Qualitative and Quantitative Anatomical Characteristics and Radial Variation of Major Cell Components in *Paulownia tomentosa* Wood Grown in Korea

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Qualitative and quantitative anatomical characteristics and radial variations of the major cell components in *Paulownia tomentosa* wood were examined using optical microscopy and X-ray diffraction to aid in wood identification and as quality indices. The vessel arrangement on the transverse surface was either ring-porous or semi-ring-porous. Most vessels had solitary pores, while some vessels had multiple radial pores. The axial parenchyma was generally confluent and partially of aliform type. Tyloses with high frequency in the vessel lumen and multiseriate rays (2 to 5 cells) were typical. The vessel diameter of earlywood and latewood was approximately 240 and 107 µm, respectively, with a range of 165 to 289 µm in earlywood and 55 to 149 µm in latewood. Ray height and fiber length were approximately 178 and 740 µm, respectively. The vessel diameter in both earlywood and latewood and the fiber length increased gradually with an increasing number of growth rings. Ray height was constant from the pith to the middle section and decreased toward the bark. The anatomical characteristics and radial variation of major components of *P. tomentosa* can be used as wood identification keys and quality indices.

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Keywords: Paulownia tomentosa; Radial variation; Vessel diameter; Ray height; Fiber length; Relative Crystallinity; Wood quality indices

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INTRODUCTION

In Korea, the self-sufficiency percentage of domestic timber is approximately 17%, and most of the domestic wood demand is met by imported timber (Korea Forest Service 2019). To increase domestic wood resources, fast-growing tree species must be cultivated.

The *Paulownia* tree, also known as princess, empress, or royal tree, has gained significant interest worldwide owing to its fast growth rate. This tree can produce a large quantity of wood in a short period and can be used as timber within 5 to 20 years after planting (Icka *et al.* 2016; Esteves *et al.* 2022). Moreover, *Paulownia* trees can absorb approximately 22 kg of carbon dioxide and emit 6 kg of oxygen annually, generating thousands of cubic meters of clean air. This is a high rate of carbon absorption for a fast-growing tree species (Touraev 2006; Angelov 2010; Esteves *et al.* 2022).

Paulownia tomentosa timber is strong for low-density wood, easily dried, hardly warped or cracked, easy to machine, and durable with regard to fire, fungi, and damage.

(Sedeer and Nabil 2003). The wood is also highly resistant to insects and termites because of its high tannin content (Angelov 2010). Therefore, it has been used in various applications such as furniture, construction, musical instruments, shipbuilding, aircraft, packing boxes, coffins, paper, plywood, cabinetmaking, and molding (Zhu *et al*. 1986; Akyildiz and Kol 2010).

Numerous studies examined the anatomical characteristics of *Paulownia* species to elucidate the properties for effective utilization, including *P. elongata* (Ates *et al*. 2008; Popović and Radošević 2011), *P. fortunei* (Ashori and Nourbakhsh 2009; Rafat 2011), and *P. tomentosa* (Olson and Carpenter 1985). The respective authors examined morphological characteristics such as lumen width, fiber length, fiber width, and cell wall thickness, which are important for the paper industry. A few studies on the radial variation in wood properties have been conducted using *Paulownia* hybrids, such as *P. elongata* x *fortunei* (Fos *et al*. 2023) and juvenile *Paulownia* Shang Tong Hybrid F1 (Tomczak et al 2023). Fos *et al*. (2023) reported that the growth ring width of *P. elongata* x *fortunei* markedly decreased from the pith to the bark, whereas vessel density tended to be constant. Tomczak *et al.* (2023) reported that the cell component characteristics of juvenile *Paulownia* hybrids, such as fiber length and vessel diameter and length, increased slightly from the pith to the bark.

The anatomical properties of branches and roots of *Paulownia* trees have been examined to obtain valuable information on optimizing the utilization of all tree components (Qi *et al*. 2014, 2016). This study revealed distinct anatomical features of *Paulownia* root wood, including lower fiber wall thickness, fiber length, relative crystallinity index, and ray numbers compared to branch wood. Furthermore, root wood exhibited greater ray widths and heights than branch wood. In addition, there were no significant differences in the anatomical characteristics of the root wood near the pith and bark. In contrast, variations were evident among the top, middle, and base parts of the root wood. Moreover, branch wood displayed radial variation in its anatomical characteristics.

