

Wood anatomical survey and wood specific gravity of 13 species of *Aglaia* (Meliaceae) from Thailand

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ABSTRACT. The wood anatomical features of 13 species of *Aglaia* from Thailand were studied and described to aid microscopic wood identification. Diagnostic features include the width of multiseriate rays, crystals, the type of paratracheal parenchyma and ray cell composition. Wood specific gravity was studied in relationship with the wood anatomy. Our results showed a high negative correlation between wood specific gravity and fibre lumen diameter, but no significant relationships between wood specific gravity and features of rays and axial parenchyma.

KEY WORDS: *Aglaia*, anatomy, Meliaceae, wood, wood specific gravity.

INTRODUCTION

Aglaia Lour. is the largest genus in the family Meliaceae and consists of about 120 species (Muellner *et al.*, 2008). In Thailand, it is represented by 32 species (Wongprasert *et al.*, 2011). *Aglaia* constitutes a medium-sized woody genus, distributed mainly in the tropical forests of the Indo-malesian region (Pannell, 1992; Muellner *et al.*, 2005).

Aglaia has received increasing scientific attention because of its bioactive potential. A group of cyclopenta[b]benzofurans from *Aglaia* were shown to have potential as anticancer drugs and as insecticides (Ishibashi *et al.*, 1993; Janprasert *et al.*, 1993; Satasook *et al.*, 1994; Nugroho *et al.*, 1997a, b; Brader *et al.*, 1998; Bacher *et al.*, 1999; Nugroho *et al.*, 1999; Dreyer *et al.*, 2001; Greger *et al.*, 2001; Kim *et al.*, 2006) as well as cytotoxic (King *et al.*, 1982; Cui *et al.*, 1997; Wu *et al.*, 1997) and antifungal compounds (Engelmeier *et al.*, 2000). The timber of *Aglaia* is used for construction work, furniture and flooring; especially *A. argentea* Blume

is often used as a mahogany substitute (Lemmens *et al.*, 1995; Mabberley *et al.*, 1995; White & Gasson, 2008).

Several authors have described the wood anatomy of many genera of Meliaceae. Their results showed great differences in wood structures within these genera (Kribs, 1930; Panshin, 1933; Metcalfe & Chalk, 1950; Desch, 1954; Ghosh *et al.*, 1963; Pennington & Styles, 1975; Wong, 1975; Datta & Samanta, 1983; Lemmens *et al.*, 1995; Negi *et al.*, 2003). The web-database InsideWood (2004 onwards; see also Wheeler, 2011) has summarized comprehensive wood anatomical information on numerous *Aglaia* species. Moll & Janssonius (1908) showed that variation within species often exceeds that between species, especially in *Aglaia*. In 2008, White & Gasson (2008) provided detailed descriptions of 18 genera of mahogany timbers in the family Meliaceae. In Thailand, Chunwarin and Sriaran (1973) presented the details of the wood anatomy of 11 species of Meliaceae. Saentrong (1990)

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described the anatomical characters of roots, stems, leaves, flowers, fruit, and seeds of *Melia azedarach* L. and *M. dubia* Cav. However, the wood anatomical data of *Aglaia* are mostly confined to a few species, and usually scattered over limited papers and some books or atlases on wood anatomy for restricted geographical regions.

Physical properties are the quantitative characteristics of wood and their behaviour to external influences other than applied forces such as directional properties, moisture content, dimensional stability, thermal and pyrolytic (fire) properties, density and electrical comical and decay resistance. Included here is specific gravity. Familiarity with the physical properties of wood is important to know the performance and strength of wood used in structural applications. Specific gravity provides a relative measure of the amount of wood substance contained in a unit volume of wood. It is calculated by dividing the oven-dry weight by the green volume measured by water displacement.

This paper focuses on the anatomy of the secondary xylem and some properties of *Aglaia* from Thailand. All detailed wood anatomical accounts in the literature have been summarized, using IAWA Hardwood List codes (IAWA Committee, 1989) in the webdatabase InsideWood (2004 and onwards; Wheeler, 2011).

MATERIALS AND METHODS

The wood anatomy of 13 species of *Aglaia* was investigated. Nine species of *Aglaia* were collected in natural sites from Nakhon Ratchasima, Narathiwat, Phangnga and Trat provinces, Thailand, by the first author and anatomical vouchers are housed in the herbarium of Science and Technology Department, Princess of Naradhiwas University (STPNU). Usually stem disks, over 5 cm in diameter, were collected from felled trees. In some cases where trees had to be conserved thick branches (diameter 4.5–6.5 cm) were sampled. In addition, four species were represented by samples from the xylarium of the Office of Forest Management and Forest Production Research, Bangkok, Thailand (FMFPR) (Table 1).

All samples were stored in the laboratory in air-dried condition until wood density determination.

Samples were softened in boiling water for 1 h, then sectioned with a sliding microtome at 10–20 µm thickness along the transverse, tangential, and radial plains. Samples were stained with safranin (safranin 2%, water soluble) and dehydrated using an ethanol dehydration series through absolute ethanol, transferred to xylene and embedded in Permunt (Biomeda, Burlingame, California, USA). To determine the fibre size and length, the wood tissues were macerated using Franklin's technique (Franklin, 1937). All the microscopic slides were stored at the herbarium of Science and Technology Department, Princess of Naradhiwas University (STPNU). Sections were observed using light microscope and compound microscope (Zeiss Axios and Zeiss Axios digital camera eyepiece, Leica DMRBE Microscope and Leica DFC 420C digital camera). The terminology, definition, and measurements of quantitative features mainly follow the IAWA standard list (IAWA Committee, 1989).

The generated data were exported to a Microsoft Excel spreadsheet. The basic standard statistics were evaluated including the average and standard deviation, the range and number of observations for specific gravity and anatomical characters. The values reported are averages. In this study the diversity in various wood anatomical characters were analysed in order to search for any relation between wood anatomical characters and wood specific gravity. The wood anatomical characters analysed were wood specific gravity, vessel grouping index, solitary vessel index, vessel density, fraction of vessel area per total area, vessel diameter, vessel element length, hydraulic diameter, intervessel pit diameter, fibre diameter, fibre lumen diameter, fibre length, fibre wall thickness, the ratio of fibre lumen diameter to fibre wall thickness, ray frequency, fraction of ray area per total area, uniseriate ray width, multiseriate ray width, uniseriate ray height and multiseriate ray height. Pearson's correlation analyses were used to explore relationships between wood anatomical variables and wood specific gravity. Analysis of variance (ANOVA) was used to calculate the significance levels of the correlations between wood anatomical characters and wood specific gravity.

Table 1. Samples of *Aglaia*, location and diameter of samples at each site in Thailand.

