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A Comparative Study on the Anatomical Characteristics of *Acacia mangium* and *Acacia hybrid* Grown in Vietnam

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Abstract: This study aimed to investigate and compare the qualitative and quantitative anatomical characteristics of *Acacia mangium* and *Acacia hybrid* in plantation forests in Vietnam. The qualitative and quantitative anatomical characteristics were evaluated according to the International Association of Wood Anatomists list of microscopic features for hardwood identification. In terms of qualitative features, *A. mangium* had a rough, hard, and fissured bark surface with a golden brown to dark brown color, whereas *A. hybrid* had a smooth and slightly scaly bark surface with greenish brown to greyish brown color, and yellowish white to pale white spots. Moreover, the heartwood–sapwood color and microscopic features of both species were identical. In terms of quantitative features, *A. mangium* had higher values in the tangential diameter of vessel lumina, vessel per square millimeter, ray number per millimeter, fiber length, and fiber wall thickness than *A. hybrid*, whereas *A. hybrid* had a higher ray height and lumen diameter than *A. mangium*. Thus, it is suggested that bark morphology and some quantitative anatomical characteristics can be used for identification and evaluation of wood quality between *A. mangium* and *A. hybrid* growing in Vietnam.

Keywords: *Acacia hybrid*; *Acacia mangium*; anatomical characteristics; fast-growing trees; plantation trees; Vietnam

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1. Introduction

Vietnam's forests had severely degraded during the previous decade, and in 1990 they started to rehabilitate with several programs of restoration and reforestation such as the Five Million Hectare Reforestation Program (5MHRP) [1,2]. These afforestation programs used fast-growing species, including *Eucalyptus* and *Acacia* spp., as a substitute to sustain the commercial supply of tree products. The fast-growing plantation trees had many advantages, such as more resistance to diseases and pest attacks, more adaptability to the soil conditions, higher wood production, etc. [3]. In 2021, Vietnam had 14,745,201 ha of forest area; comprising 10,171,757 ha of natural, and 4,573,444 ha of plantation forest. In the plantation forest, *Acacia* spp. covered over 2,200,000 ha. Moreover, the total wood production in Vietnam reached 32 million m^3, and *Acacia* spp. was the dominant species [4–6].

Acacia spp. belongs to the Mimosoideae subfamily of the Fabaceae family; and is native to Australia, Papua New Guinea, and Indonesia [7]. This fast-growing tree species can be harvested within 5–10 years with 18–20 cm diameter at breast height [8–11]. In addition, it can grow under poor soil conditions and has the ability to fix atmospheric nitrogen. This species is commonly planted in many afforestation programs conducted throughout tropical areas, such as Southeast Asia and the Pacific region [12–17]. Wood

from *Acacia* spp. is utilized as sawn wood, veneer, woodchips, household fuelwood, pulp, and paper materials [13,14,18].

The Australian *Acacia* spp. was first introduced to southern Vietnam in the early 1960s, and subsequently to northern Vietnam in the 1980s. From the year 1982 to 1985, the Research Center for Forest Tree Improvement of the Forest Science Institute of Vietnam evaluated potential Acacia species intended for commercial production and discovered that *Acacia mangium* had the greatest potential for application in wood industries. In 1991, the first natural *A. hybrid* was found at Ba Vi research station in Northern Vietnam. The antecedents of *A. hybrid* were identified as *A. mangium* and *A. auriculiformis*. Furthermore, from 1992 to 1996, Vietnamese scientist collaborated with the Australian Center for International Agricultural Research in cultivating the saplings of *A. hybrid* for commercial production, and the seedlings were released for plantations in the year 1996 [3].