To date, limited information is available on the anatomical characteristics of stem wood of *Paulownia* trees growing in Korea (Chong and Park 2008; Eom 2015). Therefore, to provide valuable information on wood identification and quality for the effective utilization of whole *Paulownia* trees grown in Korea, the present study investigated the quantitative and qualitative anatomical characteristics of three surfaces for each part, *i.e.*, near the pith (1st to 3rd growth ring), in the middle section (9th to 11th growth ring), and near the bark (16th to 18th growth ring), and the radial variation of major cell components in each growth ring of the wood.

EXPERIMENTAL

Materials

The fundamental details of the sampled trees (Table 1) were obtained from a previous study (Jo *et al.* 2021). Three *P. tomentosa* trees aged 15 to 20 years were harvested in the research forest at Kangwon National University, Chuncheon, Korea (37°77’ N, 127°81’ E). The density of *P. tomentosa* used in the present study was randomly measured from the whole part of the discs, which ranged from 0.32 to 0.34 g/cm^3.

Table 1. Basic Information of Sample Trees

Species	Age (Years)	Height (m)	D.B.H. (cm)	Density (g/cm^3)	Average Growth Ring Width (mm)	Location
Paulownia tomentosa	15	13	33.0	0.32	7.85	Chuncheon, Korea (N 37° 77’, E 127° 81’)
	18	15	42.5	0.34	9.10	
	20	17	43.0	0.33	10.10	
Notes: D.B.H. = Diameter at breast height						

Methods

Optical microscopy

The anatomical characteristics of *P. tomentosa* were observed using wooden discs from breast height, and samples were obtained from three directions in the wooden disc (Fig. 1). Wood blocks with dimensions of 10 (L) × 10 (R) × 10 (T) mm^3 were produced from three parts of the wood discs, *i.e.*, near the pith (1st to 3rd growth ring), middle section (9th to 11th growth ring), and near the bark (16th to 18th growth ring). The wooden blocks were softened through boiling in a mixture of glycerin and water (50:50). Thin slices with 15 to 20 µm thickness were prepared using a sliding microtome (Nippon Optical Works Co, Ltd., Tokyo, Japan), and the samples were stained using 1% safranin solution and 1% light green solution and dehydrated using a grade series of alcohol (50%, 70%, 90%, 95%, and 99%) and xylene. Permanent slides were prepared using Canada balsam. The tangential vessel diameter of earlywood and latewood each was measured randomly with 150 vessels in cross-sections, and ray height in micrometers was measured in 150 rays in tangential sections.

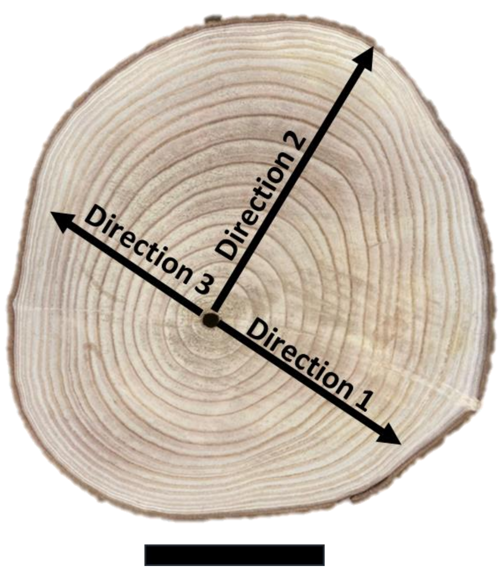

Fig. 1. Wood disc from the breast height of *P. tomentosa* stem. Scale bar: 15 cm

To examine wood fiber length, match-sized specimens were obtained from the latewood of each growth ring. The prepared specimens were soaked in Schultze reagent (100 mL 35% nitric acid [HNO_3] and 0.6 g 99.5% potassium chlorate [$KClO_3$]) for 3 days. The samples were heated at 60 to 70 °C for 1 h and stirred during the heating process until the fiber raveled (Park *et al.* 1993; Purusatama *et al.* 2024). The fiber length of the latewood in each growth ring was randomly measured using 150 fibers.

Anatomical characteristics were observed using an optical microscope (Eclipse E600; Nikon, Tokyo, Japan) and an image analysis program (IMT I-Solution Lite; British Columbia, Canada).

