Uniseriate Ray Characteristics for Wood Identification and Quality Indices of Six Korean Oak Species

Alvin Muhammad Savero,[a] Jong-Ho Kim,[b] Byantara Darsan Purusatama,[b] Denni Prasetia,[a] Imam Wahyudi,[c] and Nam-Hun Kim [a,]*

Radial variation in uniseriate ray characteristics of six Korean oak species was observed to provide information for wood identification and quality evaluation. Radial variations in uniseriate ray characteristics, such as ray height, number, and spacing, were observed at five growth ring intervals from the pith to near the bark using optical microscopy. The transition point between the juvenile and mature wood was evaluated using a segmented regression model. All species showed a comparable trend in uniseriate ray number and spacing, gradually decreasing from the pith to near the bark. Transition zones for the six Korean oak species ranged from 21 to 39 years of growth. The highest uniseriate ray heights and spacings were observed in *Quercus aliena*. *Quercus dentata* exhibited the highest number of uniseriate rays. Across all species, uniseriate ray number and spacing were higher in juveniles than in mature wood. A negative correlation was observed between the uniseriate ray number and spacing and the uniseriate ray height. The strongest positive correlation was observed between uniseriate ray number and ray spacing. The most reliable parameters for estimating the demarcation point were uniseriate ray number and spacing. The ray characteristics may be used to identify the six Korean oak species.

DOI: 10.15376/biores.19.4.7102-7119

Keywords: Korean oak species; Ray height; Ray number; Ray spacing; Uniseriate ray; Wood identification; Wood quality

Contact information: a: Department of Forest Biomaterials Engineering, College of Forest and Environmental Sciences, Kangwon National University, Chuncheon 24341, Republic of Korea; b: Institute of Forest Science, Kangwon National University, Chuncheon 24341, Republic of Korea; c: Faculty of Forestry and Environment, IPB University, Bogor 16680, Indonesia;
** Corresponding author: kimnh@kangwon.ac.kr*

INTRODUCTION

Six oak species, *Quercus variabilis* Blume (*Qv*), *Quercus serrata* Murray (*Qs*), *Quercus mongolica* Fisch. ex Ledeb (*Qm*), *Quercus dentata* Thunb. (*Qd*), *Quercus aliena* Blume (*Qal*), and *Quercus acutissima* Carruth (*Qac*) are widely distributed throughout the mountains of Korea and adapt to diverse soil conditions ranging from dry to wet (Son *et al*. 2004). They tended to form pure stands at high elevations. Oak trees demonstrate intermediate shade tolerance, which allows them to thrive beneath forest canopies. Over time, they ascend to the main canopy and establish dominant stands during the late successional stages (Lee *et al*. 2012). These oak species cover an extensive area of 1,037,650 hectares, with a combined growing stock of 159,261,862 m³ (Korea Forest Service 2022). Ecologically, oak trees play crucial roles in providing essential habitats for wildlife and understory vegetation. In addition, they contribute significantly to wood and charcoal production from an economic perspective (Kweon and Comeau 2021).

Oak species are popular for their high-quality wood, which is known for its beauty, strength, and durability (Santos *et al*. 2012). Oak trees are easily found and widely distributed worldwide (Nixon *et al*. 2006). Oak wood has diverse applications ranging from high-grade uses such as boat construction and building structures to low-grade applications such as packaging and fuelwood (Pasta *et al*. 2016; Bumgardner 2019). In Korea, oak wood has historically served as a common material in construction (Lee and Bae 2021). However, in recent years, its predominant use has shifted toward low-grade applications, notably for charcoal production (Korea Forest Service 2022).