The anatomical characteristics of *A. mangium* and its hybrids have been reported in several studies. Specifically, Abdul-Kader and Sahri [19] and Sahri et al. [20] reported that *A. mangium* from plantation forests in Malaysia were composed of diffuse-porous wood with mostly solitary and occasionally radial multiple grouping. *A. mangium* had non-septate fibers, vasicentric and aliform axial parenchyma, with mostly uniseriate rays. Prismatic crystals were also present in the axial parenchyma. Furthermore, Ogata et al. [21], Kim et al. [15], and Andianto et al. [22] also reported similar anatomical characteristics for *A. mangium*. As previously reported by Praptoyo [23] and Nirsatmanto et al. [24], *A. hybrid* grown in Indonesia were composed of diffuse-porous wood with solitary and multiple radial vessels. The axial parenchyma was vasicentric, and the rays were uniseriate and biseriate. Additionally, Yahya et al. [25] investigated the pulp quality of *A. mangium* and *A. hybrid* from Indonesia, including their fiber length, fiber diameter, lumen diameter, and fiber wall thickness. Consequently, the authors reported that *A. hybrid* had longer fibers and a higher proportion of fibers than that of *A. mangium*, however, it had a lesser proportion of vessels, parenchyma, ray cells, and also exhibited thinner cell walls. Further, Jusoh et al. [26] compared the wood quality of *A. mangium* and *A. hybrid* from Malaysia, in terms of fiber length, fiber diameter, lumen diameter, and fiber wall thickness, and reported that both species showed comparable anatomical characteristics.

However, additional information on the wood quality of *A. mangium* and *A. hybrid* grown in Vietnam are highly required for further effective utilization of both species. Thus, the present study aimed to investigate and compare the qualitative and quantitative anatomical characteristics of *A. mangium* and *A. hybrid* in plantation forests in Vietnam, to provide valuable information on identification and wood quality indices of both species.

2. Materials and Methods

2.1. Material

A pair each, of 8-year-old *A. mangium* and *A. hybrid*, were obtained from Công ty Dongwha Vietnam in Sông Công district, Thái Nguyên province, Northern Vietnam (21°30′17.74″ N, 105°50′48.102″ E). A tree each of both species was also acquired from MDF VRG Dongwha Wood County in Chơn Thành district, Bình Phước province, Southern Vietnam (11°28′56.104″ N, 106°36′16.133″ E). Thái Nguyên province in Northern Vietnam had grey degraded and red soil, with an average annual precipitation and temperature of 2025 mm and 23.2 °C, respectively, while Bình Phước province in Southern Vietnam had grey degraded soil with an average annual precipitation and temperature of 2665 mm and 25.5 °C, respectively [27,28]. The samples used in investigating the anatomical characteristics were collected from breast height. The anatomical characteristics of both species were investigated near the bark of four directions on the wood discs. Detailed information on the wood discs is provided in Table 1.

Table 1. Fundamental information of *Acacia mangium* and *Acacia hybrid* wood discs.

Growing Sites	Scientific Name	Diameter at Breast Height (cm)	Density (g/cm^3)
Northern Vietnam	*A. mangium*	13.2	0.50
	A. mangium	8.5	0.53
	A. hybrid	12.2	0.50
	A. hybrid	6.9	0.51
Southern Vietnam	*A. mangium*	9.3	0.53
	A. hybrid	8.6	0.51

2.2. Method

2.2.1. Macroscopic Characteristics

The transverse surfaces of the wood discs were abraded with coarse sandpaper (XA167, Deerfos Co., Ltd., Incheon, Korea) using a sanding machine (TW/BD-46, 2070 rpm, 450 W, Rexon Industrial Corp., Ltd., Taichung, Taiwan). The wood discs were further sanded manually using fine sandpaper (CC-600Cw, Daesung Abrasive Co., Ltd., Seoul, Korea). The images of the bark and transverse surfaces of the wood discs were captured using a mobile phone (iPhone 7+, Apple Inc., Cupertino, CA, USA).

2.2.2. Optical Microscopy

Small specimens with dimensions of 10 × 10 × 10 mm^3 (radial × tangential × longitudinal) in four directions were prepared from the nearby bark of the discs. The specimens were softened using a boiling mixture of glycerin and water (50:50) for a few days. Cross, tangential, and radial sections of 15–20 µm thickness were obtained using a sliding microtome (Nippon Optical Works Co., Ltd., Nagano, Japan). The slices were stained with 1% each of safranin and light-green solutions, followed by subsequent dehydrations using a graded series of alcohol (50%, 70%, 90%, 95%, and 99%) and xylene. Before observation, permanent slides were prepared using Canada balsam. The qualitative and quantitative anatomical characteristics were observed using an optical microscope (Eclipse E600, Nikon Corp., Tokyo, Japan) connected to an image analysis system (i-Solution Lite, IMT i-Solution Inc., Burnaby, BC, Canada), and were evaluated according to the International Association of Wood Anatomists list of microscopic features for hardwood identification [29].

