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Characterization of Anatomical and Non-Anatomical Properties for the Identification of Six Commercial Wood Species from Vietnamese Plantation Forests

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Abstract: This study investigated the anatomical and non-anatomical characteristics of six wood species, *Acacia mangium*, *Acacia hybrid*, *Dillenia pentagyna*, *Anacardium occidentale*, *Hevea brasiliensis*, and *Melaleuca cajuputi*, from a plantation in Vietnam. The anatomical characteristics and non-anatomical characteristics were observed following the International Association of Wood Anatomists (IAWA) list. All species showed diffuse porosity and non-septate fibers. Exclusively solitary vessels were only observed in *M. cajuputi.* Vestured pits were observed in *A. mangium*, *A. hybrid*, and *M. cajuputi*, and tyloses were found in *A. occidentale* and *H. brasiliensis*. We observed vasicentric axial parenchyma in *A. mangium*, *A. hybrid*, *A. occidentale*, and *H. brasiliensis*, whereas diffuse axial parenchyma was observed in *D. pentagyna* and *M. cajuputi*. Further, prismatic crystals in the axial parenchyma cells existed in *A. mangium*, *A. hybrid*, and *H. brasiliensis*, and raphides in ray cells were observed in *D. pentagyna*. Silica bodies in ray cells were found in *A. occidentale* and *M. cajuputi*. *H. brasiliensis* exhibited the greatest vessel diameter and ray height, with *D. pentagyna* exhibiting the greatest fiber length and wall thickness. All the species showed considerable differences in heartwood fluorescence, water and ethanol extract colors, and froth test reactions.

Keywords: anatomical characteristics; non-anatomical characteristics; Vietnamese commercial hardwood; wood identification; wood quality

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1. Introduction

Vietnam has a forest area of 14,745,201 ha, which consists of 10,171,757 ha of natural forest and 4,573,444 ha of plantation forest [1]. In 2021, Vietnam's total wood production surpassed 32 million m^3, and the value of forestry exports was 15.87 billion USD, with 14.72 billion USD for wood and wood products and 1.15 billion USD for non-timber forestry products [2,3]. Therefore, the forestry sector plays an important role in the national economic and rural development of Vietnam.

According to the Forest Science Institute of Vietnam [4], Vietnam's forests have a high level of biodiversity, with approximately 15,000 species of plants. Among these species, several tree species, such as *Acacia mangium*, *Acacia hybrid*, *Hevea brasiliensis*, *Dillenia pentagyna*, *Anacardium occidentale*, and *Melaleuca cajuputi*, are useful resources for wood products. *Acacia* spp. is the predominant species in Vietnam plantation forests for pulp products, sawn wood, woodchips, and veneer production [5–7]. Similar to *Acacia* spp., *H. brasiliensis* wood is commonly used for sawn wood, veneer, and pulp and paper materials [8]. *D. pentagyna* wood is utilized as sawn wood for the furniture industry and veneer for plywood [9,10]. *A. occidentale* wood is a common material for pulp and paper materials, charcoal, and firewood [11]. *M. cajuputi* wood is used for sawn wood and fuelwood [10,12].

Several studies have reported the anatomical characteristics of Vietnamese wood species. Oskolski [13] compared the anatomical features of 31 species of *Schefflera* from Vietnam, Australia, Oceania, South America, and Africa, as well as *Tupidanthus calyptratus* and *Scheffleropsis hemiepiphytica* from Vietnam. Ickert-Bond [14] reported the anatomical features of the mature and twig wood of *Pinus krempfii* from Vietnam. Kim et al. [15] compared the variation in wood properties, such as microfibril angle and fiber and vessel element lengths, of six naturals *A. hybrid* clones from Vietnam. Recently, Van Duong et al. [16] investigated the radial variation in cell morphology of *Melia azedarach* from Northern Vietnam, and Phuong et al. [17] developed an application using artificial intelligence to identify 50 popular timber species from Vietnam. Savero et al. [18] compared the anatomical features of Vietnamese *A. mangium* and *A. hybrid*.

Owing to the limited domestic wood supply for industries, Korea meets 84.8% of its total wood demand through imports from New Zealand, China, South America, and Southeast Asia, including Indonesia and Vietnam [19,20]. Korea has also invested in overseas plantation forests to secure a sustainable wood supply [21,22]. In total, this systematic plantation approach has been adopted by 34 companies in 14 countries, including Vietnam [23,24]. Korea has also invested in approximately 22,000 ha of overseas plantation forests in Vietnam, which is the second largest among the 14 countries and is primarily dominated by *acacia* and rubber trees [25].

So far, however, there is still a lack of study on the anatomical characteristics of *A. mangium*, *A. hybrid*, *D. pentagyna*, *A. occidentale*, *H. brasiliensis*, and *M. cajuputi* growing in Vietnamese plantation forests. Additionally, there is still no information regarding the non-anatomical characteristics of those species grown in Vietnam. As summarized by a few researchers [26,27], the non-anatomical characteristics such as heartwood fluorescence, the color and fluorescence of water and ethanol extracts, and the froth test, are rapid and easy methods to verify the identification of hardwood species. Therefore, this study aimed to investigate the anatomical and non-anatomical characteristics of the six commercial wood species (*A. mangium*, *A. hybrid*, *D. pentagyna*, *A. occidentale*, *H. brasiliensis*, and *M. cajuputi)* from the plantations in Vietnam to provide identification keys and quality indices for an effective utilization of those species.

2. Materials and Methods

2.1. Materials

Wood disks from six Vietnamese commercial hardwood species were used in the present study. *A. mangium*, *A. hybrid*, and *D. pentagyna* were collected from the plantation of Dongwha Vietnam Co., Ltd. (Song Cong City, Thai Nguyen Province, Vietnam; 21°30′17.74″ N, 105°50′48.102″ E). *A. occidentale*, *H. brasiliensis*, and *M. cajuputi* were obtained from the plantation of VRG Dongwha (Chon Thanh District, Binh Phuoc Province, Vietnam; 11°28′56.104″ N, 106°36′16.133″ E). Table 1 presents the fundamental sample information.

Table 1. Fundamental information of six wood species samples.