Understanding radial variations in anatomical characteristics is crucial for ensuring wood quality and optimizing the utilization of different species (Jozsa and Middleton 1994; Butterfield 2003). The radial variation, spanning from the pith to the near bark of the wood, serves as a valuable parameter for identifying the transition point between juvenile and mature wood (Panshin and de Zeeuw 1964; Lee *et al*. 2009; Kim *et al.* 2009; Darmawan *et al*. 2015; Kim *et al*. 2021). Juvenile wood undergoes significant changes in cell properties, including shorter cells, thinner cell walls, narrower cell diameter, and a higher microfibril angle (Kozlowski 1971; Tsoumis 1991; Zobel and Sprague 1998; Moore and Cown 2017). Therefore, juvenile wood exhibits inferior physical-mechanical properties (Zobel and van Buijtenen 1989; Bao *et al*. 2001; Bhat *et al*. 2001; Passialis and Kiriazakos 2004; Alteyrac *et al*. 2006; Shmulsky and Jones 2019), durability (Dünisch *et al*. 2010), and drying quality (Rulliaty 2008; Moya *et al*. 2017) compared to mature wood.

Numerous studies have investigated radial variations in the anatomical characteristics of oak wood. Previous studies have primarily focused on the axial elements of oak wood, such as fiber properties (Helińska-Raczkowska and Fabisiak 1991; Lei *et al*. 1996; Tsuchiya and Furukawa 2009; Sousa *et al*. 2014; Savero *et al*. 2024), tracheid length (Helińska-Raczkowska and Fabisiak 1991), vessel length (Helińska-Raczkowska and Fabisiak 1991; Tsuchiya and Furukawa 2009), and vessel diameter (Lei *et al.* 1996; Tsuchiya and Furukawa 2009; Tulik 2014; Savero *et al*. 2024). In addition, Sousa *et al*. (2014) explored the radial variation in the radial elements of multiseriate ray features, including the height and width. Leal *et al*. (2006) conducted a study on the radial variation in the multi- and uniseriate ray properties of oak wood.

According to Reiterer *et al*. (2002) and Elaieb *et al*. (2019), ray characteristics in oak species play a crucial role as essential parameters influencing both the physical and mechanical properties of wood. In addition, De la Paz *et al*. (2005) reported that uniseriate ray characteristics significantly influence the mechanical properties of *Quercus* spp. from Mexico. Among the six Korean oak species (*Qv*, *Qs*, *Qm*, *Qd*, *Qal*, and *Qac*), their ray anatomy exhibited similarities, as reported by Eom (2015) and Savero *et al*. (2023). These species exhibit two distinct ray sizes: uniseriate and multiseriate. The multiseriate rays are composed entirely of procumbent cells and are sometimes associated with prismatic crystals. These rays commonly consist of more than 10 seriate cells and have heights exceeding 1 mm. Similarly, the uniseriate ray also consists of procumbent cells, but the difference is that the uniseriate ray does not contain prismatic crystals.

Detailed information on the anatomical characteristics is important to complete the identification keys and quality indices for these species. As mentioned above, numerous studies have focused on general anatomical features, such as the vessel and fiber properties of oak wood; however, there remains a gap in research regarding ray characteristics, particularly uniseriate rays. Therefore, this study aimed to examine the radial variation in uniseriate ray characteristics to obtain information on the identification keys and demarcation points between juvenile and mature wood, to provide wood quality indices for six Korean oak species. In addition, the relationships between ray characteristics were observed to provide additional information for evaluating wood quality.

EXPERIMENTAL

Materials

The wood samples were collected from three trees each of six Korean oak species grown at the Kangwon National University research forest in Chuncheon City, Gangwon Province, South Korea (37° 47′ 2.8932″ N, 127° 49′ 13.368″ E). The same trees were studied as those used in the authors' previous study (Savero *et al*. 2024), and the details of the sample trees for each species are presented in Table 1.

Table 1. Sample Tree Information

Trade Name	Scientific Name	Tree No.	Breast Height Diameter (cm)	Cambial Age (years)
Oriental Cork Oak	*Quercus variabilis* Blume (*Qv*)	1	21.1	63
		2	23.8	64
		3	29.7	61
Jolcham Oak	*Quercus serrata* Murray (*Qs*)	1	22.2	69
		2	28.3	54
		3	29.5	93
Mongolian Oak	*Quercus mongolica* Fisch. ex Ledeb (*Qm*)	1	21.3	63
		2	23.7	65
		3	24.2	64
Korean Oak	*Quercus dentata* Thunb. (*Qd*)	1	21.3	82
		2	21.5	66
		3	23.7	70
Oriental White Oak	*Quercus aliena* Blume (*Qal*)	1	15.5	49
		2	20.6	44
		3	25.3	50
Sawtooth Oak	*Quercus acutissima* Carruth. (*Qac*)	1	15.7	48
		2	23.6	48
		3	25.8	48