X-ray diffraction analysis

Samples from each growth ring with dimensions of 15 (L) × 10 (T) × 1 (R) mm^3 were prepared separately from earlywood and latewood. An X-ray diffractometer (DMAX 2100V, Rigaku, Tokyo, Japan) equipped with a Cu target (λ = 0.1542 nm) was used for obtaining the X-ray diffractograms. The relative crystallinity index (CRI) was calculated using the method of Segal *et al*. (1959), as shown in Eq. 1, and the crystallite width (CRW) was measured using Scherrer's method (Lee *et al*. 2023), as shown in Eq. 2.

$$CRI = \frac{I_{200} - I_{\mathrm{am}}}{I_{200}}\ (\%) \tag{1}$$

where I_{200} and I_{am} are diffraction intensities of the crystalline region (200) at 2θ = 22.8° and the amorphous region at 2θ = 18°, respectively.

$$\mathrm{CRW} = \frac{K\lambda}{B\cos\theta}\ (\mathrm{nm}) \tag{2}$$

In Eq. 2, L, K, and λ are crystallite width, Scherrer constant (0.9), and wavelength of X-ray (λ=0.1542 nm). β and θ are half-width in radians and Bragg angle, respectively.

Statistical analysis

Differences in cell dimension between the parts were statistically analyzed using one-way analysis of variance and post-hoc Duncan's multiple range tests (SPSS ver. 21, IBM Corp., New York, USA).

RESULTS AND DISCUSSION

Qualitative Anatomical Properties

Figures 2, 3, and 4 show the anatomical characteristics of the transverse, radial, and tangential sections in different growth rings of *P. tomentosa* wood, respectively. On the transverse sections, the vessel arrangement was ring-porous or semi-ring-porous. Most of the vessels were solitary with a high frequency of tyloses, and some of the vessels were in radial multiples of 2 to 3. The axial parenchyma was generally confluent and aliform.

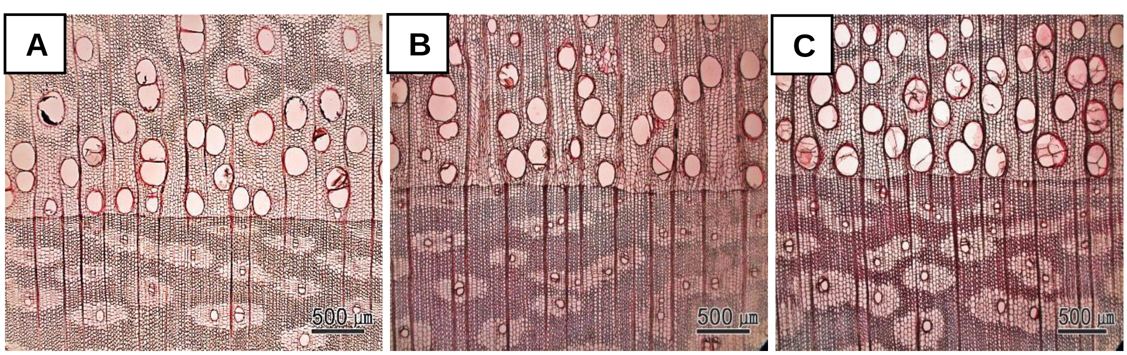

Fig. 2. Optical micrographs on transverse sections of *Paulownia tomentosa* wood. A, B, and C indicate the 1st–2nd, 9th–10th, and 17th–18th growth rings, respectively

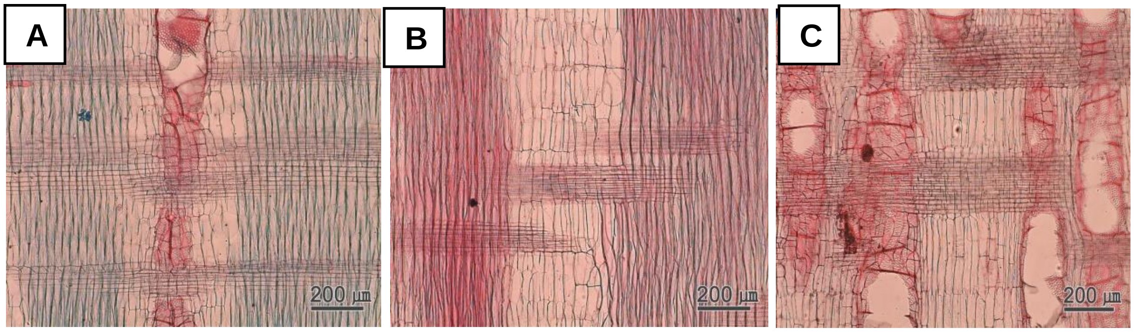

Fig. 3. Optical micrographs on radial sections of *Paulownia tomentosa* wood. A, B, and C indicate the 1st–2nd, 9th–10th, and 17th–18th growth rings, respectively