Scientific Name	Location	Sample Types	Diameter (cm)	Density (g/cm^3)
A. mangium	Plantation by Dongwha Vietnam	Disk	13.2	0.50
A. hybrid	Co., Ltd., Vietnam (21°30′17.74″ N,	Disk	12.2	0.50
D. pentagyna	105°50′48.102″ E)	Chips	-	0.75
A. occidentale	Plantation by VRG Dongwha,	Disk	7.8	0.52
H. brasiliensis	Vietnam (11°28′56.104″ N,	Disk	16.6	0.71
M. cajuputi	106°36′16.133″ E)	Disk	6.5	0.74

2.2. Methods

2.2.1. Sample Preparation for Microscopy

Specimens were prepared from four directions of the near bark (2–10 mm from the bark) of wood disks, with dimensions of 10 × 10 × 10 mm^3 (longitudinal × tangential × radial). The specimens were softened by heating a 50:50 mixture of glycerin and water for 7 h. Slices of 15–20 µm thickness from the cross, tangential, and radial sections were obtained using a sliding microtome (MSL-H, Nippon Optical Works Co. Ltd., Nagano, Japan). Slices were stained using 1% safranin and light-green solutions and then dehydrated with a succession of increasing alcohol concentrations (50%, 70%, 90%, 95%, and 99%) and xylene. Canada balsams were used to create permanent slides.

For the fiber length measurement, 20 × 5 × 5 mm^3 specimens were prepared in four directions near the bark on wood disks. The specimens were soaked in Schultz's solution following the method [28] for 3 d and then heated at 60 °C for 1 h.

2.2.2. Analysis of Qualitative and Quantitative Anatomical Characteristics

Qualitative and quantitative anatomical characteristics were evaluated according to the International Association of Wood Anatomists (IAWA) list of microscopic features for hardwood identification [27]. The optical micrographs were observed using an optical microscope (Eclipse E600, Nikon Corp., Tokyo, Japan) and analyzed with an image analysis system (i-Solution Lite, IMT i-Solution Inc., Burnaby, BC, Canada).

For quantitative anatomical characteristics, the tangential vessel diameter and the vessel number were measured on the cross-section from 50 cells and 25 areas of 1 mm^2, respectively. Ray heights and ray number per millimeter were measured on the tangential section from 50 rays and 25 times, respectively. The length of 50 fibers for the fiber dimensions was measured, and the radial and tangential fiber diameters, fiber lumen diameters, and wall thicknesses were measured from 50 cells on the cross-section.

2.2.3. Analysis of Non-Anatomical Characteristics

Non-anatomical characteristics such as the heartwood fluorescence, color and fluorescence of water and ethanol extracts, and froth test were evaluated according to the IAWA lists [27].

Fluorescence characteristics were observed from freshly trimmed transverse heartwood surfaces (planned or scraped) in a darkened room. The transverse surfaces were exposed to longwave ultraviolet light (VL-6LC, 365 nm, 6 W; Vilber, Collégien, France) at a distance of less than 100 mm.

To observe the color and fluorescence of water and ethanol extracts, thin heartwood shavings of each species were prepared and placed in a 20 mL vial. The wood shavings were covered with distilled water for water extracts and 95% ethanol for ethanol extracts. The vials were shaken for 10 to 15 s and then exposed to longwave ultraviolet light to observe the fluorescence of the extract. After determining the fluorescence, the vials were heated on a hotplate until the solution boiled, and the color was observed immediately.

Froth tests were performed using thin heartwood shavings. The shavings in a 20 mL vial were covered with distilled water and shaken for 15 s. The vial was allowed to stand for approximately 1 min after shaking. The test was positive when the froth completely covered the surface of the solution, weakly positive when the froth did not cover the entire surface, and negative if the froth was absent.

3. Results and Discussion

3.1. Qualitative and Quantitative Anatomical Characteristics

3.1.1. *Acacia mangium*

Figure 1 displays optical micrographs of the cross, radial, and tangential sections of *A. mangium* wood. In the cross-section, *A. mangium* showed indistinct growth ring boundaries. Wood porosity was diffuse with solitary and radial multiples vessels (Figure 1A).

The arrangement of axial parenchyma was aliform, vasicentric, and confluent (Figure 1A). Tyloses were absent.

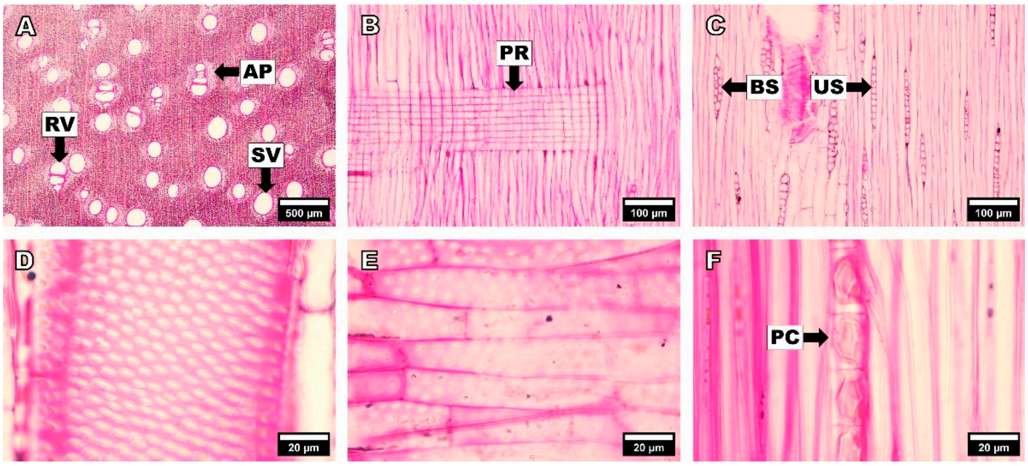

Figure 1. Optical micrographs of *Acacia mangium*. Cross-section (**A**), radial section (**B**), tangential section (**C**), intervessel pits (**D**), vessel-ray pits (**E**), and mineral inclusions (**F**). Solitary vessel (SV), radial multiple vessel (RV), axial parenchyma (AP), procumbent body ray (PR), uniseriate ray (US), biseriate ray (BS), and prismatic crystal (PC).

In the radial section, *A. mangium* showed a simple perforation plate, all body ray cells procumbent (Figure 1B), and distinct borders of vessel-ray pits, which were similar to intervessel pits (Figure 1E). Prismatic crystals were observed in the chambered axial parenchyma cells (Figure 1F).

In the tangential section, uniseriate and biseriate rays (Figure 1C) and fibers with simple to minutely bordered pits, which were non-septate (Figure 1C), were observed. Intervessel pits with a polygonal shape were alternated and vestured (Figure 1D).

For quantitative anatomical characteristics, the tangential vessel diameter and vessel numbers of *A. mangium* were 155.1 (116–200) μm and 8.7 (5–15)/mm^2, respectively. The fiber length, fiber diameter, lumen diameter, and fiber wall thickness were 882.0 (630–1300) μm, 14.1 (9–20) μm, 10.9 (7–17) μm, and 1.62 (1.14–2.37) μm, respectively. The lumen diameter was more than three times wider than the double-wall thickness of the fiber, which is categorized as a very thin-walled fiber according to the IAWA list [27]. The ray height and rays per millimeter were 200.0 (129–365) μm and 6.5 (3–11)/mm, respectively.