2.2.3. Analysis of Quantitative Anatomical Characteristics

The tangential vessel diameter on the cross section was measured from 50 cells. The vessel number was measured in 25 areas of 1 mm^2 on the cross section. The ray heights of both species were measured from 50 rays, and ray number per millimeter were measured 25 times in the tangential section. Furthermore, the radial and tangential fiber diameter, wall thickness, and lumen diameter were measured for 50 cells on the cross section.

For the measurement of fiber length; specimens of 20 mm long and 5 mm thick were prepared near the bark in each direction. The specimens were soaked in Schultz's solution (100 mL of 35% nitric acid [HNO_3] and 0.6 g of 99.5% potassium chlorate [$KClO_3$]) for 3 days, and then heated at 60 °C for 1 h [30]. The fiber length was measured from 50 fibers.

2.3. Data Analysis

Significant differences in quantitative anatomical characteristics between both species were analyzed by one-way analysis of variance (ANOVA) with a 5% significance level, using SPSS ver. 26 (IBM Corp., Armonk, NY, USA).

3. Results and Discussions

3.1. Macroscopic Characteristics of the Bark and Wood

The bark surfaces of *A. mangium* and *A. hybrid* from Vietnam are shown in Figure 1. *Acacia mangium* had rough, hard, and fissured bark surfaces with a golden- to dark-brown

color (Figure 1A). In contrast, the bark of *A. hybrid* had a smooth and slightly scaly surface with a greenish- to greyish-brown color and yellowish- to pale-white spots (Figure 1B).

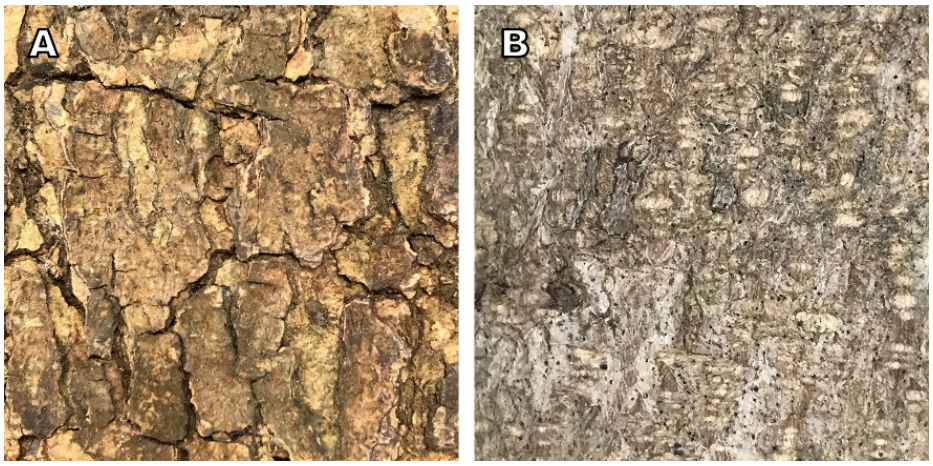

Figure 1. Bark surface of *Acacia mangium* (**A**) and *A cacia hybrid* (**B**).

Several researchers have reported the bark morphology of Acacia wood species, which are consistent with the results of our study. Specifically, Krisnawati et al. [12] reported results similar to those obtained from our study; *A mangium* from Indonesia exhibiting hard, rough, and fissured bark with brown to dark-brown color. Furthermore, Sein and Mitlöhner [13] reported that *A. mangium* from Vietnam had fissured bark with a greyish- to dark-brown color. Hedge et al. [18] also explained that *A. mangium* had a rough bark with a greyish brown to brown color. Additionally, Sein and Mitlöhner [14] reported that the morphological trait of *A. hybrid* bark was a mixture of *A. mangium* and *A. auriculiformis*, and differed from that of a typical *A. mangium*, however, it was similar to that of *A. auriculiformis* as it had a smooth and scaly bark with greenish-brown to brown color. Lastly, Sunarti et al. [31] reported that *A. hybrid* from Indonesia had a smooth bark with a greenish-brown color.

