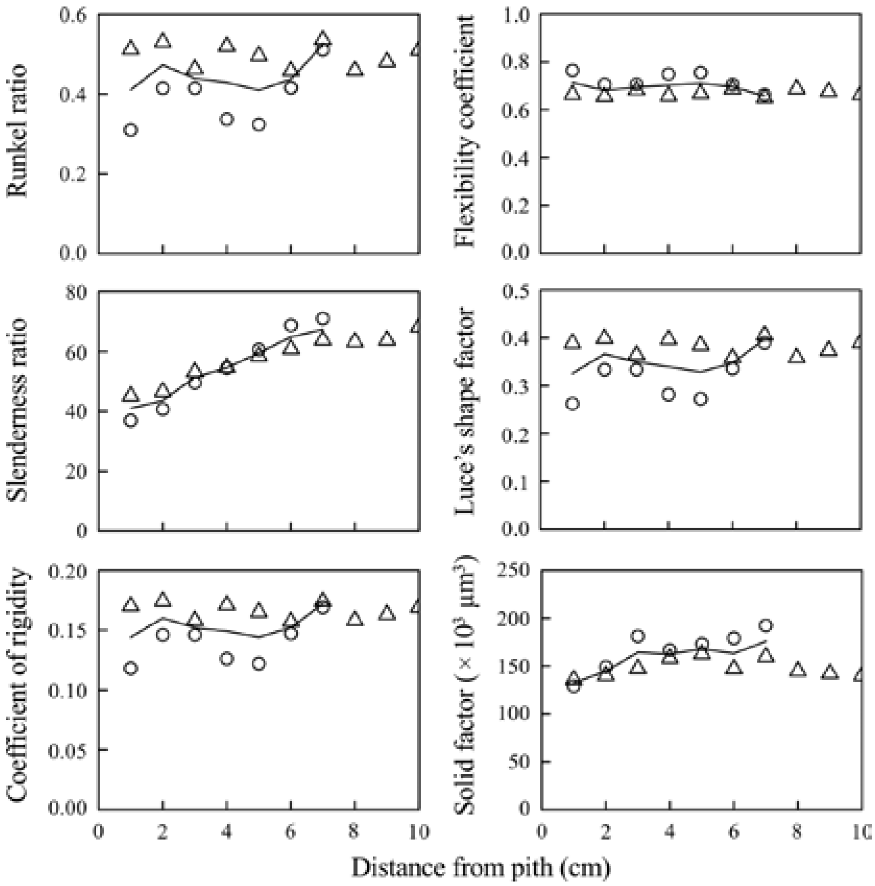

Figure 4 Radial variations of derived-wood properties.

Note: Circles, triangles, and solid line indicate data of tree no. 1 and no. 2, and mean values of two trees, respectively.

Table 4 Correlation coefficients between basic density and measured anatomical characteristics.

Factor 1	Factor 2	*r*	*p*	Factor 1	Factor 2	*r*	*p*
BD	WFL	0.253	0.344	VEL	WFD	0.072	0.791
	VEL	–0.261	0.328		WFWT	–0.334	0.206
	WFD	**–0.808**	< 0.001		VD	**0.626**	0.010
	WFWT	0.101	0.709		VF	–0.288	0.279
	VD	0.091	0.737	WFD	WFWT	–0.306	0.249
	VF	–0.239	0.373		VD	–0.333	0.207
WFL	VEL	**0.735**	0.001		VF	0.490	0.054
	WFD	–0.401	0.123	WFWT	VD	0.057	0.834
	WFWT	–0.346	0.189		VF	–0.097	0.720
	VD	**0.774**	< 0.001	VD	VF	**–0.794**	< 0.001
	VF	**–0.652**	0.006	–	–	–	–

Note: number of radial positions = 16 positions from two trees. *r*, correlation coefficient; *p*, *p*-value; BD, basic density; WFL, wood fiber length; VEL, vessel element length; WFD, wood fiber diameter; WFWT, wood fiber wall thickness; VD, vessel diameter; VF, vessel frequency. Bold values indicate correlation coefficients with *p*-values less than 0.05.

measured anatomical characteristics are listed in Table 4. Basic density was negatively correlated with wood fiber diameter ($r = -0.808$, $p < 0.001$). Significant correlations were found between wood fiber length and vessel element length ($r = 0.735$, $p = 0.001$), vessel diameter ($r = 0.774$, $p < 0.001$), and vessel frequency ($r = -0.652$, $p = 0.006$). Among the vessel morphologies, vessel diameter was significantly correlated with vessel element length ($r = 0.626$, $p = 0.010$) and vessel frequency ($r = -0.794$, $p < 0.001$).