The qualitative anatomical characteristics of *A. mangium* in the present study are consistent with those reported in previous studies. As reported by Sahri et al. [29], Ogata et al. [30], Kim et al. [31], Andianto et al. [32], and Savero et al. [18], the wood porosity of *A. mangium* was diffused with solitary and radial multiple vessels. *A. mangium* also showed aliform and vasicentric axial parenchyma, non-septate fibers, and mostly uniseriate rays. In addition, prismatic crystals existed in the axial parenchyma of *A. mangium*.

The quantitative anatomical characteristics of *A. mangium* in the present study were also consistent with those reported in previous studies. Sahri et al. [29] reported that *A. mangium* from Malaysia had tangential vessel diameters of 132–167 μm and vessel numbers of 4–8/mm^2. Ogata et al. [30] reported these values to be 150–280 μm and 4–9/mm^2, respectively. Moreover, Andianto et al. [32] reported that *A. mangium* from Indonesia had tangential vessel diameters of 201 μm. Savero et al. [18] reported that the tangential vessel diameters and vessel numbers of *A. mangium* from Vietnam were 149 μm and 9/mm^2, respectively. However, in terms of fiber dimensions, our values were lower than those reported in the previous studies. The previously reported fiber length and fiber wall thickness of *A. mangium* were 934–1018 μm and 3.3–4.3 μm [29], 700–1400 μm and 1.5–2.5 μm [30], and 1215–1240 μm and 3.7 μm [32], respectively.

3.1.2. *Acacia hybrid*

Optical micrographs of the cross, radial, and tangential sections of *A. hybrid* are presented in Figure 2. In the cross-section, *A. hybrid* showed indistinct growth ring boundaries and was diffuse-porous with solitary and radial multiple vessels (Figure 2A). The arrangement of axial parenchyma was aliform, vasicentric, and confluent (Figure 2A). Tyloses were not observed in the vessels.

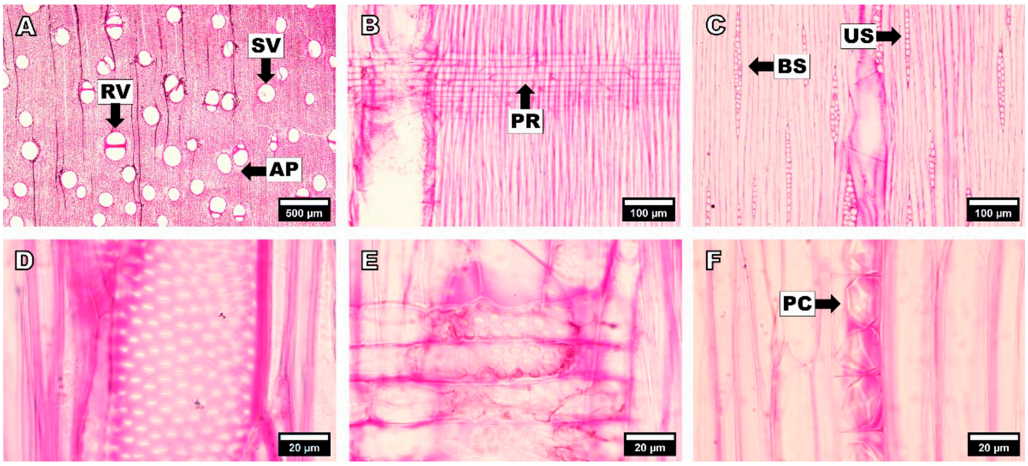

Figure 2. Optical micrographs of *Acacia hybrid*. Cross-section (**A**), radial section (**B**), tangential section (**C**), intervessel pits (**D**), vessel-ray pits (**E**), and mineral inclusions (**F**). Solitary vessel (SV), radial multiple vessel (RV), axial parenchyma (AP), procumbent body ray (PR), uniseriate ray (US), biseriate ray (BS), and prismatic crystal (PC).

In the radial section, the rays were composed of procumbent body ray cells (Figure 2B). Vessel-ray pits showed distinct borders, which were similar to intervessel pits (Figure 2E). *A. hybrid* showed simple perforation plates. There were prismatic crystals in the chambered axial parenchyma cells (Figure 2F).

In the tangential section, the rays were uniseriate and biseriate (Figure 2C). Fibers with simple to minutely bordered pits, which were non-septate, were also present (Figure 2C). The intervessel pits showed an alternate arrangement with a polygonal shape, and these pits were vestured (Figure 2D).

The tangential vessel diameters and vessel numbers in *A. hybrid* were 145.1 (86–261) μm and 7.1 (4–11)/mm^2, respectively. The fiber length was 853.2 (509–1347) μm. Fiber diameter, lumen diameter, and fiber wall thickness were 15.7 (11–21) μm, 12.4 (8–17) μm, and 1.66 (0.98–2.45) μm, respectively. The lumen diameter was greater than three times of the double-wall fiber thickness, showing a very thin-walled fiber according to the IAWA list [27]. The ray height and number were 239.9 (141–487) μm and 5.5 (3–9)/mm, respectively.

The anatomical characteristics of *A. hybrid* in the present study were consistent with those of a few previous studies. As reported by Praptoyo [33], Nirsatmanto et al. [34], and Savero et al. [18], *A. hybrid* exhibited diffuse porosity with solitary and radial multiple vessels, with vasicentric axial parenchyma and uniseriate and biseriate rays. Praptoyo [33] reported that *A. hybrid* from Indonesia had a vessel tangential diameter of 113–200 μm and vessel numbers of 4–7/mm^2, respectively. Moreover, Nirsatmanto et al. [34] and Savero et al. [18] reported these values to be 115–145 μm and 5–9/mm^2 and 133 μm and 7/mm^2 in *A. hybrid* from Indonesia and Vietnam, respectively. Moreover, the previously reported value of the fiber length and fiber wall thickness of *A. hybrid* was 1030–1040 μm and 2.0–5.2 μm [33] and 780–850 μm and 1.2–1.8 μm [34], respectively. These results indicate that, in terms of fiber dimensions, *A. hybrid* in the present study showed a lower fiber dimension than in previous studies.

3.1.3. *Dillenia pentagyna*

Figure 3 shows optical micrographs of the cross, radial, and tangential sections of *D. pentagyna*. In the cross-section, *D. pentagyna* had indistinct growth ring boundaries and diffuse porosity with solitary and tangential multiples vessels (Figure 3A). The axial parenchyma was diffuse, diffuse-in-aggregate, and scanty paratracheal (Figure 3A). Tyloses were absent in the vessels.