Methods

Sample preparation

Wood samples, in the form of disks with a thickness of 50 mm, were extracted 1.3 m above the ground (breast height). Subsequently, the wood disks were cut into wood-block specimens measuring 10 mm (longitudinal) × 10 mm (radial) × 10 mm (tangential). The specimens were prepared at five growth ring intervals from the pith to the nearby bark.

Optical microscopy

The wooden block specimens were softened by boiling them in a 1:1 mixture of water and glycerin for 12 h. Slices of the tangential surface, measuring 15 to 20 µm in thickness, were then obtained from the latewood of softened wood block using a sliding microtome (Lab Microtome, Swiss Federal Research Institute WSL, Birmensdorf, Switzerland). The slices were stained with a 1% safranin solution and light green, followed by dehydration using a series of alcohol concentrations (50%, 70%, 90%, 95%, and 99%). The stained slices were stored in xylene-filled vials. Before observation, permanent slides were prepared by attaching the stained slices to Canada balsam. Uniseriate ray characteristics were observed in the latewood in the tangential section without broad rays, as shown in Fig. 1, using an optical microscope (Eclipse E600, Nikon Corp., Tokyo, Japan) connected to an image analysis system (i-Solution Lite; IMT i-Solution Inc., Burnaby, BC, Canada). All the chemicals were the products of Daejung Chemical Co. Ltd., Siheung, South Korea.