Table 5 shows parameters of regression formula of radial variations in wood fiber increment and increase ratio of wood fiber. Increase ratio rapidly decreased up to 5 cm from pith (Figure 5). Wood fiber increment at 5 cm from the pith was corresponded to 0.10% increase ratio of it (Table 6). By using the boundary (5 cm from the pith), anatomical characteristics and derived-wood properties were calculated for core and outer wood. Results are shown in Table 7. Significant differences were found between core and

Table 5 Parameters of regression formula of radial variations in wood fiber increment and increase ratio of wood fiber.

Property	Formula	Parameter							
		a				*b*			
		Estimates	SE	*t*	*p*	Estimates	SE	*t*	*p*
Wood fiber increment (WFI)	$WFI = a \bullet \ln(RD) + b$	0.14533	0.01420	10.23	< 0.001	0.52388	0.02201	23.80	< 0.001
Increase ratio (IR)	$IR = a \bullet RD^b$	2.14402	0.09664	22.18	< 0.001	–1.98353	0.03018	–65.73	< 0.001

Note: SE, standard error; *t*, *t*-value; *p*, *p*-value.

Table 6 Estimated values of boundary radial distance from pith at different increase ratio of wood fiber increment.

Increase ratio (%)	Estimated radial distance from pith (cm)
1.00	1.47
0.50	2.08
0.30	2.70
0.20	3.31
0.10	4.69
0.05	6.65

Table 7 Comparison of core and outer wood in anatomical characteristics and derived-wood properties.

Property	Core wood ($n = 10$)		Outer wood ($n = 7$)		*t*-value (*p*-value)
	Mean	SD	Mean	SD	
BD (g/cm^3)*1	0.46	0.10	0.55	0.08	–1.898 (0.078)
WFL (mm)	0.91	0.13	1.08	0.08	**–2.976** (0.009)
WFD (μm)	18.4	1.2	16.4	0.6	**4.002** (0.001)
WFWT (μm)	2.7	0.3	2.3	0.1	0.629 (0.539)
VEL (mm)	0.25	0.04	0.26	0.05	–0.376 (0.712)
VD (μm)	133	22	146	20	–1.183 (0.255)
VF (vessels/mm^2)	9	5	6	1 >	1.634 (0.123)
RR	0.43	0.08	0.48	0.04	–1.417 (0.177)
FC	0.70	0.04	0.68	0.02	1.440 (0.171)
SR	50.0	7.7	65.6	3.7	**–4.972** (< 0.001)
LSF	0.34	0.05	0.37	0.02	–1.445 (0.169)
CR	0.15	0.02	0.16	0.01	–1.482 (0.159)
SF (× 10^3 μm^3)	154	17	158	20	–0.388 (0.704)

Note: *n*, number of radial position from two sample trees; SD, standard deviation; BD, basic density; WFL, wood fiber length; WFD, wood fiber diameter; WFWT, wood fiber wall thickness; VEL, vessel element length; VD, vessel diameter; VF, vessel frequency; RR, Runkel ratio; FC, flexibility coefficient; SR, slenderness ratio; LSF, Luce's shape factor; CR, coefficient of rigidity; SF, solid factor; *1, Number of radial position in outer wood was 6. Boundary between core and outer wood was 5 cm from pith based on the results listed in Table 6. The *t*-values with bold style indicate those with less than 0.05 of *p*-values.