The wood discs of *A. mangium* and *A. hybrid* are shown in Figure 2. *A. mangium* had distinctly different colors for heartwood and sapwood. Heartwood was greyish- to olive-brown, while sapwood was creamy- to yellowish-white (Figure 2A). In *A. hybrid*, there was a slight difference in color between the heartwood and sapwood (Figure 2B). The color of heartwood and sapwood in *A. mangium* was darker than that in the *A. hybrid* (Figure 2). In this study, the color of the heartwood and sapwood of *A. mangium* and *A. hybrid* was similar to that reported in previous studies. Specifically, Abdul-Kader and Sahri [19] reported that the heartwood color of *A. mangium* from Malaysia was dark-brown, whereas the sapwood was light-cream. Moreover, Ogata et al. [21] reported that the heartwood color of *A. mangium* was pale-brown, yellowish-brown, and brown, whereas the sapwood was pale-yellow. Sein and Mitlöhner [13] also reported that the heartwood color of *A. mangium* from Vietnam was pale olive-brown and greyish-brown to brown, and the sapwood color was yellowish-white to cream. Further, Andianto et al. [22] reported that the heartwood color of Indonesian *A. mangium* was pale- to dark-brown and the sapwood color was pale-yellow to yellow. Lastly, Praptoyo [23] reported that the Indonesian *A. hybrid* was pale-brown and yellowish- to dark-brown, and the sapwood color was pale yellowish-white to pale-yellow.

Figure 2. Wood discs of *Acacia mangium* (**A**) and *Acacia hybrid* (**B**).

3.2. Microscopic Characteristics of Wood

Optical micrographs of the cross sections of both species are presented in Figure 3. Both species were composed of diffuse-porous wood, and the vessels were mostly solitary and partly radially multiple. Additionally, tyloses were not observed in the vessels of either species. Axial parenchyma arrangement in both species was vasicentric, aliform, and confluent, and was clearly seen at low or high magnification. Our results on the anatomical characteristics of the cross-sections are supported by a number of studies, such as those of Abdul-Kader and Sahri [19], Sahri et al. [20], Ogata et al. [21], Kim et al. [15] and Andianto et al. [22]. Moreover, Praptoyo [23] and Nirsatmanto et al. [24] reported that *A. hybrid* also exhibited diffuse porosity with solitary and radial multiple vessels, as well as scanty paratracheal and vasicentric axial parenchyma.

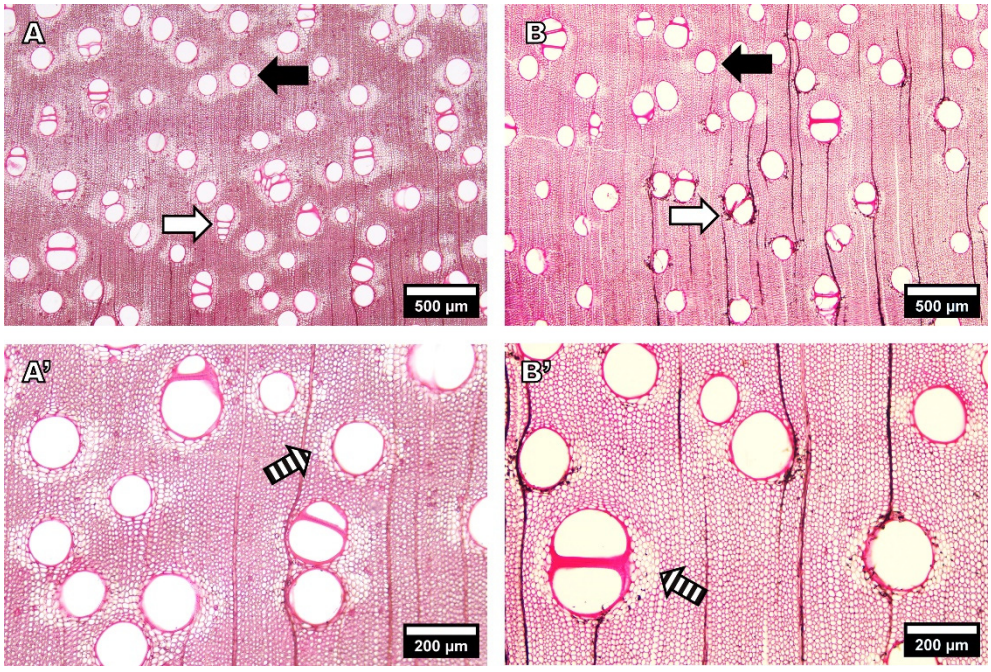

Figure 3. Optical micrographs of the cross-sections of *Acacia mangium* (**A**,**A'**) and *Acacia hybrid* (**B**,**B'**). Solitary vessel (black arrow), radial multiple vessel (white arrow), and axial parenchyma (striped arrow).