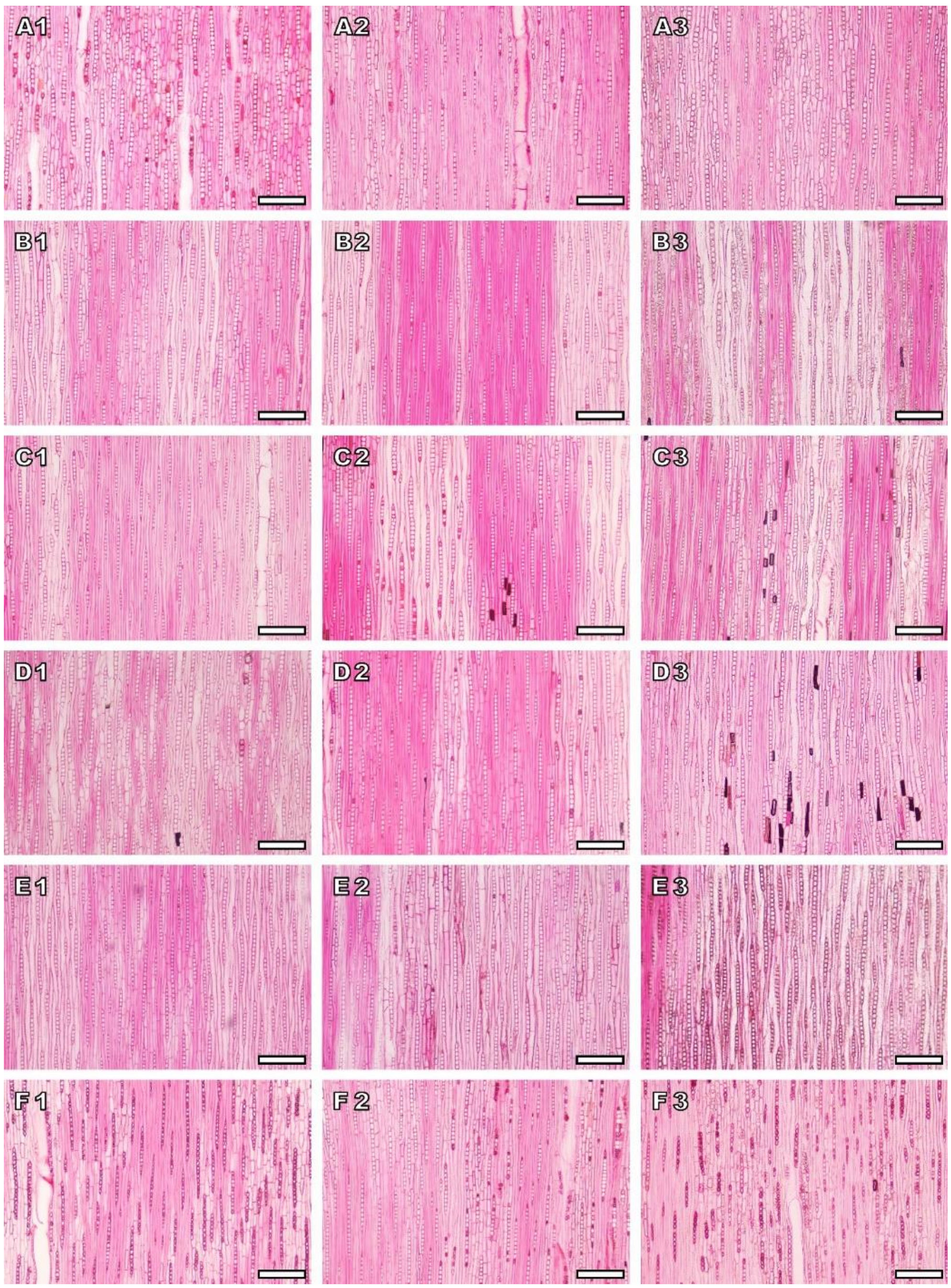

Fig. 1. Optical micrographs of uniseriate rays in tangential sections of the 10th (1), 25th (2), and 40th (3) growth ring of *Qv* (A), *Qs* (B), *Qm* (C), *Qd* (D), *Qal* (E), *Qac* (F). Scale bars: 200 µm

Uniseriate ray characteristics measurement

The uniseriate ray height, number, and spacing were evaluated following the International Association of Wood Anatomists (IAWA) list of microscopic features for hardwood identification (IAWA Committee 1989). The characteristics were determined using tangential sections of segmented samples in each five growth ring intervals obtained from three trees of each species. The ray heights (in both µm and cells) were measured from 50 uniseriate rays. The number of uniseriate rays was examined in 25 areas measuring 1 mm^2. Furthermore, the uniseriate ray spacing in tangential direction was determined using 25 measurements from a 1 mm line.

Demarcation point determination

A segmented regression model was used to evaluate the transition point between juvenile and mature wood, following the approach outlined by Rahayu *et al*. (2014). This model can be explained by using two functions within the curve. The first function, characterized by a steep slope, reflects the juvenile wood region, whereas the second function, represented by a flat line, corresponds to the mature wood region. The relationship between the uniseriate ray number and spacing, treated as dependent variables, and the number of growth rings from the pith to near the bark, considered as independent variables, was described using nonlinear regression analysis with a quadratic model and a plateau. The nonlinear least squares procedure (PROC NLIN) in SAS v.9.0 (SAS Institute Inc., Cary, NC, USA) was used to analyze the demarcation point. The proportion of mature wood was calculated using the method proposed by Savero *et al*. (2024).

Data analysis

Statistical analyses were conducted to explore the relationships between uniseriate ray characteristics among different species. One-Way Analysis of Variance (ANOVA) was used to compare means across species, followed by Duncan's test for post hoc verification at a 5% significance level. Additionally, Pearson's correlation was used to analyze the relationship between the uniseriate ray characteristics, with significance levels set at both 1% and 5%. All statistical analyses were performed using SPSS version 26 (IBM Corp., Armonk, NY, USA).

RESULTS AND DISCUSSION

Radial Variation and Demarcation Point

Uniseriate ray height

The radial variation in uniseriate ray height (µm) is depicted in Fig. 2. It demonstrated a fluctuating pattern, with an increase near the pith until 10 to 15 years of growth, followed by a decrease near the bark in all species. A similar pattern was observed in the radial variation of the uniseriate ray heights (cells), as shown in Fig. 3. However, there was a difference in trends between uniseriate ray height in µm and cells, the former exhibited an increasing trend, while the latter showed a decreasing trend.