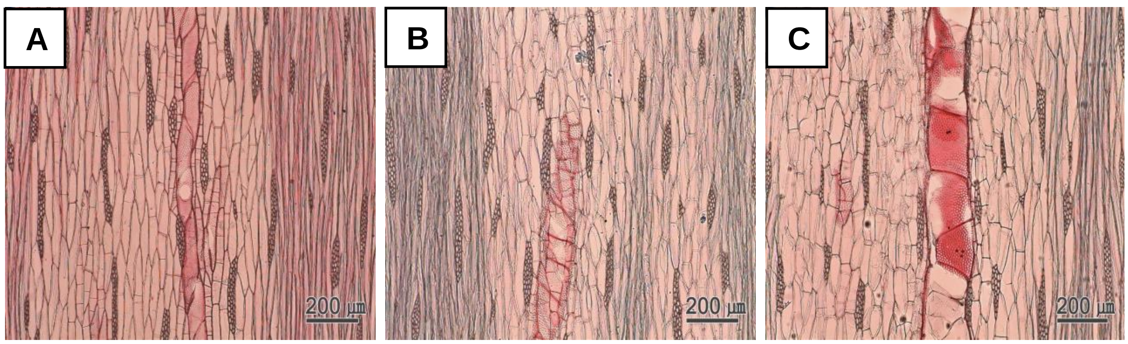

Fig. 4. Optical micrographs on tangential sections of *Paulownia tomentosa* wood. A, B, and C indicate the 1st–2nd, 9th–10th, and 17th–18th growth rings, respectively

On the radial surface, the axial parenchyma surrounded the vessel and simple perforations in the vessel and homocellular rays (universally procumbent ray cells) were clearly visible. Multi-seriate rays (3 to 5 seriate) were representative in the tangential section. The representative anatomical characteristics of *P. tomentosa* in the present study were consistent with those of *P. tomentosa* reported by Chong and Park (2008) and those of *P. coreana* reported by Eom (2015).

Quantitative Anatomical Properties

Table 2 shows the dimensions of the vessel, fiber, and ray parenchyma cells in earlywood and latewood from the pith to the bark of *P. tomentosa*. The vessel diameter ranged from 198 to 276 µm in earlywood and from 75 to 139 µm in latewood. The average values in earlywood and latewood were 240 and 107 µm, respectively. According to the IAWA list (IAWA Committee 1989), earlywood vessel diameters are categorized as features 42 and 43, and latewood vessel diameters are classified as features 41 and 42. Helmling *et al*. (2018) reported that the vessel diameter in *P. tomentosa* was about 245 µm, similar to the earlywood vessel diameter in the present study. Chong and Park (2008) found that the vessel diameter of *P. tomentosa* was 185 µm in the tangential direction and 219 µm in the radial direction.

Ray height in *P. tomentosa* wood ranged from 193 to 155 µm, with a mean of 178 µm (Table 2). Nasir and Mahmood (2000) and Chong and Park (2008) noted that ray height of *P. tomentosa* was 266 and 284 µm, respectively, which was higher than that observed in the present study. In addition, Qi *et al*. (2016) reported that the ray height in the root wood of *P. tomentosa* was 280 to 340 µm, which was higher than the ray height in the stem wood of the present study. Ray height may help distinguish between taxa in some woods

(IAWA Committee 1989).

In the current study, fiber length of *P. tomentosa* wood ranged from 613 to 875 µm, and the average length was approximately 740 µm, which corresponds to feature 71 according to the IAWA list for hardwood identification. Ates *et al*. (2008) reported that fiber length of *P. tomentosa* was 820 µm, and general fiber length in hardwood species was in a range of 0.7 to 1.6 mm. Helmling *et al*. (2018) also reported a fiber length of 560 µm in *P. tomentosa*. Chong and Park (2008) and Olson and Carpenter (1985) recorded a fiber length of approximately 800 µm, which is similar to the results of our study. Most studies on fiber length of *P. tomentosa* have shown values of less than 1 mm.