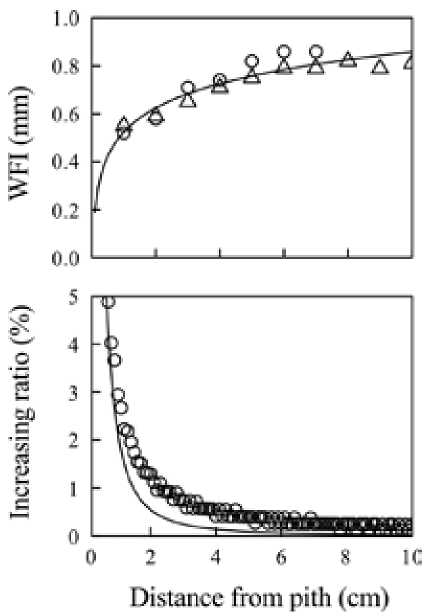

Figure 5 Radial variations of wood fiber increment and increase ratio of wood fiber increment.

Note: WFI, wood fiber increment. Circles, triangles, and solid line in upper graph indicate data of tree no. 1 and no. 2, and mean values of two trees, respectively.

outer wood in wood fiber length, wood fiber diameter, and slenderness ratio.

3.2 Chemical and pulp properties

Table 8 shows the mean values of chemical and pulp properties. Mean values in heartwood were 6.0%, 16.4%, 7.2%, 0.4%, 23.5%, 74.9%, 59.5%, 54.8%, and 11.5 for hot-water extracts, 1% NaOH extracts, organic solvent extracts, ash, Klason lignin, holocellulose, α-cellulose, pulp yield, and kappa number, respectively. In sapwood, mean values were 1.8% for hot-water extracts, 9.9% for 1% NaOH extracts, 2.1% for organic solvent extracts, 0.8% for ash, 22.5% for Klason lignin, 77.6% for holocellulose, 63.4% for α-cellulose, 52.9% for pulp yield, and 14.3 for kappa number, respectively.

The effect of wood type (heartwood or sapwood) on chemical and pulp properties are shown in Table 9. Although *p*-values were relatively high in linear mixed-effect models for extracts and ash, variance component ratio of wood type showed quite higher values that exceeding 80%. In addition, based on the parameters in random effects, heartwood was characterized by higher extractive contents and lower ash contents compared to sapwood. Holocellulose content and kappa number also showed relatively high variance component ratios for wood type.

Table 8 Statistical values of amounts of wood chemical components and kraft pulp properties.

Property	Tree No. 1				Tree No. 2				Mean / total			
	HW (n = 3)		SW (n = 3)		HW (n = 3)		SW (n = 3)		HW (n = 6)		SW (n = 6)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
HWE (%)	5.4	0.6	1.4	0.4	6.5	0.6	2.2	0.6	6.0	0.8	1.8	0.7
AE (%)	16.5	0.7	8.4	1.4	16.2	1.3	11.4	1.7	16.4	1.0	9.9	2.1
OSE (%)	5.8	0.4	1.7	0.1	8.5	0.3	2.6	0.1	7.2	1.5	2.1	0.5
Ash (%)	0.3	0.1	0.8	0.1	0.5	0.1	0.8	0.1	0.4	0.1	0.8	0.1
KL (%)	22.4	2.1	21.5	1.1	24.7	1.0	23.5	1.3	23.5	1.9	22.5	1.5
HC (%)	74.8	0.9	79.4	0.7	75.0	1.1	75.8	1.5	74.9	0.9	77.6	2.2
AC (%)	58.9	0.9	70.3	2.9	60.0	0.3	56.6	1.5	59.5	0.8	63.4	7.8
KPY (%)	55.7	12.2	54.5	3.3	53.8	2.2	51.2	2.0	54.8	2.9	52.9	3.1
KN	3.8	1.6	14.0	2.5	10.9	1.2	14.7	1.4	11.5	1.4	14.3	1.9

Note: HW, heartwood; SW, sapwood; n, number of replicates; SD, standard deviation; HWE, hot-water extracts; AE, alkaline extracts (1% NaOH extracts); OSE, organic solvent extracts (ethanol-toluene extracts); KL, Klason lignin; HC, holocellulose; AC, α-cellulose; KPY, kraft pulp yield; KN, kappa number.

Table 9 Parameters of linear mixed-effects models for chemical and pulp properties with random effects of wood type.