The radial variation pattern of uniseriate ray height in µm and cells did not exhibit a juvenile-to-mature wood pattern. Additionally, segmented regression model analysis could not be conducted because the pattern did not fit well ($R^2 < 0.2$). This study is consistent with a previous study by Zobel and Sprague (1998), who reported no distinct juvenile-to-mature wood pattern in the ray height of *Celtis occidentalis*.

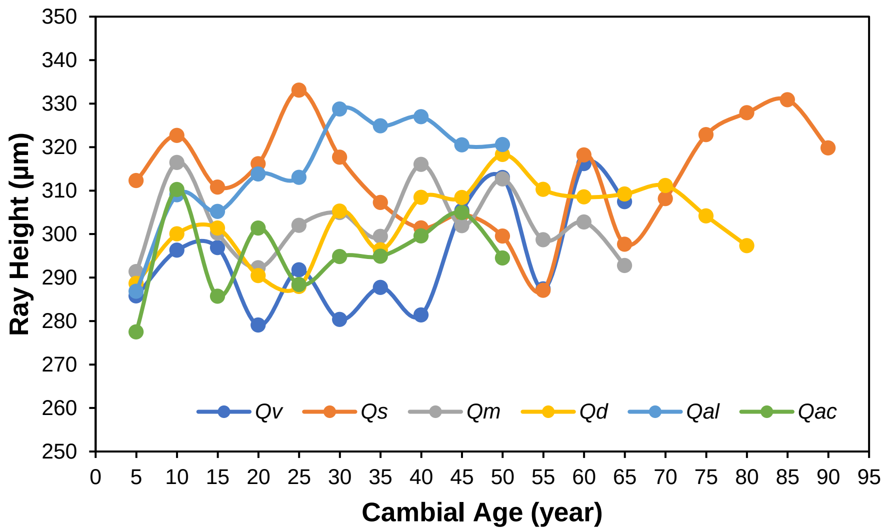

Fig. 2. Uniseriate ray height (µm) of six Korean oak species

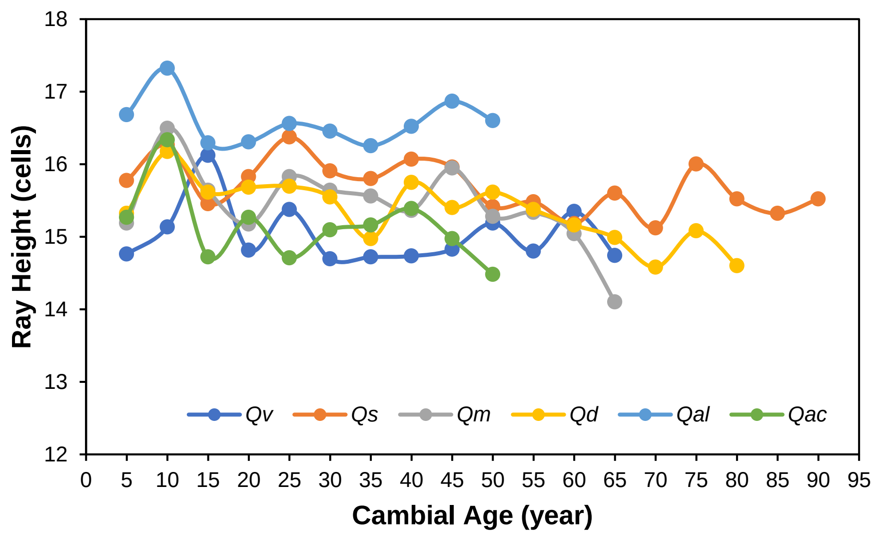

Fig. 3. Uniseriate ray height (cells) of six Korean oak species

Compared with the present study, Leal *et al*. (2006) also observed a similar radial variation trend in *Q. suber* from Portugal. The height of uniseriate rays (µm) increased from the pith to near the bark, while the height of uniseriate ray (cells) decreased. In addition, Sousa *et al*. (2014) examined a similar trend in *Q. faginea* from Portugal, which was characterized by a decrease in the height of the uniseriate rays (cells).