Table 2. Cell Dimensions of *Paulownia tomentosa* Wood

<table>
<tr><th colspan="2">Characteristics</th><th>Near Pith (1^{st} to 3^{rd} growth ring)</th><th>Middle (9^{th} to 11^{th} growth ring)</th><th>Near Bark (16^{th} to 18^{th} growth ring)</th><th>IAWA List (1989)</th></tr>
<tr><td rowspan="4">Vessel Diameter (µm)</td><td>Earlywood</td><td>198 (20)^{a}</td><td>247 (4)^{b}</td><td>276 (7)^{c}</td><td>Feature 42 (100 to 200 µm) Feature 43 (≤ 200 µm)</td></tr>
<tr><td></td><td colspan="3">240 (36)</td><td></td></tr>
<tr><td>Latewood</td><td>75 (10)^{a}</td><td>109 (10)^{b}</td><td>139 (7)^{c}</td><td>Feature 41 (50 to 100 µm) Feature 42 (100–200 µm)</td></tr>
<tr><td></td><td colspan="3">107 (26)</td><td></td></tr>
<tr><td colspan="2" rowspan="2">Ray height (µm)</td><td>193 (5)^{b}</td><td>186 (5)^{b}</td><td>155 (7)^{a}</td><td rowspan="2">-</td></tr>
<tr><td colspan="3">178 (17)</td></tr>
<tr><td colspan="2" rowspan="2">Fiber length (µm)</td><td>613 (7)^{a}</td><td>737 (43)^{b}</td><td>875(20)^{c}</td><td rowspan="2">Feature 71 (≤ 900 µm)</td></tr>
<tr><td colspan="3">740 (115)</td></tr>
<tr><td colspan="6">Notes: The numbers in parentheses are the standard deviations. The same superscript letter next to the mean value in each column denotes non-significant differences between parts at the 5% significance level.</td></tr>
</table>

Radial Variation of Cell Components

Figure 5 shows the radial variation in vessel diameter in earlywood and latewood from the pith to the bark in *P. tomentosa* wood. The vessel diameters in earlywood and latewood increased gradually as the number of growth rings increased. There were significant differences in vessel diameters between the parts (Table 2). The vessel diameter was the greatest near the bark, the smallest near the pith, and intermediate in the middle section.

Despite the absence of research on radial variation in vessel diameter in the stem wood of *Paulownia tomentosa*, the results of the present study align with the observed radial variation in vessel diameter in juvenile *Paulownia* hybrids and other hardwood species. Tomczak *et al.* (2023) reported that the vessel diameter and length of *Paulownia* hybrids increased slightly from the pith to bark. Liu *et al*. (2020) also reported that in six

Catalpa bungei clones, vessel diameter in earlywood increased with increasing growth ring number, but it was radially insignificant in latewood. Naji *et al*. (2013) found that the mean vessel diameter near the bark of different clones of *Hevea brasiliensis* was larger than that near the pith. Leal *et al*. (2007) reported that the vessel size in *Quercus suber* wood increased linearly from the pith to the bark. The tangential vessel diameter in *Eucalyptus camaldulensis* clones increases from the pith to the bark and becomes constant in certain growth rings (Veenin *et al*. 2005).

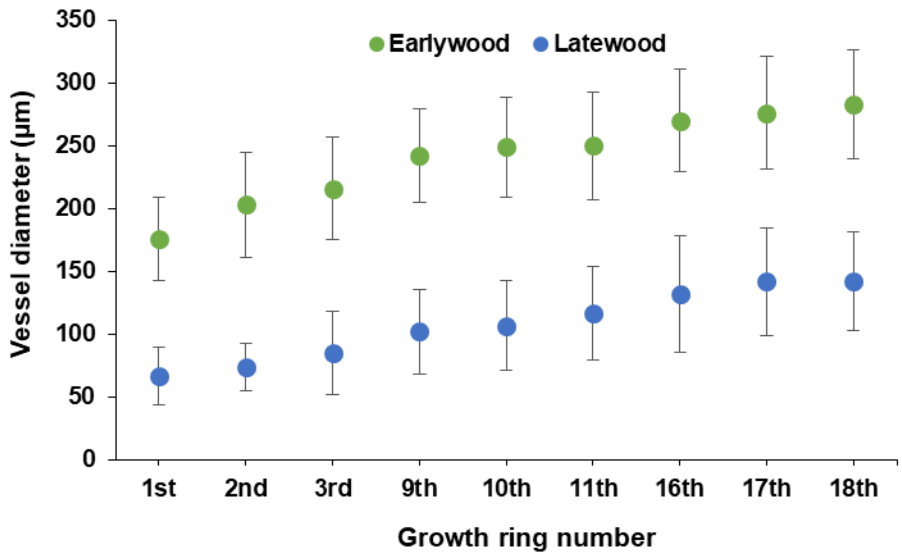

Fig. 5. Radial variation of tangential diameter of earlywood and latewood vessel in *Paulownia tomentosa* wood