Scientific name (number of specimen studied)	Province	Origin	Sample no.	Collector	Latitude WGS84	Longitude WGS84	Diameter (cm)
<i>A. crassinervia</i> Kurz ex Hiern (1)	Phangnga	STPNU	063	S. Khaopakro	98.470583	8.994028	7.2
<i>A. cucullata</i> (Roxb.) Pellegr. (1)	Xylarium	FMFPR	3370	Unknown	-	-	-
<i>A. elaeagnoides</i> Benth. (1)	Trat	STPNU	024	S. Khaopakro	102.675222	12.399167	19.0
<i>A. elliptica</i> Blume (1)	Narathiwat	STPNU	015	S. Khaopakro	101.628361	6.615139	4.5
<i>A. forbesii</i> King (1)	Narathiwat	STPNU	013	S. Khaopakro	101.628361	6.615139	5.0
<i>A. grandis</i> Korth. (1)	Trat	STPNU	022	S. Khaopakro	102.669167	12.389889	15.0
<i>A. lawii</i> (Wight) C.J.Saldanha	Xylarium	FMFPR	3287	Unknown	-	-	-
<i>A. leptantha</i> Miq. (1)	Trat	STPNU	021	S. Khaopakro	102.669083	12.389833	29.7
<i>A. oligophylla</i> Miq. (1)	Nakhon Ratchasima	STPNU	036	S. Khaopakro	101.845278	14.4425	13.7
<i>A. silvestris</i> (M.Roem.) Merr. (1)	Xylarium	FMFPR	3308	Unknown	-	-	-
<i>A. spectabilis</i> (Miq.) S.S.Jain & Bennet (1)	Trat	STPNU	023	S. Khaopakro	102.669167	12.389889	32.5
<i>A. spectabilis</i> (Miq.) S.S.Jain & Bennet (1)	Nakhon Ratchasima	STPNU	032	S. Khaopakro	101.845278	14.4425	30.0
<i>A. tenuicaulis</i> Hiern(1)	Narathiwat	STPNU	016	S. Khaopakro	101.837194	5.794167	5.0
<i>A. tomentosa</i> Teijsm. & Binn. (1)	Xylarium	FMFPR	1402	Unknown	-	-	-

Note: Origin: STPNU = herbarium of Science and Technology Department, Princess of Naradhiwas University (Thailand), FMFPR = xylarium of the Office of Forest Management and Forest Production Research, Bangkok (Thailand).

RESULTS

Wood anatomical survey of Genus *Aglaia*

Growth boundaries

In *Aglaia*, growth boundaries are absent or indistinct, rarely distinct (*A. cucullata* (Roxb.) Pellegr., *A. elaeagnoidea* Benth.) (Table 2, Fig. 1). If present, they are marked by slightly thicker walls of radially flattened fibres in the latewood.

Vessels

Pore distribution and vessel grouping (transverse section)

Only diffuse porous wood was found in *Aglaia* (Figs. 1–2). The pores are solitary and in radial multiples (Fig. 1–2) of mainly 2 or 3 and sometimes up to 4 pores (Table 2). The solitary pores are round to oval in all species. Three patterns in pore grouping are distinguished: solitary pores dominant, radial multiples pores dominant and a more or less equal mix of solitary pores and radial multiples. Solitary pores are dominant in *A. cucullata*, *A. grandis*; while radial multiples are dominant in *A. spectabilis* and *A. tenuicaulis* (Table 2).

Shape of vessel elements

Vessel elements range from barrel-shaped to short or long oblong and linear with or without tails (tapering or ligulate extension at one or both ends). Furthermore, the end walls are oblique or horizontal (Fig. 3A).

Vessel density and element sizes

Vessel density ranges from 5 pores/mm² in *A. cucullata* to 31/mm² in *A. crassinervia* and *A. tenuicaulis* (Table 2, Fig. 1). This feature has a high diagnostic value for identification at the sectional level: in section *Aglaia*, the vessel density varies from 10 to 31 pores/mm²; in section *Amoora*, it varies from 5–8 pores/mm²; and in section *Neoaglaia* is 11 pores/mm². Average tangential vessel diameter ranges from 53 ± 139 µm in *A. crassinervia* to 211 ± 55 µm in *A. spectabilis* (Table 3, Fig. 2). There is a distinct correlation between vessel density and vessel diameter, the species with higher vessel density tend to have a narrower vessel diameter, and vice versa. The average vessel element length varies from 349 ± 93 µm in *A. leptantha* to 652 ± 117 µm in *A. tomentosa* (Table 3), this

feature has no significantly different between sections.

Perforation plates

All species of *Aglaia* have exclusively simple perforations (Fig. 3A). The perforation is usually round to oval. The inclination of the perforation plates varies from horizontal to oblique.

Wall pitting

The intervessel pit arrangement in all species of *Aglaia* is alternate. The pits are round to oval and/or slightly polygonal in shape. Their average size in horizontal direction is mostly minute, ca. 2 ± 0.4 µm in *A. crassinervia* to 5 ± 0.5 µm in *A. spectabilis* (Table 3, Fig. 3B). This feature has no diagnostic value at the species or section level. Vessel-ray and vessel-parenchyma pits are similar to intervessel pits in arrangement, shape, and size (Metcalf & Chalk, 1950, 1983; Fig. 3C).

Tyloses and deposits

Tyloses are always absent. Vessel deposits (gums) were observed in many species, but usually very few and only in some vessels (Fig. 3D).

Vessel wall thickenings

Vessel wall thickenings were not found in *Aglaia*.

Fibres

The mechanical tissue of all *Aglaia* species is composed of septate fibres (Fig. 4A–B) with simple to minutely bordered pits, mainly in the radial walls (Table 2). Fibre wall thickness varies from thin (2.7 ± 0.4 µm in *A. tenuicaulis*) to thick (5.2 ± 0.5 µm in *A. elaeagnoidea*) (Table 2–3, Fig. 4C–D), according to the IAWA definitions (Wheeler *et al.*, 1989; thin-walled: fibre lumina 3 or more times wider than the double wall thickness; thin- to thick-walled: fibres lumina less than 3 times the double wall thickness; thick-walled: fibre lumina almost completely closed). In most *Aglaia* species, the majority of the fibres are thin- to thick-walled (Table 2). However, the variation within a single sample occasionally only shows thin- or thick-walled fibres. This feature has no significantly different between sections. The average fibre diameter ranges from 11 ± 1 µm in *A. tenuicaulis* to 20 ± 3 µm in *A. spectabilis* and the average fibre lumen diameter