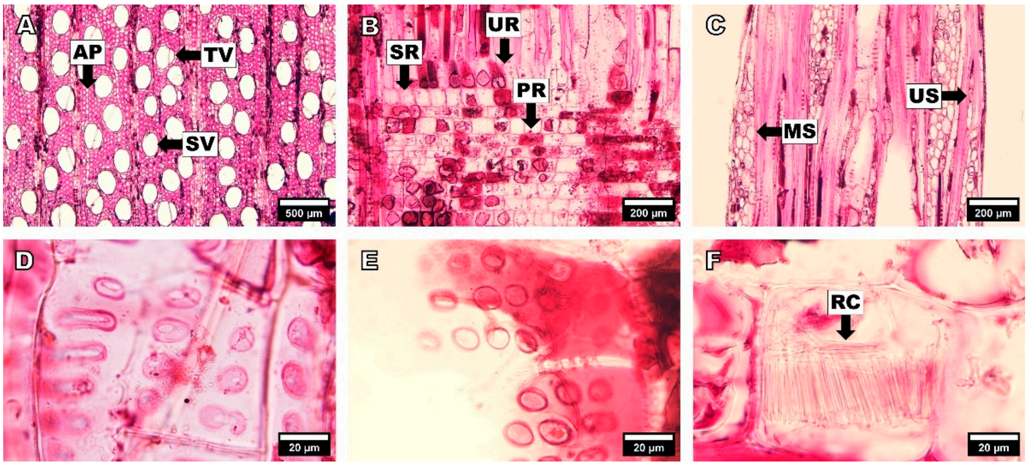

Figure 3. Optical micrographs of *Dillenia pentagyna* Cross-section (**A**), radial section (**B**), tangential section (**C**), intervessel pits (**D**), vessel-ray pits (**E**), and mineral inclusions (**F**). Solitary vessel (SV), tangential multiple vessel (TV), axial parenchyma (AP), procumbent body ray (PR), square body ray (SR), upright body ray (UR), uniseriate ray (US), multiseriate ray (MS), and raphides (RC).

In the radial section, the rays were composed of procumbent body ray cells with over four rows of upright and/or square marginal cells (Figure 3B). The perforated plates were scalariform. Disjunctive ray parenchyma cell walls were also observed. Vessel-ray pits were much reduced in borders to apparently simple with rounded or angular shapes (Figure 3E). Raphides were observed in the body ray cells (Figure 3F).

In the tangential section, the ray width was uniseriate and multiseriate with 4–7 seriates (Figure 3C). Non-septate fibers with bordered pits in both the radial and tangential walls were present (Figure 3C). The intervessel pits were arranged in a scalariform and opposite manner (Figure 3D).

The quantitative anatomical characteristics of *D. pentagyna* were observed as follows: tangential diameter of vessel lumina of 163.9 (91–216) µm, vessels per square millimeter of 9.1 (6–15)/mm^2, fiber length of 1405.0 (944–1791) µm, fiber diameter of 48.8 (39–59) µm, fiber lumen diameter of 23.5 (18–33) µm, and a fiber wall thickness of 12.7 (9–16) µm. The fiber lumen diameter was almost equal to the double-wall thickness of the fiber, which is classified as thin- to thick-walled according to the IAWA list [27]. The ray height was greater than 1 mm.

According to Martawijaya et al. [35], Ogata et al. [30], and Itoh et al. [10], *Dillenia* spp. are diffuse-porous with exclusively solitary vessels and non-septate fibers with large bordered pits. The axial parenchyma was diffuse, reticulate, and scanty and paratracheal. The rays consisted of two distinct sizes: uniseriate and broad rays. Raphides were present in the ray cells.

Studies on the quantitative anatomical characteristics of *Dillenia* spp. are relatively few. Martawijaya et al. [35] reported that the vessel lumina diameter, vessels per square millimeter, and fiber length of *Dillenia* spp. grown in Indonesia were 100–200 µm, 3–7/mm^2, and 2852 µm, respectively. Ogata et al. [30] reported these parameters to be 40–240 µm, 4–11/mm^2, and 2200–3000 µm, respectively. These results indicate that our findings on vessel lumina diameter and vessels per square millimeter were in line with those of previous studies, whereas the fiber length determined in the present study was shorter than that in previous studies. These differences in anatomical characteristics could be attributed to different growing sites.

3.1.4. *Anacardium occidentale*

Figure 4 shows optical micrographs of the cross, radial, and tangential sections of *A. occidentale*. In the cross-section, *A. occidentale* had indistinct growth ring boundaries, diffuse-porous with partly solitary, radial multiples, and very small cluster vessels (Figure 4A). The arrangement of axial parenchyma was vasicentric, aliform, lozenge-aliform, and confluent (Figure 4A). Tyloses were also present in the vessels (Figure 4A).

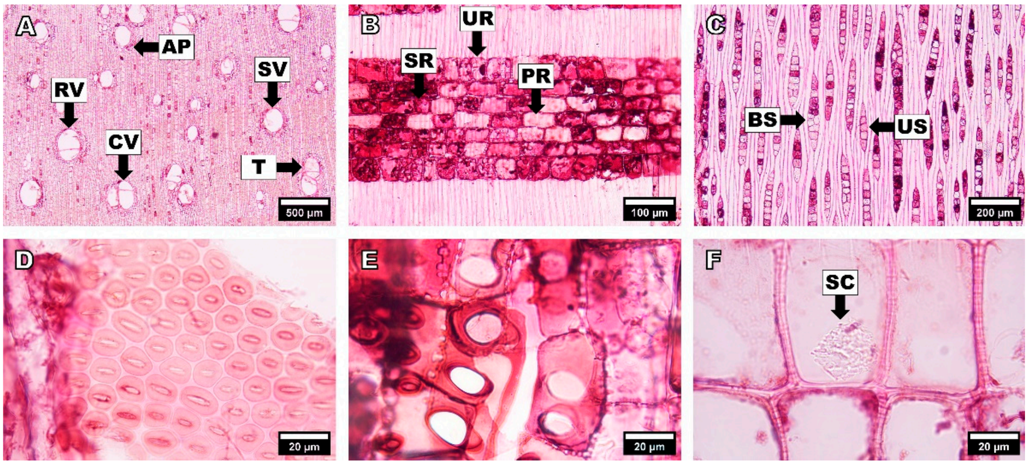

Figure 4. Optical micrographs of *Anacardium occidentale*. Cross-section (**A**), radial section (**B**), tangential section (**C**), intervessel pits (**D**), vessel-ray pits (**E**), and mineral inclusions (**F**). Solitary vessel (SV), radial vessel (RV), cluster vessel (CV), axial parenchyma (AP), tyloses (T), procumbent body ray (PR), square body ray (SR), upright body ray (UR), uniseriate ray (US), biseriate ray (BS), and silica bodies (SC).