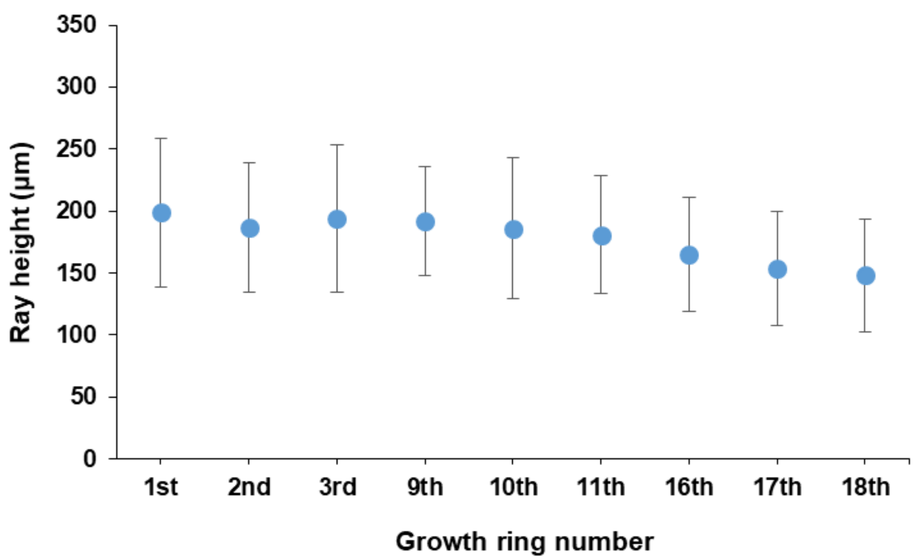

Fig. 6. Radial variation of ray height in *Paulownia tomentosa* wood

The radial variation in the ray height of *P. tomentosa* wood is shown in Fig. 6. Ray height showed a constant value from the pith to the middle part and then gradually decreased toward the bark. There are contrasting results on the radial variation of ray height in hardwoods. Lee *et al*. (2009) found that ray height of *Castanea crenata* wood was highest near the pith and then gradually decreased with increasing growth ring number. In contrast, Longui *et al*. (2014) found that ray features oscillated in the radial direction, and there was no significant change from the pith to the bark.

Figure 7 shows the radial variation in latewood fiber length in *P. tomentosa* wood. The fiber length was comparable between the 1st and 3rd growth ring and gradually increased until the 16th growth ring. However, it tended to remain constant near the bark. Olson and Carpenter (1985) found that wood fiber length varied with tree height and increased from the pith to the bark. Lee *et al*. (2010) found that the fiber lengths of both earlywood and latewood in seven chestnut (*Castanea crenata*) cultivars grown in Korea tended to increase as the number of growth rings increased. Nugroho *et al*. (2012) reported that the wood fibers of several hardwoods were shortest near the pith, and their lengths increased rapidly and nonlinearly, reflecting a prominent characteristic of juvenile wood. Many previous studies have shown a similar tendency in the radial variation of the fiber length in various wood species, such as *Robinia pseudoacacia* (Stringer and Olson 1987), *Eucalyptus* (Bhat *et al*. 1990, Longui *et al*. 2014), *Alnus rubra* (Gartner *et al*. 1997), *Populus* (Debell *et al*. 2002), *Acacia mangium* (Honjo *et al*. 2005), *Casuarina equisetifolia* (Chowdhury *et al*. 2009), *Hevea brasiliensis* (Naji *et al*. 2013), and *Alnus glutinosa* (Kiaei *et al*. 2016).