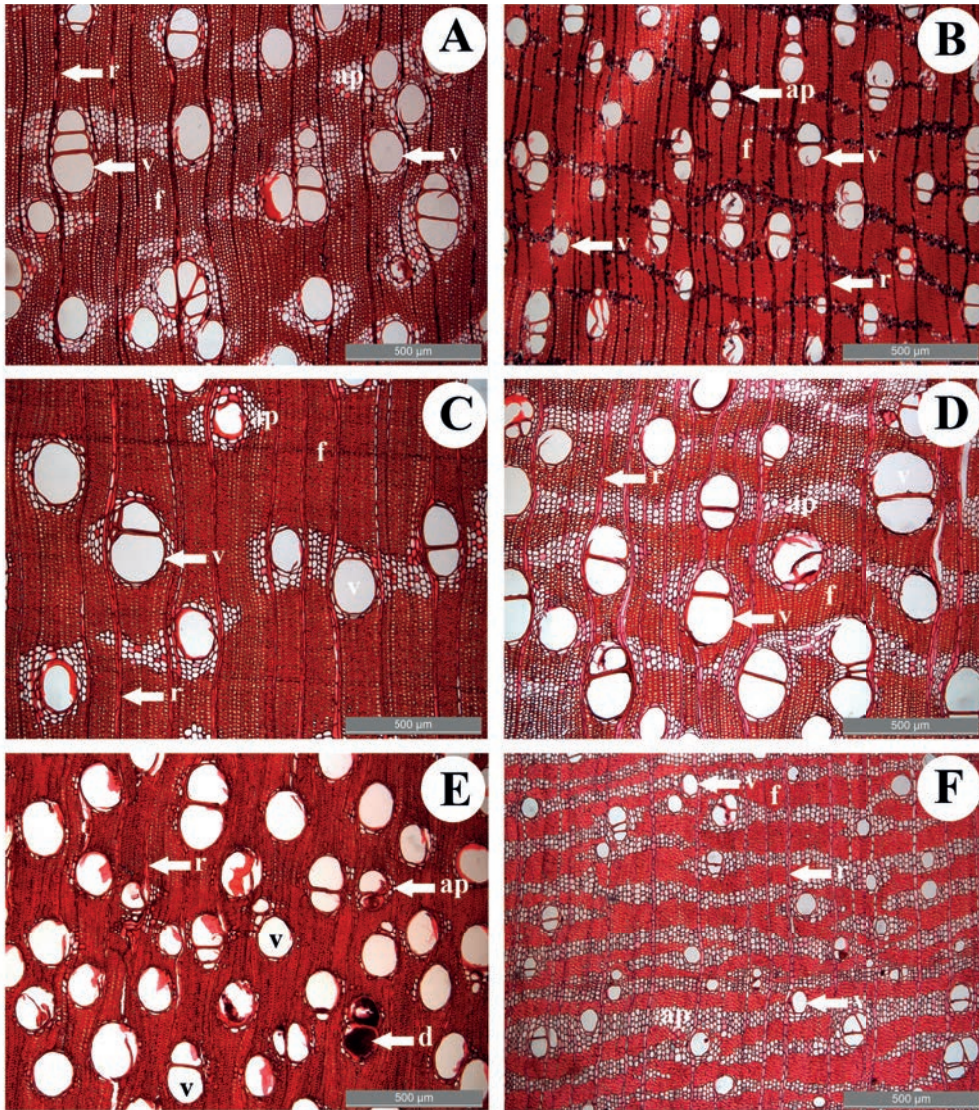


Figure 1. A–B) Cross-section, growth boundaries are absent or indistinct in *A. grandis* (A), and rarely distinct in *A. elaeagnoidea* (B). C–F) Cross-section, vessel density ranging from very low vessel density in *A. cucullata* (C), to low vessel density in *A. lawii* (D) and *A. tomentosa* (E), to medium vessel density in *A. crassinervia* (F). ap = axial parenchyma, d = deposit, f = fibre, r = ray, sqc = square ray cell, ur = upright ray, v = vessel.

varies from $4 \pm 1 \mu\text{m}$ in *A. elaeagnoidea* and *A. crassinervia* to $11 \pm 3 \mu\text{m}$ in *A. spectabilis* (Table 3). The average fibre length in *Aglaia* varies greatly, from $980 \pm 115 \mu\text{m}$ in *A. oligophylla* to $1,562 \pm 211 \mu\text{m}$ in *A. spectabilis* (Table 3). Fibre length is a good diagnostic value for identification between section *Amoora* and section *Neoaglaia* and between section *Aglaia* and section *Neoaglaia*. However, it has no significant difference between section *Aglaia* and section *Amoora*.

Axial parenchyma

The distribution of the parenchyma can be of the following types (Table 2):

1) Paratracheal parenchyma occurs mainly in regularly bands of more than 3 cells wide(, or narrower,) or in abundant aliform to confluent patterns in which the wings are very wide (Fig. 5A–C). *Aglaia crassinervia* and *A. leptantha* have the regularly band type, whereas *A. elliptica*, *A. forbesii*, *A. lawii* and *A. oligophylla* have confluent to regularly band type.

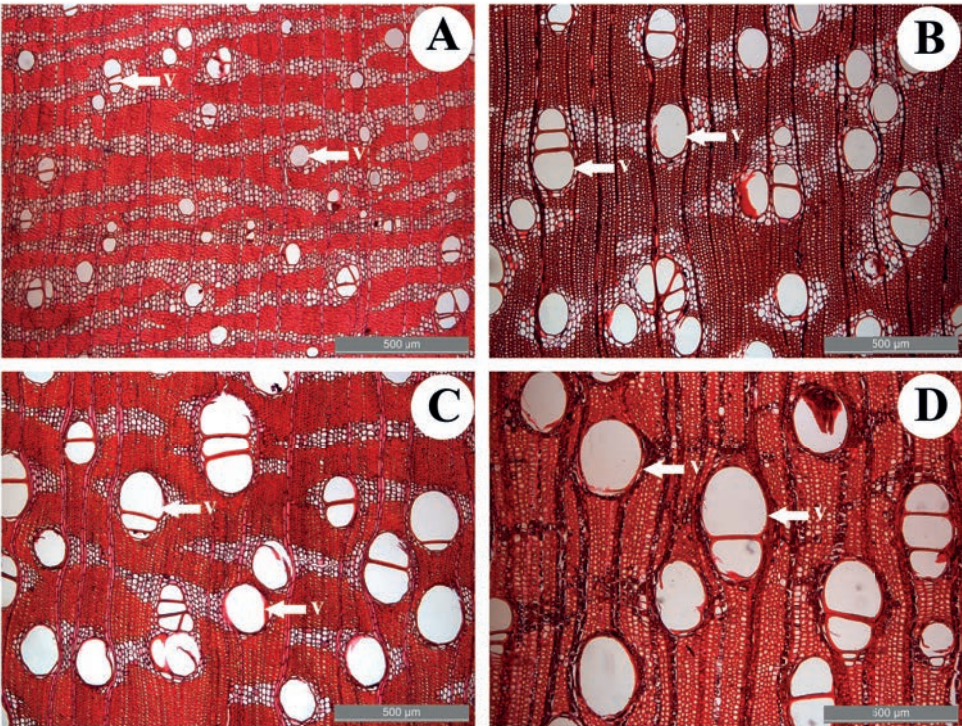


Figure 2. Cross-section, vessel element diameter ranging from medium in *A. crassinervia* (A) to large in *A. grandis* (B), *A. silvestris* (C) and *A. spectabilis* (D). v = vessel.