Optical micrographs of the radial sections of both species are shown in Figure 4. Procumbent body ray cells and vessel-ray pitting with distinct borders, similar to intervessel pits, were found in both species.

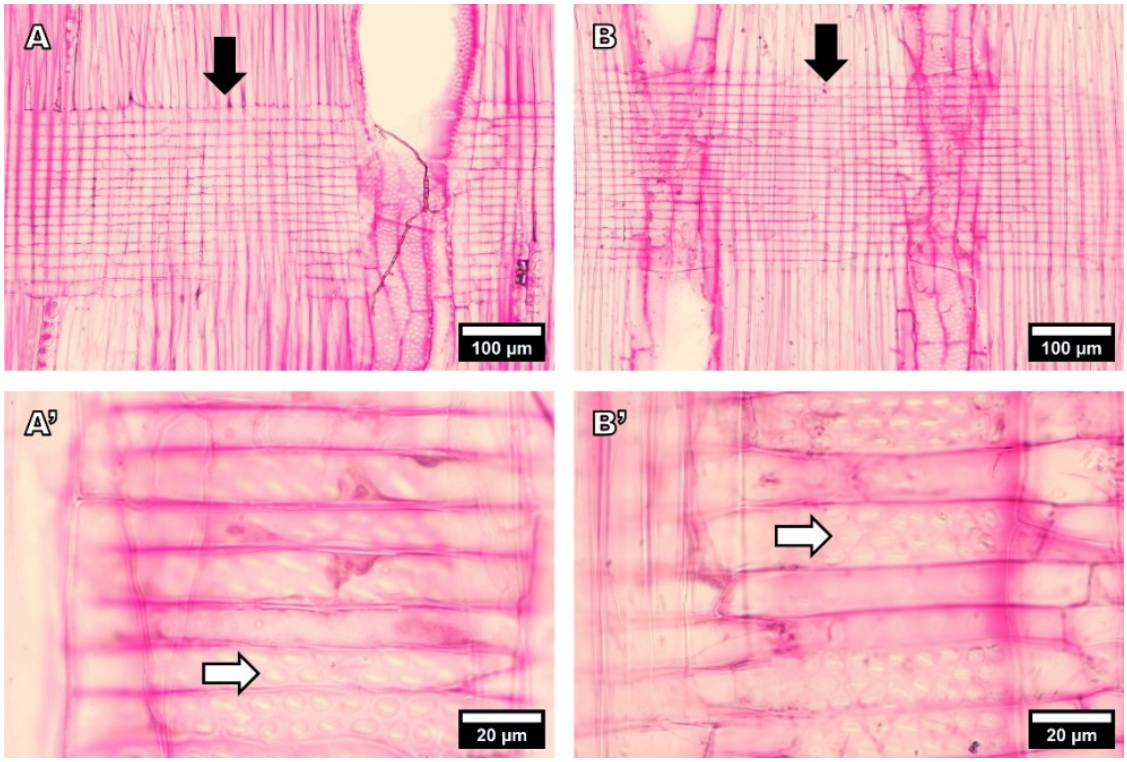

Figure 4. Optical micrographs of radial sections of *Acacia mangium* (**A**,**A'**) and *A. hybrid* (**B**,**B'**). Procumbent body ray cells (black arrow) and vessel-ray pitting (white arrow).

In previous studies, *A. mangium* exhibited procumbent body ray cells and vessel-ray pits similar to intervessel pits [15,20–22]. As reported by Praptoyo [23] and Nirsatmanto et al. [24], the *A. hybrid* also showed characteristics similar to those of *A. mangium*.