Property	Fixed-effect				Random-effect		Variance components		
	Estimates	SE	t-value	p-value	HW	SW	δw	δr	δw (%)
HWE	3.876	2.076	1.867	0.313	2.055	–2.055	8.533	0.509	94.37
AE	13.137	3.216	4.085	0.153	3.146	–3.146	20.232	2.708	88.20
OSE	4.647	2.504	1.856	0.315	2.461	–2.461	12.326	1.293	90.51
Ash	0.608	0.175	3.476	0.178	–0.170	0.170	0.060	0.010	85.42
KL	23.010	0.512	44.970	0.014	0.033	–0.033	0.034	2.938	1.14
HC	76.261	1.337	57.020	0.011	–1.162	1.162	3.108	2.818	52.45
AC	61.450	1.970	31.200	0.020	–0.681	0.681	2.683	30.475	8.09
KPY	53.819	0.941	57.20	0.011	0.141	–0.141	0.265	9.031	2.85
KN	12.930	1.415	9.138	0.069	–1.250	1.250	3.537	2.803	55.79

Note: SE, standard error; HW, heartwood; SW, sapwood; HWE, hot-water extracts; AE, alkaline extracts (1% NaOH extracts); OSE, organic solvent extracts (ethanol-toluene extracts); KL, Klason lignin; HC, holocellulose; AC, α-cellulose; KPY, kraft pulp yield; KN, kappa number; δw, variance component of wood type; δr, residual variance component.

4 Discussion

4.1 Comparison of mean values with data from previous researches

Up to date, anatomical characteristics, derived-wood properties, amounts of chemical components, and kraft pulp characteristics have been reported in several *Acacia* species by many researchers (Tables 10 and 11; Sahri et al. 1993; Malinen et al. 2006; Chowdhury et al. 2009, 2013; Kojima et al. 2009; Yahya et al. 2010; Jusoh et al. 2014; Muhammad et al. 2018). Obtained values of these characteristics in the present study (Tables 3 and 8) were in the range of those reported in the previous studies. Thus, it is considered that *Acacia* wood obtained from the plantation in Gabon can be used as raw material for pulp and paper production.

Table 10 Comparison of anatomical characteristics and derived-wood properties in *Acacia* species.

Species	Tree age	Country	BD (g/cm^3)	WFL (mm)	WFD (μm)	WFWT (μm)	VEL (mm)	VD (μm)	VF ($no./mm^2$)	RR	FC	SR	CR	References
A. aulacocarpa	7	Thailand	0.53	0.60										Malinen et al. (2006)
A. auriculiformis	4	Vietnam	0.47											Kha (2000)
	11	Bangladesh	0.57	0.98			0.24							Chowdhury et al. (2009)
	11	Malaysia		1.13										Kojima et al. (2009)
	7	Indonesia	0.52	0.88	16.7	2.8				0.55	0.67	52.7	0.17	Yahya et al. (2010)
	11	Bangladesh			12.6	2.0		123.9						Chowdhury et al. (2013)
	7	Malaysia	0.64	0.89	17.8	2.5				0.39		50.0		Jusoh et al. (2014)
	10	Malaysia	0.70	0.95										Muhammad et al. (2018)
	3.8	Vietnam	0.50											Viet et al. (2020)
A. crassicarpa	7	Thailand	0.50	0.76										Malinen et al. (2006)
	UK	Indonesia	0.48											Martins et al. (2020)
A. mangium	4	Malaysia		0.93	24.7	3.3		91 – 188	5 – 8					Sahri et al. (1993)
	8	Malaysia		1.02	20.3	4.3		91 – 188	5 – 8					Sahri et al. (1993)
	4	Vietnam	0.41											Kha (2000)
	7	Thailand	0.54	0.65										Malinen et al. (2006)
	11	Malaysia		1.07										Kojima et al. (2009)
	7	Indonesia	0.46	0.98	19.4	2.6				0.37	0.73	51.3	0.13	Yahya et al. (2010)
	7	Malaysia	0.46	0.93	17.4	2.0				0.31		54.0		Jusoh et al. (2014)
	10	Malaysia	0.58	0.85										Muhammad et al. (2018)
	7	Indonesia	0.43											Ngadianto et al. (2020)
	3.8	Vietnam	0.37											Viet et al. (2020)
A. melanoxylon	35 - 49	Portugal	0.52	0.74	18.9									Santos et al. (2012)
Acacia hybrid	4	Vietnam	0.46											Kha (2000)
	11	Malaysia		1.14										Kojima et al. (2009)
	7	Indonesia	0.49	1.07	18.8	2.5				0.37	0.73	57.4	0.13	Yahya et al. (2010)
	7	Malaysia	0.47	0.96	17.2	2.2				0.35		57.0		Jusoh et al. (2014)
	10	Malaysia	0.63	1.09										Muhammad et al. (2018)