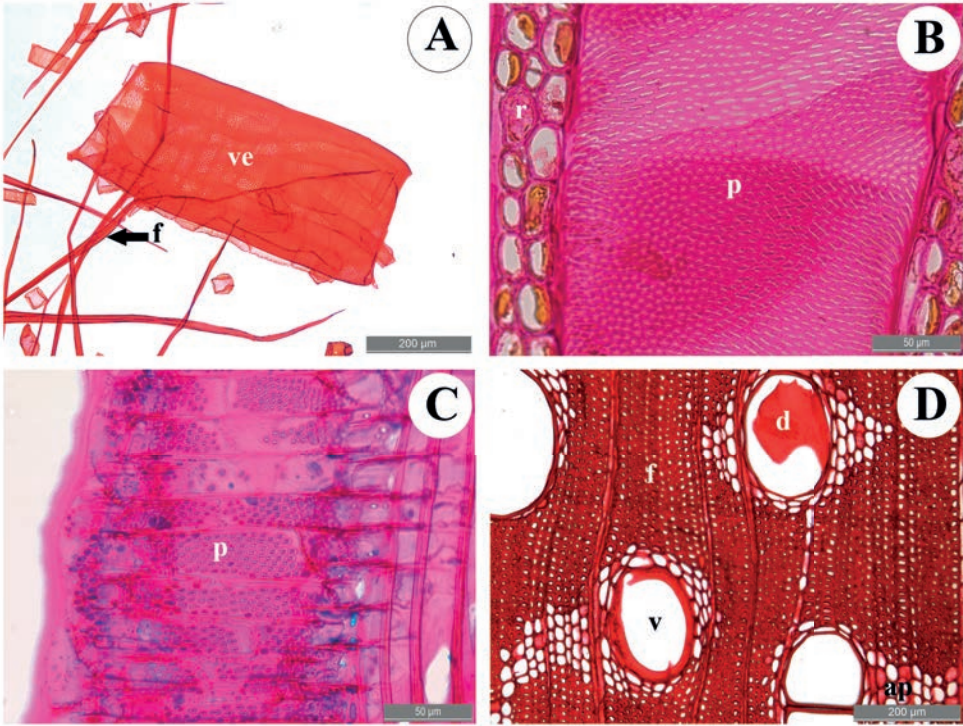


Figure 3. A) Perforation plates simple (*A. spectabilis*). B-C) wall pitting: B) Transverse-section, intervessel pits alternate and round, oval or slightly polygonal in shape (*A. spectabilis*), C) Radial-section, vessel ray pits similar to intervessel pits in size and shape (*A. spectabilis*), D) Cross-section, gums and other deposits in vessels (*A. cucullata*). ap = axial parenchyma, d = deposit, f = fibre, r = ray, p = pit, v = vessel, ve = vessel element.

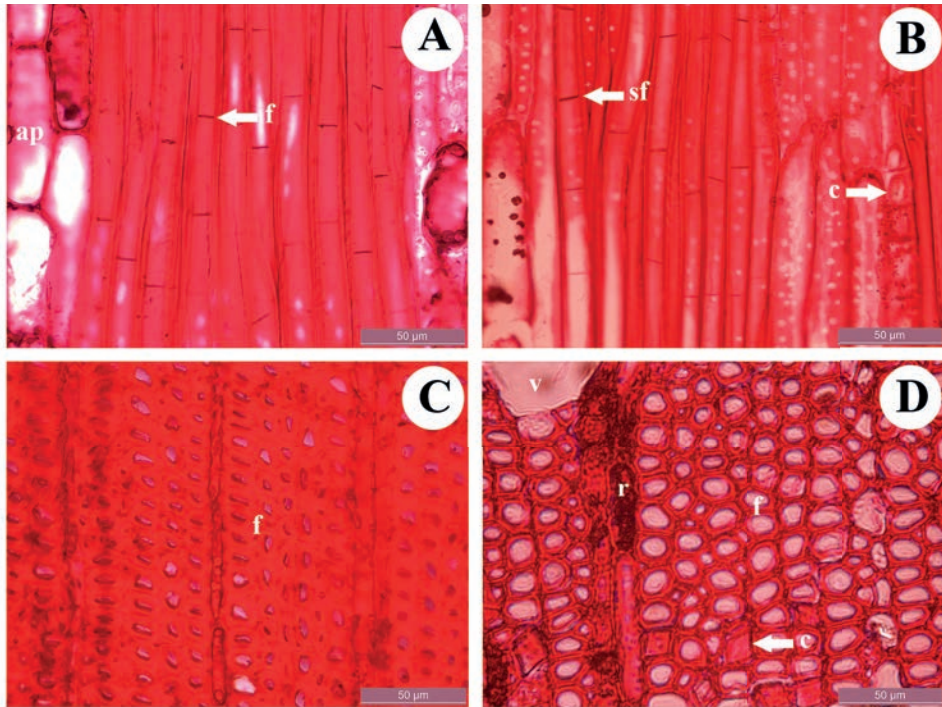


Figure 4. A-B) septate fibres: A) Radial-section, septate fibres with simple pits in *A. forbesii*, B) Radial-section, septate fibres with border pits in *A. elliptica*. C-D) Fibre wall thickness: C) Cross-section, thick fibre wall in *A. elaeagnoidea*. D) Cross-section, thin to thick fibre wall in *A. elliptica*. ap = axial parenchyma, c = crystal, f = fibre, r = ray, p = pit, sf = septate fibre, v = vessel.

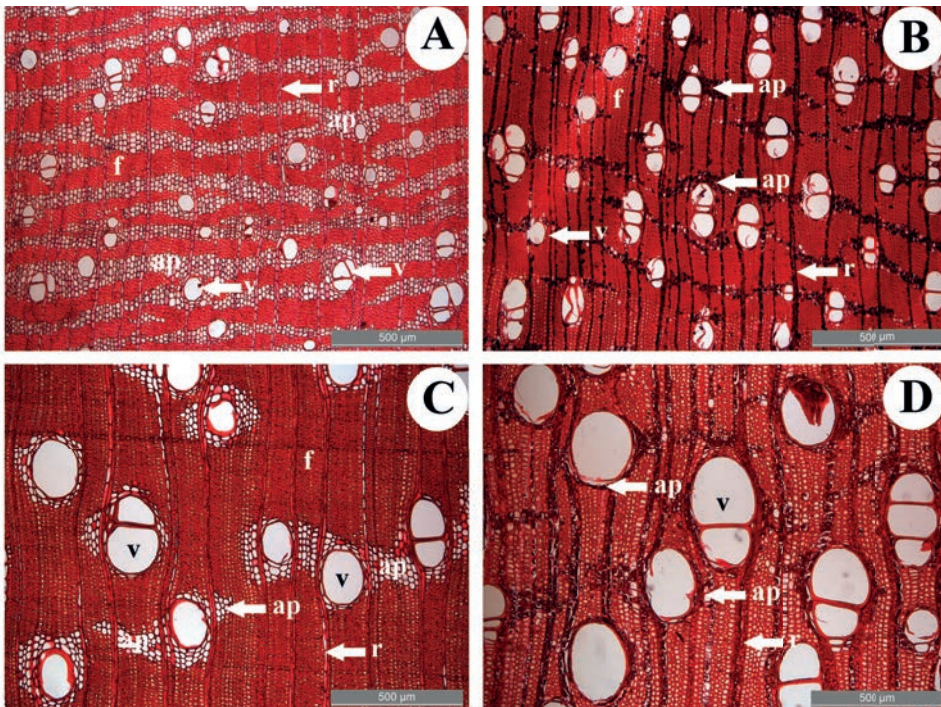


Figure 5. Axial parenchyma types. A-C) paratracheal bands: A) Cross-section, regular banded axial parenchyma (more than 3 cells wide) in *A. crassinervia*, B) Cross-section, narrow banded axial parenchyma (up to 3 cells wide) in *A. elaeagnoidea*, C) Cross-section, aliform to confluent in *A. cucullata*. D) Cross-section, vasicentric in *A. spectabilis*. ap = axial parenchyma, f = fibre, r = ray, v = vessel.

2) Vasicentric parenchyma is present in 1–5 cells wide sheaths, and occasionally weakly aliform to confluent (Fig. 5D). This type occurs in *A. tomentosa* and *A. spectabilis*.

3) In *A. cucullata* and *A. grandis* paratracheal parenchyma is predominantly aliform or confluent (Fig. 5C).

The number of parenchyma cells per strand in *Aglaia* is 4–7. The shape and length of the parenchyma strands differ between vessel-adjacent axial parenchyma and parenchyma without any vessel contact. In the vessel-adjacent parenchyma, the strands form a wavy pattern on the vessel walls, whereas in the other case the strands have less cells and form straight axial lines.