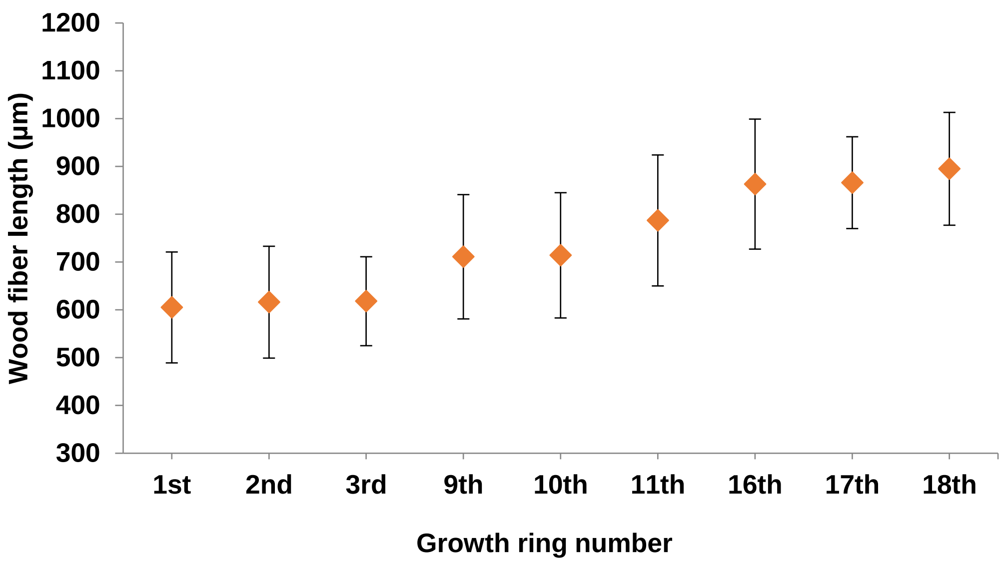

Fig. 7. Radial variation of latewood fiber length in *Paulownia tomentosa* wood

Cellulose Crystalline Characteristics

The crystalline properties of earlywood and latewood from the pith to the bark of *P. tomentosa* are listed in Table 3. There was no difference in the CrI between earlywood and latewood, and the average CrI in earlywood and latewood was approximately 67%. The CRW ranged from 2.1 to 3.3 nm in earlywood and from 2.7 to 3.1 nm in latewood, showing no difference in the crystallite width between earlywood and latewood. The CrI in the present study was slightly higher than that in *P. tomentosa* branch wood reported by Qi et al. (2014), which was 61%. Furthermore, Qi *et al.* (2016) reported that *P. tomentosa* root wood showed lower CrI than the stem wood in the present study, ranging from 42%

to 49%. The CRW of the stem wood in the present study was comparable with those of branch and root wood in the previous studies (Qi *et al.* 2014; 2016).

Table 3. Crystalline Characteristics of *P. tomentosa* Wood

Part	CRI (%)		CRW (nm)	
	Earlywood	Latewood	Earlywood	Latewood
Near Pith (1st – 6th growth ring)	67.5 (7.0)	68.1 (2.4)	2.9 (0.4)	2.9 (0.1)
Middle (7th – 12th growth ring)	67.0 (3.2)	67.0 (3.6)	2.9 (0.2)	2.8 (0.1)
Near Bark (13th – 18th growth ring)	68.3 (2.2)	65.2 (3.0)	2.9 (0.2)	2.9 (0.2)
Average	67.6 (4.4)	66.8 (3.1)	2.9 (0.3)	2.9 (0.1)
Note: Numbers in parentheses are standard deviations.				