Figure 5 shows optical micrographs of the tangential sections of both species. The ray width was mostly uniseriate, and sometimes biseriate in both species. The arrangement of the intervessel pits alternated with a polygonal shape, and the pits were mostly vestured. Both species also had prismatic crystals in their axial parenchyma cells, as shown in Figure 6. Crystals were more frequently observed in *A. mangium* than in the *A. hybrid*. In previous studies, *A. mangium* exhibited uniseriate and biseriate rays, alternate intervessel pits with polygonal shapes, and vestured pits [15,20–22]. Praptoyo [23] and Nirsatmanto et al. [24] reported that *A. hybrid* also showed characteristics similar to those of *A. mangium*.

Detailed information on the qualitative anatomical characteristics of both species is presented in Table 2. Overall, *A. mangium* and *A. hybrid* grown in Vietnam showed similar microscopic features. Our results are consistent with those of the previous studies. According to Sunarti et al. [32], *A. hybrid* exhibits similar anatomical characteristics in roots, stems, and leaves compared to those of *A. mangium* and *A. auriculiformis*. Moreover, Ogata et al. [21] reported that *A. auriculiformis* has microscopic features similar to that of *A. mangium*.

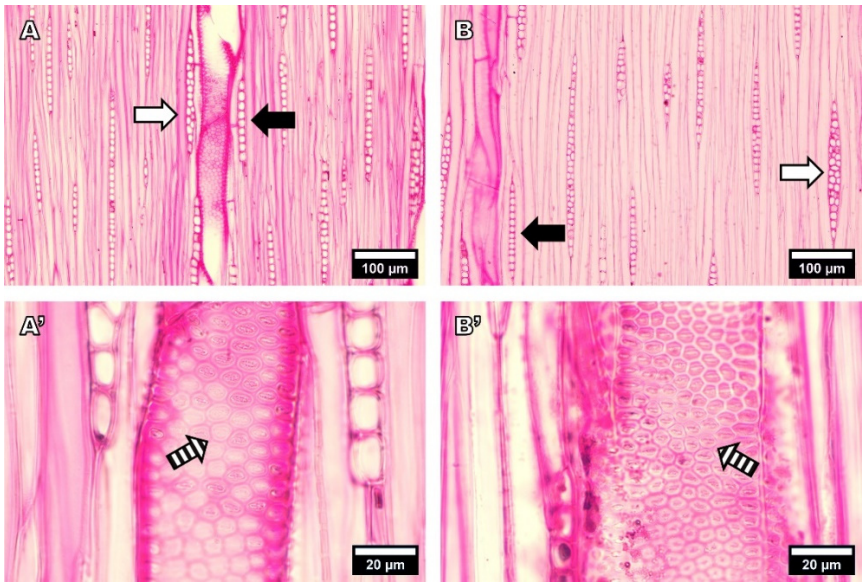

Figure 5. Optical micrographs of the tangential sections of *Acacia mangium* (**A**,**A′**) and *A. hybrid* (**B**,**B′**). Uniseriate ray (black arrow), biseriate ray (white arrow), and vestured intervessel pit (striped arrow).

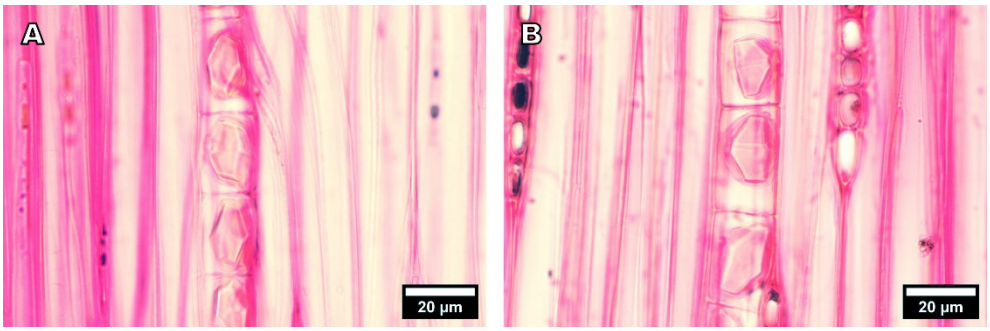

Figure 6. Optical micrographs prismatic crystal in chambered axial parenchyma cells of *Acacia mangium* (**A**) and *A. hybrid* (**B**).

Table 2. Qualitative anatomical characteristics of both *Acacia mangium* and *Acacia hybrid* based on the International Association of Wood Anatomists (IAWA) feature list.