Ray parenchyma

Ray frequency

The uniseriate and multiseriate forms (2–4 cells wide) are found together, with a frequency of 7 per mm in *A. silvestris* to 20 per mm in *A. tenuicaulis* (Table 3, Fig. 6). This feature is not of diagnostic

value because of wide infrageneric variation in ray frequency.

Ray width

In *Aglaia*, multiseriate rays mostly are 2 cells wide, whereas *A. cucullata* and *A. spectabilis* show multiseriate rays of 2–4 cells wide (Table 2). The width of uniseriate rays ranges from $7 \pm 2 \mu\text{m}$ in *A. tomentosa* to $20 \pm 6 \mu\text{m}$ in *A. spectabilis*, while multiseriate rays range from $16 \pm 6 \mu\text{m}$ in *A. forbesii* to $47 \pm 12 \mu\text{m}$ in *A. spectabilis* (Table 3).

Ray height

The height of uniseriate rays varies from $61 \pm 15 \mu\text{m}$ in *A. tomentosa* to $247 \pm 104 \mu\text{m}$ in *A. elaeagnoidea*. The height of multiseriate rays varies from $179 \pm 53 \mu\text{m}$ in *A. lawii* to $411 \pm 172 \mu\text{m}$ in *A. spectabilis* (Table 3). Fused rays are present in all studied species.

Ray compositions

Multiseriate rays are composed of procumbent body cells and 1–2 rows of upright or square or procumbent marginal cells (Fig 7). There is a great

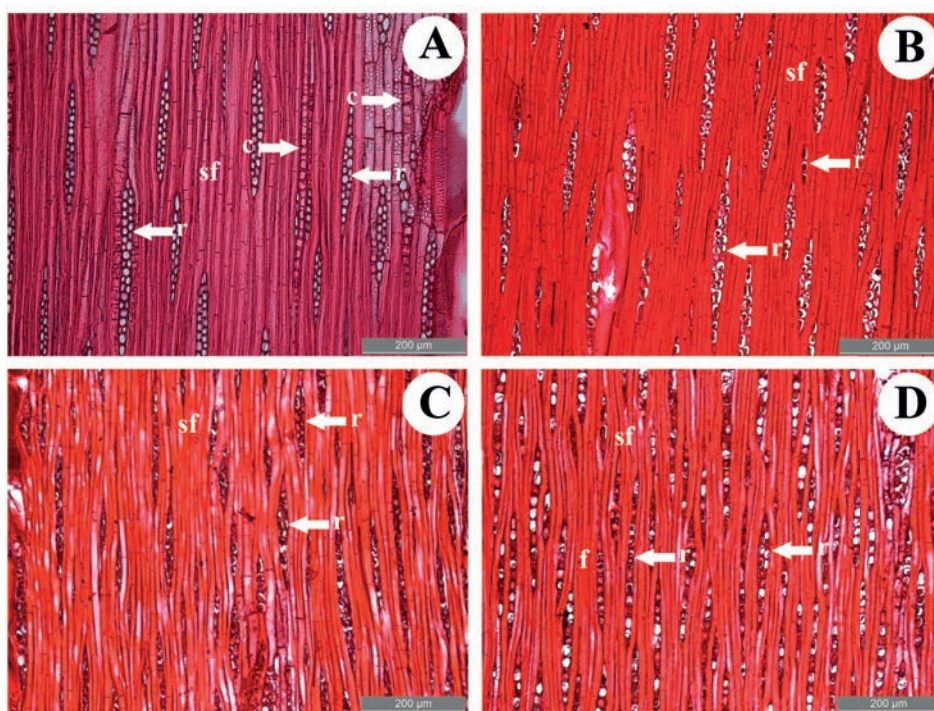


Figure 6. Ray parenchyma. A) Transverse-section, normal spaced ray in *A. silvestris*. B-C) Transverse-section, fairly close spaced ray in *A. oligophylla* (B) and *A. leptantha* (C). D) Transverse-section, close spaced ray in *A. tenuicaulis*. c = crystal, f = fibre, r = ray, sf = septate fibre.

variation in the arrangement and number of the upright, square or procumbent marginal cells, and this may be useful for identification. For instance, *A. silvestris* and *A. tomentosa* have procumbent cells (Fig 7E–F), whereas, in *A. elliptica* there are occasionally up to 2 square to upright marginal cells (Fig 7C–D).

Mineral inclusions

Crystals and Silica

The only type of crystals observed in *Aglaia* are prismatic crystals, which occur in all studied species, except *A. spectabilis*. The crystals are often located in chambered axial parenchyma cells, and more rarely in non-chambered axial parenchyma cells and ray cells (Table 2). No crystals were observed in the fibres (Table 2). Silica bodies are absent.