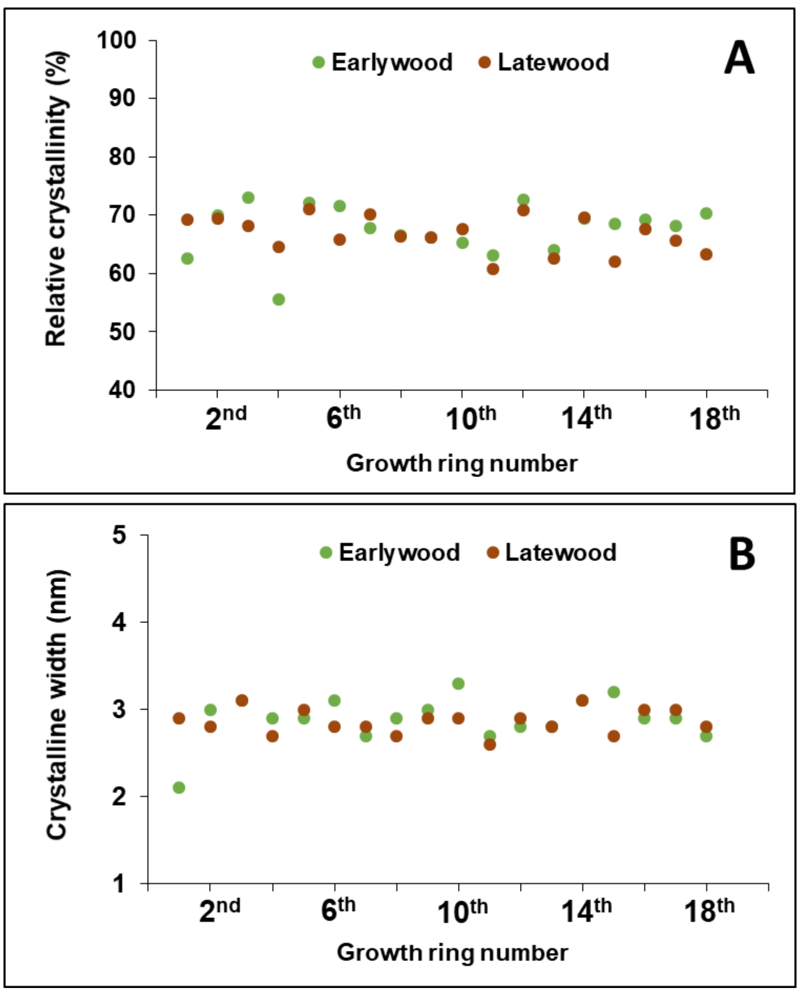

Fig. 8. Relative crystallinity (A) and crystallite width (B) in earlywood and latewood from pith to bark in *Paulownia tomentosa* wood

The radial variations in the CrI and CRW are presented in Fig. 8. The crystalline properties of the *P. tomentosa* properties were almost constant from pith to bark of *P. tomentosa* wood. Qi *et al*. (2014) showed no significant differences in crystalline characteristics among tension, lateral, and opposite woods in branch wood of *Paulownia* trees. Qi *et al*. (2016) reported that the relative crystallinity of root wood of *P. tomentosa* was slightly different in the three parts in the vertical direction (top, middle, and base). In addition, in the radial direction, the root wood near the bark showed a slightly higher relative crystallinity than that near the pith. Andersson *et al*. (2003) reported that crystallinity near the pith increased as a function of the growth ring, and it was nearly constant in mature wood of *Picea abies*. Andersson *et al*. (2015) also reported that neither width nor length of cellulose crystallites correlated with the number of growth rings in the pith of *Ginkgo biloba*. Purusatama and Kim (2018) reported that the relative crystallinity of compression, lateral, and opposite woods increased slightly with an increasing number of growth rings, whereas the crystallite width was constant. Purusatama *et al*. (2020) studied the crystalline characteristics of compression, opposite, and lateral wood in the stem wood of Korean red pine. They reported that the relative crystallinity increased slightly from the 5th to 15th growth rings and was almost similar from the 20th to 40th growth rings. In addition, there was no difference in the crystal width as the number of growth rings increased. Kim *et al.* (2022) reported that the relative crystallinity index and crystallite width of *Larix gmelinii* and *Larix kaempferi* tended to be constant from near the pith toward the bark. Purusatama *et al*. (2024) reported that CrI increased from near the pith to the bark in Sumatran pine and Agathis woods, whereas CRW was constant.

CONCLUSIONS

This study confirmed previous results on the qualitative anatomical characteristics of three surface types of *Paulownia tomentosa* wood.

1. In the quantitative analyses, the vessel diameter in earlywood and latewood was 240 and 107 μm, respectively, and these dimensions were categorized as features 43 and 42, respectively. The ray height of *P. tomentosa* wood ranged from 136 to 222 μm, presenting an average ray height of approximately 178 μm. The average fiber length was approximately 740 μm, corresponding to feature 71 indicating the shortest fiber length in hardwoods. The relative crystallinity and crystal width are approximately 67% and 2.9 nm, respectively.
2. The vessel diameters and fiber length increased gradually as the number of growth rings increased, showing significant differences in each zone. Ray height was constant from the pith to the middle and decreased toward the bark. There was no typical radial variation in the relative crystallinity or crystal width of *P. tomentosa*.
3. In practical terms, information on the qualitative and quantitative anatomical characteristics, radial variation patterns of major cell components, and crystalline properties of *P. tomentosa* can be used as wood identification keys and quality indices to utilize the wood effectively. In addition, further studies on the physical and mechanical properties with the relationship between those properties and the anatomical characteristics are needed.

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