In the radial section, the rays consisted of procumbent, square, and upright cells (Figure 4B). We also observed vessel-ray pits with significantly reduced borders that were apparently simple with rounded or angular shapes (Figure 4E); moreover, simple perforated plates were also observed. Silica bodies were observed in the ray cells (Figure 4F).

In the tangential section, the rays were mostly uniseriate and sometimes biseriate (Figure 4C). The fibers were non-septate with simple to minutely bordered pits (Figure 4C). Intervessel pits with alternating polygonal shapes were observed (Figure 4D).

In terms of quantitative anatomical characteristics, the tangential diameter of vessel lumina and vessels per square millimeter in *A. occidentale* were 155.2 (69–284) μm and 4.9 (1–8)/mm^2, respectively. Fiber properties of *A. occidentale* were observed as follows: length, 622.5 (427–1058) μm; diameter, 14.2 (11–18) μm; lumen diameter, 11.4 (9–15) μm; and wall thickness, 1.39 (1.06–1.75) μm. The fiber was classified as a very thin-walled fiber according to the IAWA list [27]. The ray height and rays per millimeter were 374.6 (158–843) μm and 10.6 (6–15)/mm^2, respectively.

As reported by Terrazas Salgado [36] and Gupta and Agarwal [37], *A. occidentale* comprises diffuse-porous wood with solitary and radial multiple vessels. Tyloses are present in the vessels. The fibers were non-septate with vasicentric, aliform, lozenge-aliform, and confluent axial parenchyma. The rays were uniseriate and biseriate, with silica bodies in the ray cells. Terrazas Salgado [36] reported the vessel lumina tangential diameter, vessels per square millimeter, and fiber length of *A. occidentale* to be 22–330 μm, 5–14/mm^2, and 607–1228 μm, respectively. Moreover, Gupta and Agarwal [37] reported the values to be 54–200 μm, 3–13/mm^2, and 481–856 μm, respectively.

3.1.5. *Hevea brasiliensis*

Optical micrographs of the cross, radial, and tangential sections of *H. brasiliensis* are shown in Figure 5. In the cross-section, *H. brasiliensis* had indistinct growth ring boundaries and was diffuse-porous with solitary, radial multiples, and very small cluster vessels (Figure 5A). The axial parenchyma was vasicentric and banded, including reticulate, narrow, and marginal bands (Figure 5A). Tyloses were rarely found (Figure 5A).

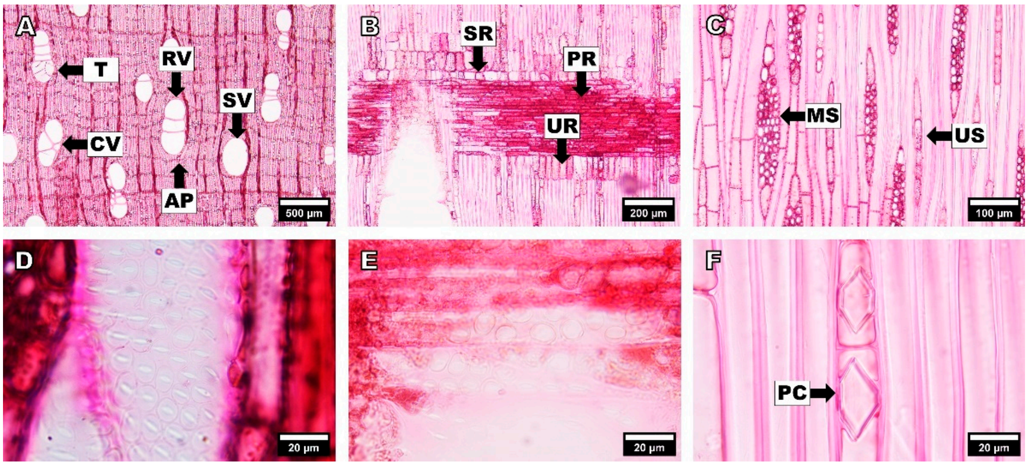

Figure 5. Optical micrographs of *Hevea brasiliensis*. Cross-section (**A**), radial section (**B**), tangential section (**C**), intervessel pits (**D**), vessel-ray pits (**E**), and mineral inclusions (**F**). Solitary vessel (SV), radial vessel (RV), cluster vessel (CV), axial parenchyma (AP), tyloses (T), procumbent body ray (PR), square body ray (SR), upright body ray (UR), uniseriate ray (US), multiseriate ray (MS), and prismatic crystal (PC).

In the radial section, the rays comprised procumbent body ray cells with mostly 2–4 rows of upright and/or square marginal cells (Figure 5B). Vessel-ray pits showed significantly reduced borders and appeared simple with rounded or angular shapes (Figure 5E). Simple perforated plates were also observed. Prismatic crystals were observed in the chambered axial parenchyma cells (Figure 5F).

In the tangential section, *H. brasiliensis* showed uniseriate rays, a smaller multiseriate ray with 2–3 seriates, and larger multiseriate rays with 4–5 seriates (Figure 5C). Fibers with simple to minutely bordered pits, which were non-septate, were observed (Figure 5C). The intervessel pits were arranged alternately in a polygonal shape (Figure 5D).

The quantitative anatomical characteristics of *H. brasiliensis* were as follows: tangential diameter of vessel lumina, 173.6 (82–260) µm; vessels per square millimeter, 4.8 (1–11)/mm^2; fiber length, 1287.7 (782–2793) µm; fiber diameter, 17.2 (14–23) µm; fiber lumen diameter, 9.9 (7–15) µm, and fiber wall thickness, 3.66 (2.78–5.04) µm. The fiber lumen diameter was classified into a thin- to thick-walled fiber according to the IAWA list [27]. *H. brasiliensis* had a ray height of 479.8 (135–878) µm and ray number of 8.4 (6–11)/mm.

As reported by Ogata et al. [30] and Perdigão et al. [38], the wood porosity of *H. brasiliensis* diffuses with solitary and radial multiples vessels. It has non-septate fibers and vasicentric, reticulate, and banded axial parenchyma. The rays are uniseriate and multiseriate. There were prismatic crystals in the axial parenchyma. However, with respect to the existence of tyloses, there have been controversial findings. Ogata et al. [30] reported that tyloses were present in *H. brasiliensis*, whereas Perdigão et al. [38] reported that tyloses were absent.