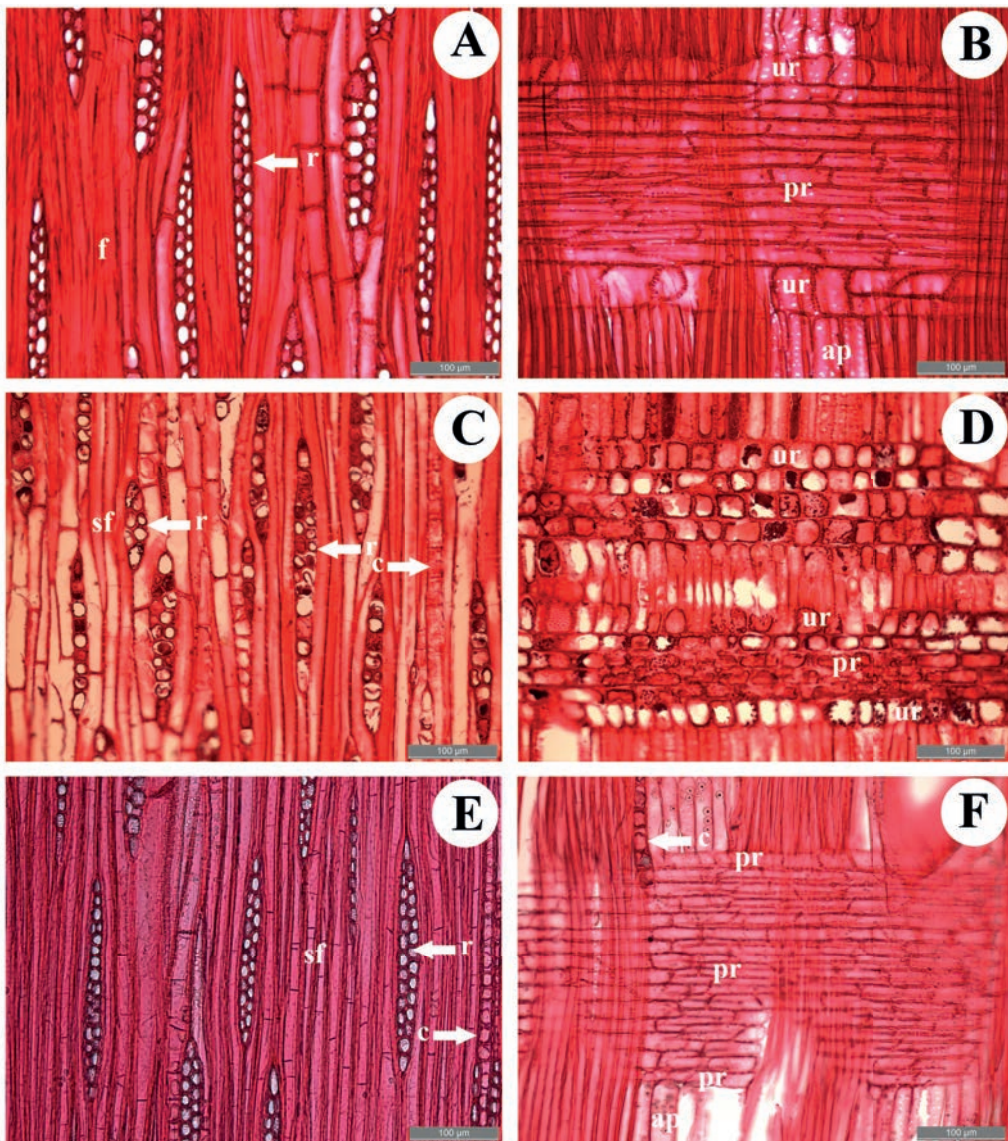


Figure 7. Ray components. A–B) Heterogeneous ray type III composed of procumbent ray cells with a single row of marginal ray cells in *A. cucullata*: Transverse-section (A) Radial-section (B). C–D) Heterogeneous rays type III composed of procumbent ray cells with mostly a single row of marginal ray cells, occasionally up to 2 rows in *A. elliptica*: Transverse-section (C), Radial-section (D). E–F) Homogeneous ray in *A. silvestris*: Transverse-section (E), Radial-section (F). ap = axial parenchyma, c = crystal, f = fibre, pr = procumbent ray, r = ray, sf = septate fibre, ur = upright ray.

Table 2. Summary of selected qualitative wood anatomical features that vary within selected *Aglaia* species from Thailand.

Scientific name	Growth ring 1)	Radial multiple vessels	Pore grouping 2)	Fibre pits 3)	Ratio of fibre wall thickness 4)	Paratracheal parenchyma type 5)	Ray frequency 6)	Ray types 7	Multiseriate ray width (cell)	Crystals distribution 8)	Weight 9)	Texture 10)
<i>A. crassinervia</i> Kurz ex Hiern	0,1	2-3	1	0	2	2 ⁺ ,3 ⁺ ,4 ⁺⁺	2	3	2	3	3	0
<i>A. cucullata</i> (Roxb.) Pellegr.	2	2-3	0	0	1	1 ⁺ ,2 ⁺⁺ ,3 ⁺⁺	1	3	2-3	3	2	2
<i>A. elaeagnoides</i> Benth.	2	2-3	1	0	2	1 ⁺ ,2 ⁺ ,3 ⁺⁺ ,5 ⁺	3	3	2	3	2	0
<i>A. elliptica</i> Blume	0	2-3(4)	1	1	1	2 ⁺ ,3 ⁺ ,4 ⁺⁺	2	3	2	3	1	0
<i>A. forbesii</i> King	0	2-3(4)	1	0	1	2 ⁺ ,3 ⁺ ,4 ⁺⁺	2	3	2	3	2	0
<i>A. grandis</i> Korth.	1	2-3	0	0	1	1 ⁺ ,2 ⁺⁺ ,3 ⁺⁺	2	3	2	3	2	1
<i>A. lawii</i> (Wight) C.J.Saldanha	0	2-3	1	0	1	2 ⁺ ,3 ⁺ ,4 ⁺⁺	1	3	2	1,3	2	1
<i>A. leptantha</i> Miq.	1	2-3	0	0	1	3 ⁺ ,4 ⁺⁺ ,5 ⁺	2	3	2	3	3	1
<i>A. oligophylla</i> Miq.	0	2-3(4)	1	0	1	1 ⁺ ,2 ⁺ ,3 ⁺⁺ ,4 ⁺⁺	2	3	2	3	3	0
<i>A. silvestris</i> (M.Roem.) Merr.	0	2-3	1	0	1	2 ⁺ ,3 ⁺⁺ ,4 ⁺	1	0	2	3	1	1
<i>A. spectabilis</i> (Miq.) S.S.Jain & Bennet (023)	0	2-3(4)	2	0	1	2 ⁺ ,3 ⁺⁺	2	3	2-3(4)	0	1	3
<i>A. spectabilis</i> (Miq.) S.S.Jain & Bennet (032)	0	2-3(4)	2	0	1	1 ⁺⁺ ,2 ⁺ ,3 ⁺	2	3	2-3(4)	0	1	2
<i>A. tenuicaulis</i> Hiern	0	2-3(4)	1	0	1	2 ⁺ ,3 ⁺⁺ ,5 ⁺⁺	3	3	2	3	2	0
<i>A. tomentosa</i> Teijsm. & Binn.	0	2-3	1	0	1	1 ⁺⁺ ,2 ⁺ ,3 ⁺	1	0	2	3	1	1

1) Growth rings: 0 = absent; 1 = distinct to faint; 2 = distinct.

2) Pore grouping based on percentage of solitary vessel index: 0 = solitary vessels dominant; 1 = solitary and radial pores equal; 2 = radial multiples dominant.

3) Fibre pits: 0 = simple; 1 = bordered

4) Ratio of fibre wall thickness based on ratio of fibre lumen diameter to twice the fibre wall thickness: 0 = <1; 1 = 1-3; 2 = >3

5) Paratracheal parenchyma type: 0 = scanty; 1 = vasicentric; 2 = aliform; 3 = confluent; 4 = regular banded; 5 = narrow banded; ++ = common; + = sometimes; ± = rare

6) Ray frequency based on the number of rays per mm: 0 = <5 rays/mm; 1 = 6-9 rays/mm; 2 = 10-13 rays/mm; 3 = 14-20 rays/mm; 4 = ≥ 21 rays/mm

7) Ray type: 0 = homogeneous rays; 1 = heterogeneous rays type I; 2 = heterogeneous rays type II; 3 = heterogeneous rays type III

8) Crystals distribution: 0 = absent; 1 = in upright ray cells; 2 = in procumbent ray cells; 3 = in axial parenchyma

9) Weight based on specific gravity: 0 = <0.50; 1 = 0.50-0.60; 2 = >0.60-0.75; 3 = >0.75-0.90

10) Texture of wood based on vessel element diameter: 0 = <100 µm; 1 = 100-150 µm; 2 = >150-200 µm; 3 = >200-250; 4 = >250-300; 5 = >300 µm

Table 3. Summary of selected quantitative wood anatomical features that vary within *Aglaia* species from Thailand, mean values shown.