Features	Descriptions
Growth Rings	Growth ring boundaries indistinct or absent (2).
Vessels	Wood diffuse-porous (5). Vessels mostly solitary (9) and partly in radial multiples (10). Simple perforation plates present (13). Intervessel pits alternate (22). Shape of alternate pits polygonal (23). Vestured pits (29). Vessel-ray pits with distinct borders, similar to intervessel pits (30). Tyloses absent.
Tracheids and Fiber	Fibers with simple to minutely bordered pits (61). Non-septate fibers present (66). Fibers very thin-walled (68).
Axial Parenchyma	Axial parenchyma vasicentric (79). Axial parenchyma aliform (80). Axial parenchyma confluent (83).
Ray	Ray width 1 to 3 cells (97). All ray cells procumbent (104).
Mineral inclusions	Prismatic crystals in chambered axial parenchyma cells (142).

Note: Numbers in parentheses denote the IAWA feature list for hardwood identification.

3.3. Quantitative Anatomical Characteristics of Wood

3.3.1. Vessel Characteristics

The quantitative anatomical characteristics of *A. mangium* and *A. hybrid* are presented in Table 3. The *A. mangium* and *A. hybrid* each had a tangential vessel lumina diameter of 149.2 and 133.2 µm, and vessels per square millimeter of 9.4 and 6.7 /mm^2, respectively. *A. mangium* had higher tangential diameter of vessel lumina and vessels per square millimeter than those of *A. hybrid*. The one-way ANOVA results showed that the vessel parameters were significantly different at the 5% level between *A. mangium* and *A. hybrid*.

Table 3. Quantitative anatomical characteristics of *A. mangium* and *A. hybrid*.

Parameters	*A. mangium*	*A. hybrid*
Tangential diameter of vessel lumina (µm)	149.2 [a] (21.0)	133.2 [b] (22.2)
Vessels per square millimeter	9.4 [a] (2.1)	6.7 [b] (1.5)
Ray height (µm)	200.4 [a] (38.6)	235.4 [b] (51.6)
Rays per millimeter	6.7 [a] (1.6)	5.7 [b] (1.4)
Fiber length (µm)	830.3 [a] (134.8)	797.4 [b] (148.0)
Fiber diameter (µm)	13.8 [a] (2.3)	14.4 [a] (2.8)
Lumen diameter (µm)	10.3 [a] (2.3)	11.1 [b] (2.6)
Fiber wall thickness (µm)	1.72 [a] (0.32)	1.63 [b] (0.28)

Note: Numbers in parentheses are standard deviations. The listing of the same superscript letters beside the means values within columns denotes insignificant outcomes at the 5% significance level for comparisons between species.

Numerous studies have reported the parameters of the tangential diameter of vessel lumina and vessels per square millimeter for *A. mangium* and *A. hybrid*. Specifically, Sahri et al. [20] reported that the tangential diameters of the vessel lumina and vessels per square millimeter of *A. mangium* from Malaysia were 132–167 µm and 4–8 /mm^2, respectively. Ogata et al. [21] also reported that the tangential diameters of the vessel lumina and vessels per square millimeter of *A. mangium* were 150–280 µm and 4–9 /mm^2, respectively. Furthermore, Nugroho et al. [33] reported that the tangential diameter of vessel lumina and vessels per square millimeter of *A. mangium* from Indonesia were 132–142 µm and 7–9 /mm^2, respectively. The authors also revealed that there was no difference in parameters among *A. mangium* from various seed provenances. Additionally, Praptoyo [23] reported that the tangential diameter of vessel lumina and vessels per square millimeter of *A. hybrid* from Indonesia were 113–200 µm and 4–7 /mm^2, respectively. Lastly, Nirsatmanto et al. [24] also reported that *A. mangium* and *A. hybrid* from Indonesia had a tangential vessel lumina diameter of 115–145 µm and vessels per square millimeter of 5–9 /mm^2.

3.3.2. Ray Characteristics

The *A. mangium* and *A. hybrid* each had a ray height of 200.4 and 235.4 µm, and ray numbers of 6.7 and 5.7 /mm, respectively. *A. mangium* had a higher ray number per millimeter than that of *A. hybrid*, whereas *A. hybrid* exhibited a higher ray height than that of *A. mangium*. The ANOVA results showed that the ray parameters between *A. mangium* and *A. hybrid* were significantly different at the 5% level. According to a study by Ogata et al. [21], the maximum ray height of *A. mangium* was 230–450 µm.