In terms of quantitative anatomical characteristics, Ogata et al. [30] showed that tangential vessel lumina diameters, vessels per square millimeter, and the fiber length of *H. brasiliensis* were 100–280 µm, 1–4/mm^2, and 800–1600 µm, respectively. Perdigão et al. [38] reported tangential vessel diameters of 71–249 µm and vessel numbers of 1–15/mm^2.

3.1.6. *Melaleuca cajuputi*

Optical micrographs of the cross, radial, and tangential sections of *M. cajuputi* are shown in Figure 6. In the cross-section, *M. cajuputi* had indistinct growth ring boundaries. Wood porosity was diffuse, with exclusively solitary vessels (90% or more) (Figure 6A). The axial parenchyma was diffuse, confluent, and had narrow bands or lines up to three cells wide (Figure 6A). Tyloses were not observed in the vessels.

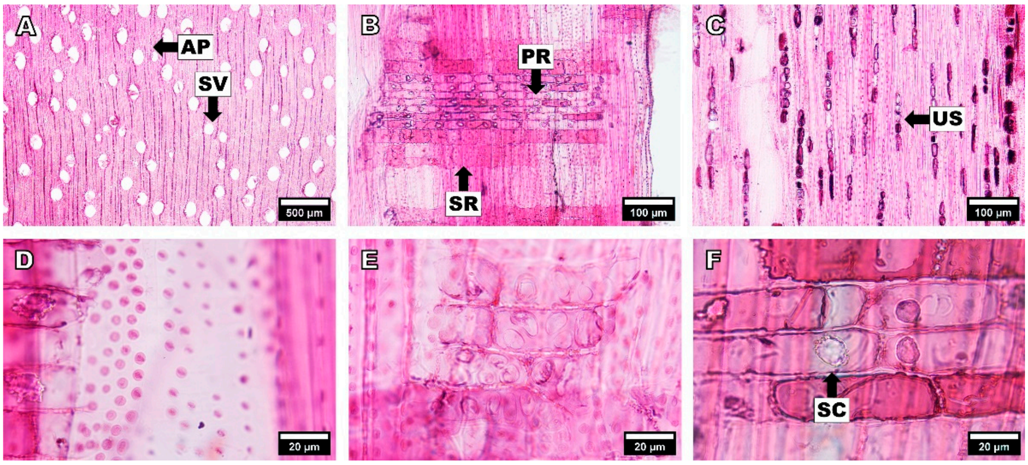

Figure 6. Optical micrographs of *Melaleuca cajuputi*. Cross-section (**A**), radial section (**B**), tangential section (**C**), intervessel pits (**D**), vessel-ray pits (**E**), and mineral inclusions (**F**). Solitary vessel (SV), axial parenchyma (AP), procumbent body ray (PR), square body ray (SR), upright body ray (UR), uniseriate ray (US), and silica bodies (SC).

In the radial section, the body ray cells were procumbent, with one row of upright and/or square marginal cells (Figure 6B). The vessel-ray pits showed significantly reduced borders compared to simple and rounded or angular pits (Figure 6E). The perforated plates were simple. Silica bodies were observed in the ray cells (Figure 6B,F).

In the tangential section, the ray was exclusively uniseriate (Figure 6C). The fibers were non-septate with bordered pits in both the radial and tangential walls (Figure 6C). Intervessel pits showed alternating arrangements and were vestured (Figure 6D).

The tangential vessel diameter and vessel numbers for *M. cajuputi* were 119.6 (51–166) μm and 9.2 (5–16)/mm^2, respectively. The fiber length, fiber diameter, lumen diameter, and fiber wall thickness were 821.5 (597–1224) μm, 15.3 (9–19) μm, 8.7 (5–12) μm, and 3.26 (2.29–4.18) μm, respectively. The lumen diameter was less than three times wider than the double-wall thickness of the fiber, which is categorized as a thin- to thick-walled fiber according to the IAWA list [27]. The ray height and rays per millimeter were 259.0 (71–470) μm and 11.1 (8–15)/mm, respectively.

Ingle and Dadswell [39], Ogata et al. [30], and Itoh et al. [10] reported that *Melaleuca* spp. are diffuse-porous with exclusively solitary vessels. It had non-septate fibers with distinctly bordered pits. The axial parenchyma was diffuse and had a narrow, discontinuous band. The rays were exclusively uniseriate and silica bodies were present in the ray cells. Ingle and Dadswell [39] reported that the vessel diameter, vessel numbers, and fiber length of *Melaleuca* spp. were 45–180 μm, 5–20/mm^2, and 430–1130 μm, respectively. Moreover, Ogata et al. [30] reported these values to be 130–200 μm, 11–15/mm^2, and 800–1200 μm, respectively.

3.2. Non-Anatomical Characteristics

3.2.1. *Acacia mangium*

Of the non-anatomical characteristics of *A. mangium*, the heartwood presented yellow or green fluorescence (Figure 7A). The water- and ethanol-extracted samples showed a brown and yellow color (Figure 8) with no fluorescence. The froth test showed a weakly positive reaction (Figure 9A).

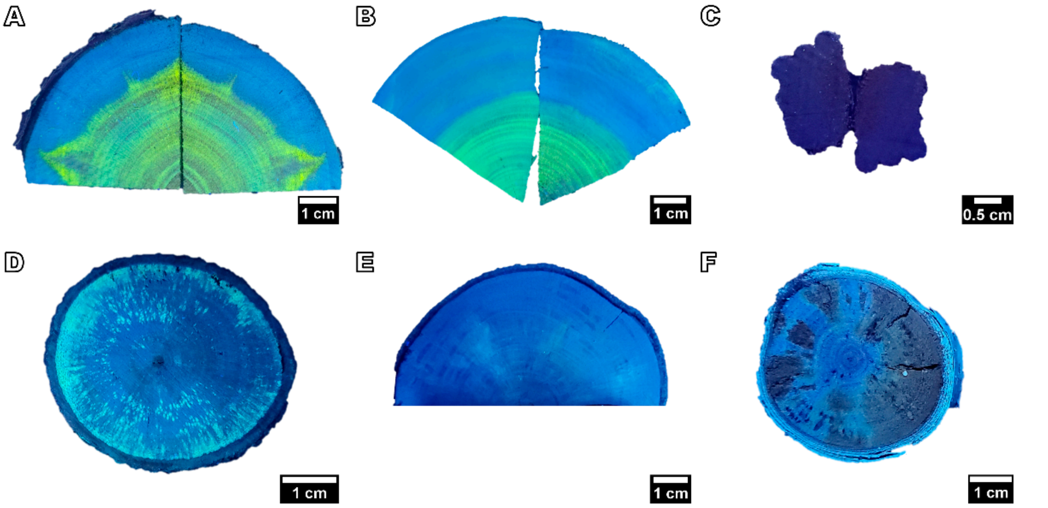

Figure 7. Heartwood fluorescence of *Acacia mangium* (**A**), *Acacia hybrid* (**B**), *Dillenia pentagyna* (**C**), *Anacardium occidentale* (**D**), *Hevea brasiliensis* (**E**), and *Melaleuca cajuputi* (**F**). Disks (**A**,**B**,**D**–**F**) and chips (**C**).