Scientific name	Wood specific gravity	Solitary vessel index	Vessel density (per mm ²)	Fraction of vessel area per total area	Vessel diameter (µm)	Vessel element length (µm)	Hydraulic diameter (µm)	Intervessel pit diameter (µm)	Fibre diameter (µm)	Fibre lumen diameter (µm)	Fibre length (µm)	Fibre wall thickness (µm)	Fraction of fibre area per total area	Rays frequency (per mm)	Uniseriate ray width (µm)	Multiseriate ray width (µm)	Uniseriate ray height (µm)	Multiseriate ray height (µm)	Fraction of ray area per total area	Fraction of ray area per total area	Wood specific gravity
<i>A. crassinervia</i> Kurz ex Hiern	0.76	0.55	31	0.08	53	438	95	2	13	4	1,123	4.7	0.58	10	11	20	110	186	0.11	0.24	0.76
<i>A. cucullata</i> (Roxb.) Pellegr.	0.63	0.70	5	0.11	165	562	317	3	14	7	1,409	3.5	0.64	9	10	25	107	338	0.17	0.09	0.63
<i>A. elaeagnoides</i> Benth.	0.68	0.35	28	0.08	70	455	118	3	14	4	1,141	5.2	0.67	16	12	23	247	366	0.21	0.05	0.68
<i>A. elliptica</i> Blume	0.56	0.61	22	0.06	59	464	83	3	14	9	1,329	2.7	0.58	11	15	26	101	214	0.19	0.17	0.56
<i>A. forbesii</i> King	0.62	0.50	22	0.06	69	468	102	4	14	5	1,023	4.2	0.75	10	12	16	175	202	0.08	0.10	0.62
<i>A. grandis</i> Korth.	0.67	0.74	14	0.13	119	504	174	3	14	8	1,256	3.3	0.60	10	14	23	135	243	0.12	0.15	0.67
<i>A. lawii</i> (Wight) C.J.Saldanha	0.64	0.49	11	0.17	127	438	196	3	17	7	994	4.7	0.62	8	10	20	87	179	0.11	0.11	0.64
<i>A. leptantha</i> Miq.	0.77	0.68	10	0.12	120	349	156	3	14	7	1002	3.7	0.66	13	10	21	130	204	0.15	0.08	0.77
<i>A. oligophylla</i> Miq.	0.77	0.39	23	0.10	66	411	119	4	14	5	980	4.7	0.52	11	10	21	112	228	0.16	0.22	0.77
<i>A. silvestris</i> (M.Roem.) Merr.	0.54	0.53	11	0.18	124	572	185	3	15	8	1423	3.6	0.62	7	9	19	97	247	0.10	0.10	0.54
<i>A. spectabilis</i> (Miq.) S.S.Jain & Bennet (023)	0.53	0.59	6	0.34	211	488	341	4	16	11	1495	2.8	0.43	11	14	35	113	411	0.27	0.04	0.53
<i>A. spectabilis</i> (Miq.) S.S.Jain & Bennet (032)	0.61	0.29	8	0.22	175	604	317	5	20	11	1562	4.3	0.35	10	20	47	144	350	0.33	0.03	0.61
<i>A. tenuicaulis</i> Hiern	0.69	0.28	31	0.08	62	462	86	3	11	6	1035	2.7	0.51	20	14	25	217	277	0.24	0.18	0.69
<i>A. tomentosa</i> Teijsm. & Binn.	0.59	0.67	20	0.24	130	652	177	3	13	5	1348	3.7	0.59	9	7	19	61	260	0.13	0.03	0.59

Physical features

Wood specific gravity of *Aglaia* wood

The wood specific gravity of the *Aglaia* specimens (oven-dry) are listed in Table 3. They range from 0.53 ± 0.02 in *A. spectabilis* to 0.77 ± 0.04 in *A. oligophylla* and may be classified into 3 classes: 1) comparatively light (wood specific gravity 0.50–0.60), found in *A. elliptica*, *A. silvestris*, *A. spectabilis* and *A. tomentosa*; 2) comparatively heavy (wood specific gravity 0.60–0.75), in *A. cucullata*, *A. elaeagnoidea*, *A. forbesii*, *A. grandis*, *A. lawii* and *A. tenuicaulis*; and 3) heavy (wood specific gravity 0.75–0.90), observed in *A. crassinervia*, *A. leptantha* and *A. oligophylla* (Table 2).

Colour

In *Aglaia*, the colour of sapwood in dried material varies from yellowish brown to pale brown to brown to reddish brown (Table 2).

Texture

The texture of *Aglaia* wood can be divided into 3 groups using the vessel diameter: very fine (vessel diameter less than 100 μm) was found in *A. crassinervia*, *A. elliptica*, *A. tenuicaulis*, *A. oligophylla*, *A. forbesii* and *A. elaeagnoidea*; fine (vessel diameter between 100 and 150 μm) was found in *A. grandis*, *A. leptantha*, *A. silvestris*, *A. lawii* and *A. tomentosa*; and medium (vessel diameter more than 150 to 200 μm) occurs in *A. cucullata* and *A. spectabilis* (Table 2).

Comprehensive wood anatomical generic description

Aglaia Lour.

Sapwood yellowish brown, pale brown to reddish brown. Texture very fine to medium, generally straight grained and comparatively light to heavy weight (specific gravity 0.53–0.77 oven dry). Growth boundaries absent or indistinct, rarely distinct. Wood diffuse-porous.

Vessels solitary and in radial multiples of 2–3(–4). Pores circular to oval, 5–31 pores/ mm^2 , with mean vessel tangential diameter 53–211 μm . Vessel element length 349–652 μm . Perforation plates simple. Intervessel pits alternate, with horizontal diameter of 2–5 μm , shape round, oval or slightly polygonal. Vessel-ray pits similar to

intervessel pits in size and shape. Tyloses absent. Gums and other deposits present in some of the heartwood vessels. Fibres exclusively septate with simple pits to minutely bordered pits or bordered pits mainly in the radial walls, rarely in the tangential walls, 11–20 μm wide and 980–1562 μm long, wall 2.7–5.2 μm thick. Axial parenchyma predominantly paratracheal, forming bands of 2–7 cells wide, occasionally up to 9 cells wide, sometimes discontinuous and tending to aliform and/or confluent. Vasicentric parenchyma in 1–5 cells wide sheaths, only present in *A. tomentosa* and *A. spectabilis*. Axial parenchyma strands of 4–7 cells.

Rays not storied, composed of uniseriate and multiseriate rays, never more than 2 cells wide, except *A. cucullata* and *A. spectabilis* with occasionally up to 4 cells; sometimes fused. Frequency 7–20 rays/ mm , percentage of ray fraction 8.0–32.8. Uniseriate rays 7–20 μm wide, 61–247 μm high. Multiseriate rays 16–47 μm wide, 179–411 μm high; usually heterogeneous composed of procumbent ray cells with mostly a single row of marginal ray cells, occasionally up to 2 rows in *A. elliptica*. Procumbent ray cells predominately narrow and elongate procumbent, rarely short procumbent cells. The marginal ray cells composed of upright cells or square cells or mixed upright and square cells, occasionally procumbent cells; rays homogeneous in *A. silvestris* and *A. tomentosa*. Prismatic crystals present in chains of chambered axial parenchyma cells, rarely in non-chambered axial parenchyma and ray cells; no crystals observed in *A. spectabilis*. Silica bodies absent.

Wood anatomical features in relation to wood specific gravity

Across all individuals, species and sites, the following wood anatomical variables showed significant correlations (Table 4).

Wood specific gravity was negatively correlated with vessel element length, fibre lumen diameter, fibre length and fraction of vessel area per total area (Table 4). No significant relationships were found between wood specific gravity and vessel diameter, as well as, between wood specific gravity and fibre wall thickness, and also between wood specific gravity and ray and axial parenchyma features.

Table 4. Correlations coefficients between anatomical features and wood specific gravity.