Note: BD, basic density; WFL, wood fiber length; WFD, wood fiber diameter; WFWT, wood fiber wall thickness; VEL, vessel element length; VD, vessel diameter; VF, vessel frequency; RR, Runkel ratio; FC, flexibility coefficient; SR, Slenderness ratio; CR, coefficient of rigidity. *Acacia* hybrid is hybrid of *A. mangium* and *A. auriculiformis*.

Table 11 Comparison of wood chemical components and kraft pulping properties in *Acacia* species.

Species	Tree age	Country	HWE (%)	AE (%)	OSE (%)	Ash (%)	KL (%)	HC (%)	AC (%)	KPY (%)	KN	References
A. aulacocarpa	7	Thailand	8.6	16.9		0.7						Malinen et al. (2006)
A. auriculiformis	4	Vietnam	3.6	13.1		1.5	25.7			47.1	21.0	Kha (2000)
	7	Indonesia						71.3	40.6			Yahya et al. (2010)
	10	Malaysia					33.9					Muhammad et al. (2018)
A. crassicarpa	7	Thailand	6.9	15.9		0.1						Malinen et al. (2006)
		Indonesia							44.4	53.8		Martins et al. (2020)
A. dealbata	18	Portugal								51.2	12.4	Santos et al. (2006)
A. mangium	4	Vietnam	3.4	12.7		1.3	22.6			47.1	20.6	Kha (2000)
	7	Indonesia			4.5	0.2	27.1	70.9				Pinto et al. (2005)
	7	Thailand	6.5	17.3		0.4						Malinen et al. (2006)
	7	Indonesia						80.4	45.7			Yahya et al. (2010)
	10	Malaysia					35.1					Muhammad et al. (2018)
A. melanoxylon	22	Portugal								53.2	10.9	Santos et al. (2006)
	35 – 49	Portugal				0.3 – 0.5	19.5 – 22.4			47.9 – 55.0	11.1 16.6	Santos et al. (2012)
Acacia hybrid	4	Vietnam	3.7	13.5		1.2	25.7			51.1	21.0	Kha (2000)
	4	Malaysia	0.6 – 1.2	10.0 – 13.5		0.2 – 0.4		78.5 – 81.6	50.2 – 54.6			Rafeadah and Rahim (2007)
	7	Indonesia						82.9	45.5			Yahya et al. (2010)
	10	Malaysia					32.0					Muhammad et al. (2018)

Note: HWE, Hot-water extracts; AE, alkaline extracts (1% NaOH extracts); OSE, organic solvent extracts (ethanol-toluene extracts); KL, Klason lignin; HC, holocellulose; AC, α-cellulose; KPY, kraft pulp yield; KN, kappa number. *Acacia* hybrid is hybrid of *A. mangium* and *A. auriculiformis*.

4.2 Boundary between core and outer wood

Wood of many tropical fast-growing tree species can be divided into two parts, core and outer wood based on the radial variations of anatomical characteristics or wood properties (Zobel and van Buijtenen 1989; Honjo et al. 2005; Kojima et al. 2009; Ishiguri et al. 2012; Nugroho et al. 2012). Boundary between core and outer wood was 6 cm from pith in basic density variations for 5- and 7-year-old *A. mangium* (Makino et al. 2012), 7 to 9 cm from pith in wood property variations for 11-year-old *A. auriculiformis* (Chowdhury et al. 2009), about 5 cm from pith in wood fiber length variations for 23 years old *A. mangium* (Nugroho et al. 2012), and about 6 cm and 7.5 cm from pith in wood fiber length variation for 11-year-old *A. mangium* and *A. auriculiformis* (Kojima et al. 2009). In the present study, boundary between core and outer wood was 5 cm from pith based on the results from fiber length increment and radial variations of anatomical characteristics (Table 6 and Figures 3 and 5). The obtained result is in the range of the boundary previously reported by other researchers (Honjo et al. 2005; Kojima et al. 2009; Ishiguri et al. 2012; Nugroho et al. 2012).