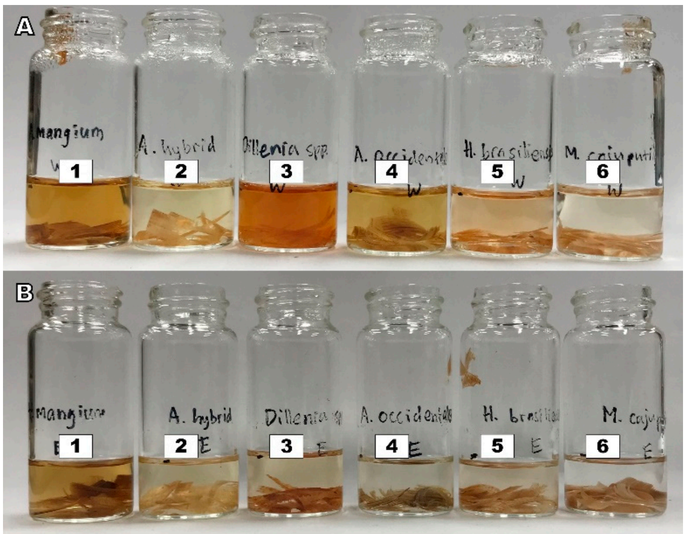

Figure 8. Water (**A**) and ethanol (**B**) extract color for *Acacia mangium* (1), *Acacia hybrid* (2), *Dillenia pentagyna* (3), *Anacardium occidentale* (4), *Hevea brasiliensis* (5), and *Melaleuca cajuputi* (6).

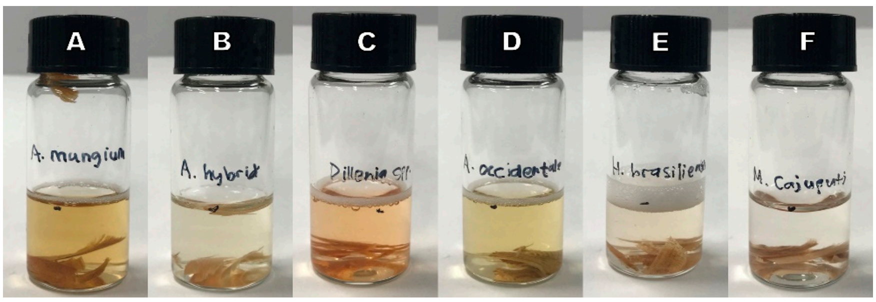

Figure 9. Froth tests of Acacia mangium (**A**), *Acacia hybrid* (**B**), Dillenia pentagyna (**C**), Anacardium occidentale (**D**), Hevea brasiliensis (**E**), and Melaleuca cajuputi (**F**).

The heartwood fluorescence, water extract color and fluorescence, and froth test results of *A. mangium* in the present study are in line with *Acacia* spp. of previous studies [26,27,40].

3.2.2. *Acacia hybrid*

The heartwood of *A. hybrid* showed a yellow or green fluorescence color similar to that of *A. mangium* (Figure 7B), and the extracts from water and ethanol showed no fluorescence. However, the color of *A. hybrid* water and ethanol extracts differed from that of *A. mangium*, displaying shades of yellow (Figure 8). The difference in extract color between *A. hybrid* and *A. mangium* may be due to the extractives content of both species. According to Moya et al. [41], the lightness (L*) parameters in wood color showed a significantly negative correlation with extractives content in the wood, whereas the red-green (a*) parameters had a positive correlation with extractives content. Froth test results were negative (Figure 9B). The difference in the froth reaction between *A. hybrid* and *A. mangium* could be attributed to the saponin content in the heartwood [27].

The present study showed similar fluorescence characteristics for the heartwood and extracts from water and ethanol to *Acacia* spp. In previous studies [26,27], *Acacia* spp. showed yellow or green fluorescence from the heartwood and no fluorescence from water and ethanol extracts. However, the froth test showed a weakly positive reaction, which was different from that of *A. hybrid* in the present study.

3.2.3. *Dillenia pentagyna*

The heartwood of *D. pentagyna* was not fluorescent (Figure 7C). The water extract presented purple fluorescence and a red or orange color (Figure 8A), whereas the ethanol extract showed purple fluorescence and shades of red color (Figure 8B). The froth test showed a weakly positive reaction (Figure 9C).

The results of the present study on heartwood fluorescence are consistent with those of a previous study. As reported by Avella et al. [42], 27 Dilleniaceae species had no heartwood fluorescence.

3.2.4. *Anacardium occidentale*

Anacardium occidentale heartwood exhibited green or blue fluorescence (Figure 7D). The water extract showed a yellow color (Figure 8A) without fluorescence, whereas the ethanol extract presented shades of yellow color (Figure 8B) without fluorescence. The froth test was weakly positive (Figure 9D), similar to that of *A. mangium* and *D. pentagyna.*

As reported by the IAWA committee [27], the heartwood of *Anacardium* spp. shows yellow or green fluorescence, which is in line with the results of the present study.

3.2.5. *Hevea brasiliensis*

The heartwood of *H. brasiliensis* exhibited no fluorescence (Figure 7E). Both the water and ethanol extracts showed shades of red color (Figure 8) with blue fluorescence. A large amount of froth was observed, indicating a positive reaction for the froth test (Figure 9E).

Silva Guzmán et al. [43] reported that *H. brasiliensis* from Mexico was non-fluorescent for the heartwood, displayed blue or green fluorescence for the water extract test and purple fluorescence for the ethanol extract test, and had a negative reaction for the froth test.

3.2.6. *Melaleuca cajuputi*

Blue or purple fluorescence was observed for the heartwood of *M. cajuputi* (Figure 7F). In the water and ethanol extracts, *M. cajuputi* was neither fluorescent nor colorless (Figure 8). In addition, the froth test result was negative (Figure 9F).

3.3. Summary of Anatomical and Non-Anatomical Characteristics

The anatomical and non-anatomical characteristics of the six Vietnamese wood species based on the IAWA feature lists are presented in Tables 2 and 3, respectively.