3.3.3. Fiber Characteristics

The fiber length of *A. mangium* and *A. hybrid* was 830.3 and 797.4 µm. *A. mangium* had a longer fiber length than that of *A. hybrid*. The ANOVA results revealed that there was significant in fiber length between *A. mangium* and *A. hybrid*.

The fiber length of *A. mangium* growing in Malaysia was reported by Abdul-Kader et al. [19] and Sahri et al. [20] as 940–1120 and 934–1018 µm, respectively. In addition, Andianto et al. [22] and Nugroho et al. [33] investigated the fiber length of *A. mangium* from Indonesia, which was evaluated as 1215–1240 and 890–940 µm, respectively. Furthermore, as reported by Kim et al. [34], the fiber lengths of *A. hybrid* growing in Vietnam and Indonesia were 860–930 and 1030–1040 µm, respectively [23]. As mentioned in a few studies, *A. hybrid* growing in Indonesia and Malaysia had longer fiber lengths than that of *A. mangium* [25,26]. In contrast, Nirsatmanto et al. [24] reported that *A. mangium* had a longer fiber length than that of *A. hybrid*.

The fiber diameters of *A. mangium* and *A. hybrid* were evaluated as 13.8 and 14.4 µm, respectively, and there was no significant difference between the two species. In addition, *A. mangium* had a significantly smaller lumen diameter than that of *A. hybrid,* that is, 10.3 and 11.1 µm, respectively. Furthermore, the fiber wall thickness was 1.72 µm for *A. mangium* and 1.63 µm for *A. hybrid*, which were significantly different.

Several studies have reported on the fiber diameter, lumen diameter, and fiber wall thickness of the *Acacia* spp. Specifically, Abdul-Kader and Sahri [19] and Sahri et al. [20] each reported that *A. mangium* from Malaysia had fiber diameter of 21.8–25.0 and 20.3–24.7 µm; lumen diameter of 16.3–18.8 and 11.8–18.2 µm, and fiber wall thickness of 3.3–4.2 and 3.3–4.3 µm, respectively. In addition, Nugroho et al. [33] and Andianto et al. [22] each reported that the fiber diameter of *A. mangium* from Indonesia was 23.8–25.2 and 26.0 µm; and fiber wall thickness of 2.0–2.2 and 3.7 µm, respectively. Moreover, Praptoyo [23] reported that *A. hybrid* from Indonesia had a fiber diameter of 15.5–22.6 µm and a fiber wall thickness of 2.0–5.2 µm. Furthermore, Yahya et al. [25] reported that *A. mangium* from Indonesia exhibited parameters comparable to those of A. hybrid. Jusoh et al. [26] also showed that the fiber diameter and lumen diameter of *A. mangium* from Malaysia were higher than those of *A. hybrid*, while the fiber wall thickness of *A. mangium* was lower than that of *A. hybrid*. Lastly, Nirsatmanto et al. [24] reported that *A. mangium* from Indonesia showed higher parameter values than that of *A. hybrid*.

4. Conclusions

- Macroscopically, the bark of *A. mangium* exhibited rough, hard, and fissured surfaces with a golden brown to dark brown color, whereas *A. hybrid* had a smooth, slightly scaly bark surface with greenish brown to greyish brown color and yellowish white to pale white spots. Both species had a greyish brown to olive brown heartwood color, while the sapwood was pale white to yellowish white.
- Microscopically, both wood species exhibited diffuse porosity, with solitary and radial multiple vessels. Non-septate fibers; vasicentric and aliform axial parenchyma cells, and prismatic crystals were observed in the axial parenchyma of both species. The rays were uniseriate and biseriate, with procumbent body ray cells.
- *Acacia mangium* had higher values with respect to the tangential diameter of vessel lumina, vessel per square millimeter, ray number per millimeter, fiber length, and fiber wall thickness compared to those of *A. hybrid*, whereas *A. hybrid* had a higher ray height and lumen diameter than that of *A. mangium*.

Thus, it is suggested that bark morphology and some quantitative anatomical characteristics can be used for identification and evaluation of wood quality between *A. mangium* and *A. hybrid* growing in Vietnam.

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Data Availability Statement: The datasets generated and analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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