4.3 Relationships between measured properties

Basic density is correlated with anatomical characteristics in many tropical fast-growing tree species (Chowdhury et al. 2009; Yahya et al. 2010; Nugroho et al. 2012). Chowdhury et al. (2009) reported that air-dry density of wood was significantly correlated with wood fiber diameter (r = –0.712) and wood fiber wall thickness (r = 0.671) in 11-year-old *A. auriculiformis* grown in Bangladesh. In 23-year-old *A. mangium* planted in Indonesia, wood density was positively correlated with fiber wall area percentage which was defined as the ratio of total area of fiber wall per total area of measured image (r = 0.70 to 0.82 at different radial positions) (Nugroho et al. 2012). Similar negative correlation between basic density and wood fiber diameter was found in the present study (Table 4). On the other hand, no correlation was found between basic density and wood fiber wall thickness: this is due to the almost stable values of wood fiber wall thickness from pith to bark in the samples used in the present study (Figure 3).

In the present study, with an exception, vessel morphologies were closely related with each other, and wood fiber length was significantly correlated with vessel morphologies (Table 4). Noshiro and Baas (2000) reported that vessel element length was significantly correlated with wood fiber length and tangential vessel diameter in *Cornus* species. Erdene-Ochir et al. (2021) reported that a positive significant correlation was found between wood fiber length and vessel element length in *Betula platyphylla* grown in Mongolia. Although the results in the previous studies were not obtained in the tropics, relationships among vessel morphologies and wood fiber length obtained in the present study are similar with those of other previous researches (Noshiro and Baas 2000; Erdene-Ochir et al. 2021). In *Acacia*, correlations between vessel morphologies or between wood fiber length and vessel morphologies might be related with xylem maturation process: matured cambium produces longer cells and fewer number and larger diameter vessels.

4.4 Effects of wood types on pulp and paper quality

In the present study, wood of *A. mangium* was classified into two types, core and outer wood in anatomical characteristics and derived-wood properties, and heartwood and sapwood in chemical and kraft pulp properties. As shown in Table 7, significant differences between core and outer wood were found in wood fiber length, wood fiber diameter, and slenderness ratio. Although the amounts of extracts in heartwood showed higher than those in sapwood, kappa number in heartwood showed relatively lower values compared to that in sapwood. Based on the results, it is concluded that effects of wood type (core or outer wood, and heartwood or sapwood) on pulp and paper quality might be limited on *Acacia* species grown in Gabon.

5. Conclusion

In the present study, anatomical characteristics, derived-wood properties, amounts of chemical components, kraft pulp characteristics were evaluated for wood of *Acacia* sp. grown in Gabon. Obtained values in these characteristics were in the range of wood from plantation grown *Acacia* species reported by previous researches. Based on the radial variations of wood fiber length, xylem maturation of *Acacia* species in Gabon might occur after 5 cm from pith: starting radial position of xylem maturation is almost the same with other that of *Acacia* species planted in other countries. Furthermore, measured characteristics in the present study did not differ between heartwood and sapwood or core and outer wood, suggesting that wood obtained at the all radial positions is considered as good raw materials for pulp and paper production. Based on the results, it is concluded that raw materials of pulp and paper can be supplied from plantation of *Acacia* species in Gabon instead of natural forests.

Acknowledgements

We would like to thank to Dr. Koumba Pambo Aurelie Flore (National parks Agency of Gabon), Mr. Stanislas Stephen Mouba (General director of Environment department in the Waters and Forests Ministry), Professor Lee White (Minister of Forests and Waters Ministry in Gabon), and Mrs. Eyenbiang Ndong Valerie Olympa for legal sampling in Gabon.

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