Table 2. Anatomical characteristics of Vietnamese wood species based on International Association of Wood Anatomist (IAWA) feature lists.

<table>
<tr><th rowspan="2">Parameters</th><th colspan="6">Vietnamese Wood Species</th></tr>
<tr><th>A. mangium</th><th>A. hybrid</th><th>D. pentagyna</th><th>A. occidentale</th><th>H. brasiliensis</th><th>M. cajuputi</th></tr>
<tr><td>Growth rings</td><td colspan="6">Indistinct or absent (2)</td></tr>
<tr><td>Porosity</td><td colspan="6">Wood diffuse-porous (5)</td></tr>
<tr><td>Vessel groupings</td><td colspan="5">Multiples (10)</td><td>Exclusively solitary (9)</td></tr>
<tr><td>Perforation plates</td><td colspan="2">Simple (13)</td><td>Scalariform (14)</td><td colspan="3">Simple (13)</td></tr>
<tr><td>Intervessel pits</td><td colspan="2">Alternate (22) with polygonal shape (23)</td><td>Scalariform (20) and opposite (21)</td><td colspan="2">Alternate (22) with polygonal shape (23)</td><td>Alternate (22)</td></tr>
<tr><td>Vestured pits</td><td colspan="2">Present (29)</td><td colspan="3">Absent</td><td>Present (29)</td></tr>
<tr><td>Vessel-ray pitting</td><td colspan="2">Distinct borders, similar to intervessel pits (30)</td><td colspan="4">Much reduced borders, pits rounded or angular (31)</td></tr>
<tr><td>Vessel diameter</td><td colspan="6">100–200 µm (42)</td></tr>
<tr><td>Vessel number</td><td colspan="3">5–20/mm^2 (47)</td><td colspan="2">≤ 5/mm^2 (46)</td><td>5–20/mm^2 (47)</td></tr>
<tr><td>Tyloses</td><td colspan="3">Absent</td><td colspan="2">Present (56)</td><td>Absent</td></tr>
<tr><td>Fiber pits</td><td colspan="2">Simple to minutely bordered pits (61)</td><td>Distinctly bordered pits (62) and pits common in both radial and tangential walls (63)</td><td colspan="2">Simple to minutely bordered pits (61)</td><td>Distinctly bordered pits (62) and pits common in both radial and tangential walls (63)</td></tr>
<tr><td>Septate fibers</td><td colspan="6">Non-septate (66)</td></tr>
<tr><td>Fiber wall thickness</td><td colspan="2">Very thin-walled (68)</td><td>Thin- to thick-walled (69)</td><td>Very thin-walled (68)</td><td colspan="2">Thin- to thick-walled (69)</td></tr>
<tr><td>Fiber length</td><td colspan="2">≤ 900 µm (71)</td><td>900–1600 µm (72)</td><td>≤900 µm (71)</td><td>900–1600 µm (72)</td><td>≤900 µm (71)</td></tr>
<tr><td>* Axial parenchyma</td><td colspan="2">Vasicentric (79), aliform (80), and confluent (83)</td><td>Diffuse (76), diffuse-in-aggregates (77), and scanty paratracheal (78)</td><td>Vasicentric (79), aliform (80), lozenge-aliform (81), and confluent (83)</td><td>Vasicentric (79), reticulate (87), in narrow bands (86), and in marginal (89).</td><td>Diffuse (76), confluent (83), and in narrow bands (86)</td></tr>
<tr><td>Ray width</td><td colspan="2">1 to 3 cells (97)</td><td>1 to 3 cells (97) and larger rays commonly 4- to 10-seriate (98)</td><td>1 to 3 cells (97)</td><td>1 to 3 cells (97) and larger rays commonly 4- to 10-seriate (98)</td><td>Exclusively uniseriate (96)</td></tr>
<tr><td>Ray composition</td><td colspan="2">All cells procumbent (104)</td><td>Procumbent with over 4 rows of upright and/or square marginal cells (108)</td><td>Procumbent, square, and upright cells mixed throughout the ray (109)</td><td>Procumbent with mostly 2–4 rows of upright and/or square marginal cells (107)</td><td>Procumbent with one row of upright and/or square marginal cells (106)</td></tr>
<tr><td>Ray number</td><td colspan="6">4–12/mm (115)</td></tr>
<tr><td>Mineral inclusions</td><td colspan="2">Prismatic crystals (142)</td><td>Raphides (149)</td><td>Silica (160)</td><td>Prismatic crystals (142)</td><td>Silica (160)</td></tr>
</table>

Note: The numbers in parentheses denote the IAWA feature list for hardwood identification. * Bold letters indicate the most common axial parenchyma.

Table 3. Non-anatomical characteristics of Vietnamese wood species based on IAWA feature lists.

Parameters	**Vietnamese Wood Species**					
	A. mangium	***A. hybrid***	***D. pentagyna***	***A. occidentale***	***H. brasiliensis***	***M. cajuputi***
Heartwood fluorescence	Yellow or green (204)		Not fluorescent	Green or blue (204)	Not fluorescent	Blue or purple (204)
Water extract fluorescence	Not fluorescent		Purple (205)	Not fluorescent	Blue (205)	Not fluorescent
Water extract color	Brown (206)	Shades of yellow (208)	Red or orange (207)	Yellow (208)	Shades of red (207)	Colorless (206)
Ethanol extract fluorescence	Not fluorescent		Purple (210)	Not fluorescent	Blue (210)	Not fluorescent
Ethanol extract color	Yellow (208)	Shades of yellow (208)	Shades of red (207)	Shades of yellow (208)	Shades of red (207)	Colorless (206)
Froth test	Weakly positive (215)	Negative	Weakly positive (215)		Positive (215)	Negative

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

4. Conclusions

Regarding anatomical characteristics, all species showed similar characteristics in a few parameters such as indistinct growth ring, diffuse porosity, non-septate fibers, vessel diameter of 100–200 µm, and ray number of 4–12/mm. All the species showed distinctive characteristics in most of the evaluated parameters, especially in axial parenchyma, ray width and composition, and mineral inclusion.

In terms of non-anatomical characteristics, all species had distinctive heartwood fluorescence and color in the water and ethanol extracts. The fluorescence of the water and ethanol extracts was only observed for *D. pentagyna* and *H. brasiliensis*. The froth test showed a positive reaction for *H. brasiliensis*, a weakly positive reaction for *A. mangium*, *D. pentagyna*, and *A. occidentale*, and a negative reaction for *A. hybrid* and *M. cajuputi*.

In summary, the six wood species from the plantation in Vietnam exhibited distinctive differences in anatomical and non-anatomical characteristics. Our results can be used as identification keys and quality indices for the effective utilization of each species.

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