Anatomical features	r
	Wood specific gravity
Vessel grouping index	0.235
Vessel density (per mm ²)	0.433
Vessel diameter (μm)	-0.493
Vessel element length (μm)	-0.641*
Hydraulic diameter (μm)	-0.443
Fibre diameter (μm)	-0.360
Fibre lumen diameter (μm)	-0.629*
Fibre length (μm)	-0.723**
Fibre wall thickness (μm)	0.477
The ratio of fibre wall thickness to fibre lumen diameter	0.444
Rays frequency (per mm)	0.365
Multiseriate ray width (μm)	-0.280
Multiseriate ray height (μm)	-0.371
Fraction of vessel area per total area	-0.535*
Fraction of ray area per total area	-0.192
Fraction of fibre area per total area	0.157
Fraction of axial parenchyma area per total area	0.528

Note: *P < 0.05, **P < 0.01, ***P < 0.001. Critical values for significance levels: at 0.05 is 0.532; at 0.01 is 0.661; and 0.001 is 0.780. r = correlation coefficients (N = 14).

DISCUSSION

The general anatomical characters of the 13 species of Thai *Aglaia* studied are growth boundaries indistinct or absent, wood diffuse-porous, perforations simple, intervessel pits minute, and rays heterocellular with mostly a single marginal row of square to upright ray cells. Many of these features are common in other Meliaceae genera as well (InsideWood, 2004 onwards; Metcalfe & Chalk, 1950; Pennington & Styles 1975). However, *Aglaia* species from Thailand are variable in both qualitative and quantitative characters, vessel grouping, vessel density, vessel diameter, fiber wall thickness, and especially in axial parenchyma patterns and ray volume.

In Meliaceae, the mean vessel diameter ranges from 50–200 μm (Metcalfe and Chalk, 1950),

those of *Aglaia* (53–210 μm) are mostly within this range. However, Lemmens *et al.* (1995) gave an average vessel diameter range of (75–)115–155 μm in *Aglaia*, and according to Ogata *et al.* (2008), the vessel diameter of *Aglaia* ranges are (100–)130–250(–320) μm. Mean fibre length of Meliaceae ranges from 600–1900 μm (Metcalfe and Chalk, 1950) and the mean fibre length of *Aglaia* varies from 900–1600 μm (Lemmens *et al.*, 1995). They all agree with our range of 980–1560 μm for average fibre lengths. In our study, axial parenchyma usually is confluent to banded, but in section *Amoora*, occasionally is vasicentric to aliform as mentioned by Ogata *et al.* (2008). Moreover, the number of parenchyma cells per strand in *Aglaia* is 4–7, whereas the previous studied Meliaceae have strand lengths between 4–8 cells (Lemmens *et al.*, 1995). In all *Aglaia* species, prismatic crystals are

usually abundant in chambered axial parenchyma cells, but no crystals were found in fibre cells, which is contrasted by Nei *et al.* (2003). Crystals were not observed in *A. spectabilis*. Silica bodies are absent. The differences found across species may reflect the combination of environmental plasticity and genetic differences (Barajas Morales, 1985; Baas, 1986; Baas *et al.*, 2004; Wheeler *et al.*, 2007; Choat *et al.*, 2007 and Baas & Wheeler, 2011).

Aglaia is a highly diverse woody genus in the Meliaceae and the taxonomy within *Aglaia* also remains problematic. *Aglaia* showed three taxonomic units based on DNA data and secondary metabolites: section *Aglaia*, section *Amoora* and section *Neoaglaia* (Muellner *et al.*, 2005) and all three sections and species within *Aglaia* are polyphyletic, although accessions of them were largely consistent and clustered (Grudinski *et al.*, 2014). Our study reveals that the species within each section have a similar wood anatomy, different from the species in the other sections. However, because our study is only based on a small sample and mostly a single specimen per species, we are not certain that we covered the complete variation in characters in *Aglaia* and the variation within the species.

Wood specific gravity associated with wood anatomical features

Wood specific gravity is a parameter that integrates a number of wood anatomical variables such as tissue proportions, cell wall thickness and relative cell lumen areas (Hacke & Sperry, 2001; Hacke *et al.*, 2006; Baas & Wheeler, 2011) and also cell wall material of the fibres and cell wall materials of the rays (Fujiwara, 1992).

Relationship between wood specific gravity and vessel features

As mention in previous studies, wood specific gravity had negative relationship with total vessel area (Jacobsen *et al.*, 2007a) or vessel area and vessel fraction (Preston *et al.*, 2006). In our study, wood specific gravity is also negatively associated with the fraction of vessel area per total area. However, no significant relationship occurs between vessel density and wood specific gravity, in contrast with Martínez-Cabrera *et al.* (2009). Preston *et al.* (2006) reported that vessel density

and vessel diameter had a low correlation with wood specific gravity. Similarly, our study shows no significant relationship between vessel diameter and wood specific gravity. Therefore, vessel density and vessel diameter might be independent of wood specific gravity and related to habit (Wheeler *et al.*, 2007). Cell length; vessel element length and fibre length show a co-incidental correlation with wood specific gravity.

Relationship between wood specific gravity and fibre features

Wood specific gravity is negatively correlated with fibre lumen diameter. The fibres with wide lumens tend to be present in low specific gravity woods as mentioned by Martínez-Cabrera *et al.* (2009). In our study, fibre diameter and fibre wall thickness are independent of wood density, whereas Jacobsen *et al.* (2005, 2007b) reported that wood specific gravity was correlated with decreasing sizes in fibre cells. Our study shows that fibre wall thickness is not correlated with fibre lumen diameter, although, it is strongly positively correlated with fibre wall to lumen ratio. In addition, wall thickness alone is not associated with wood specific gravity. Our study shows that fibre wall thickness increases with decreasing fibre lumen diameter. Wood specific gravity is a primarily a function of the cell wall fraction in wood, which in turn is dominated by fibre wall thickness and the fraction of fibre tissue.

Our study shows that no significant correlations exist between wood specific gravity and ray and axial parenchyma features, perhaps the influence of phylogenetic constraints (Martínez-Cabrera *et al.*, 2009).

CONCLUSIONS

The wood anatomy of *Aglaia* shows infrageneric variation in characters such as multiseriate ray width (cell), crystal occurrence, paratracheal parenchyma type and ray type.

Significant differences between sections were found in vessel density, vessel diameter, hydraulic diameter, fibre length and multiseriate ray height.

Significant correlation coefficients were found between wood specific gravity and vessel

element length, fibre lumen diameter, fibre length and fraction of vessel area per total area. The highest negative correlation was found between wood specific gravity and fibre lumen diameter. However, neither ray parenchyma features nor axial parenchyma features have significant relationships with wood specific gravity.

ACKNOWLEDGEMENTS

We wish to thank Mr Kusol Tangjaipitak from Kasetsart University and Alexander Scholz from the Institute of Systematic Botany and Ecology, Ulm University, for technical assistance. We also thank Mr Thawatchai Wongprasert from the Forest Herbarium for the information on Meliaceae, Mr Pisant Khaopakro for collecting samples and the Office of Forest Management and Forest Production Research, Bangkok, Thailand, for wood samples from the xylarium. We are grateful to Dr Chamlong Phengklai for contributing helpful identify on our specimens, Prof Steven Jansen and Prof Pieter Baas for their valuable comments and suggestions on our work. This research was granted by the Office of the Higher Education Commission, Thailand, to S. Khaopakro under the program Strategic Scholarships for Frontier Research Network.

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