Uniseriate ray number and ray spacing

Figure 4 illustrates the radial variation in the uniseriate ray numbers for the six Korean oak species. Initially, the uniseriate ray numbers were high near the pith but decreased until 20 to 40 years of the growth ring. Subsequently, they stabilized with a slight increase toward the bark for all species, except for *Qs*. *Qs* gradually decreased from near the pith to 30 years of growth, after which it remained constant until near the bark.

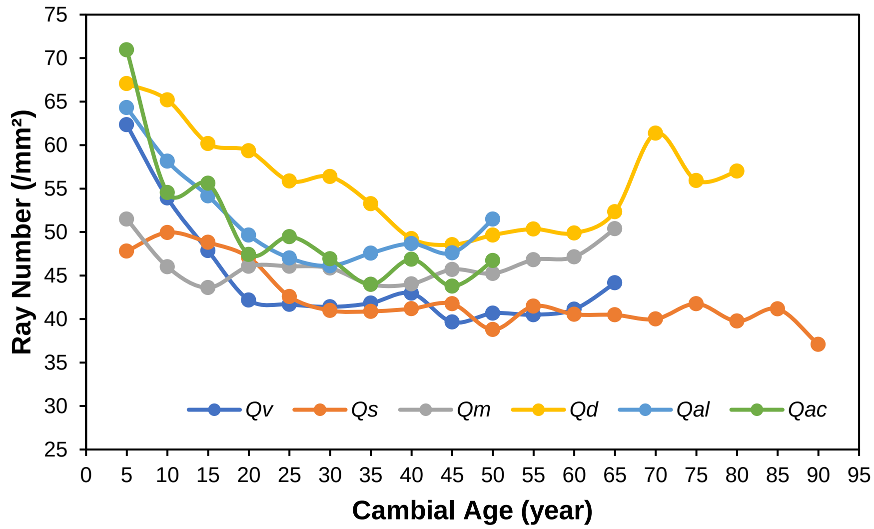

Fig. 4. Uniseriate ray number of six Korean oak species

The demarcation points between juvenile and mature wood were analyzed using a segmented regression model. The radial variation pattern of the uniseriate ray number fitted well ($R^2 > 0.8$). The transition zone of the uniseriate ray numbers ranged from 21 to 37 years of growth, with the lowest at *Qm* and the highest at *Qd* (Table 2). In the mature wood proportion, *Qm* had the highest proportion at 67%, whereas *Qal* had the lowest proportion (44%).

Table 2. Demarcation Points and Mature Wood Proportion of Six Korean Oak Species using Segmented Regression Model

Parameters		**Six Korean Oak Species**					
		Qv	***Qs***	***Qm***	***Qd***	***Qal***	***Qac***
Uniseriate Ray Number	Demarcation Point (year)	26^{bc} (2.7)	31^{ab} (5.7)	21^{c} (3.2)	37^{a} (2.5)	27^{bc} (2.3)	23^{c} (3.8)
	Mature Wood Proportion (%)	59^{ab} (4.3)	57^{ab} (7.8)	67^{a} (5.0)	49^{bc} (3.4)	44^{c} (4.7)	52^{bc} (7.7)
Uniseriate Ray Spacing	Demarcation Point (year)	26^{b} (6.8)	39^{a} (7.0)	31^{ab} (5.9)	25^{b} (3.4)	28^{b} (3.8)	24^{b} (3.2)
	Mature Wood Proportion (%)	59^{ab} (10.6)	46^{bc} (9.6)	52^{abc} (9.3)	66^{a} (4.6)	42^{c} (7.8)	50^{bc} (6.7)

Note: Numbers in parentheses represent standard deviations. The same superscript letters next to the mean values within columns indicate non-significant differences at the 5% significance level, as determined by Duncan's test for comparisons between species.

The radial variation in the uniseriate ray spacing exhibited a similar pattern to that of the uniseriate ray numbers for the oak species (Fig. 5). Initially, it was high near the pith and gradually decreased until 20 to 30 years of growth, after which it slightly increased toward the bark.

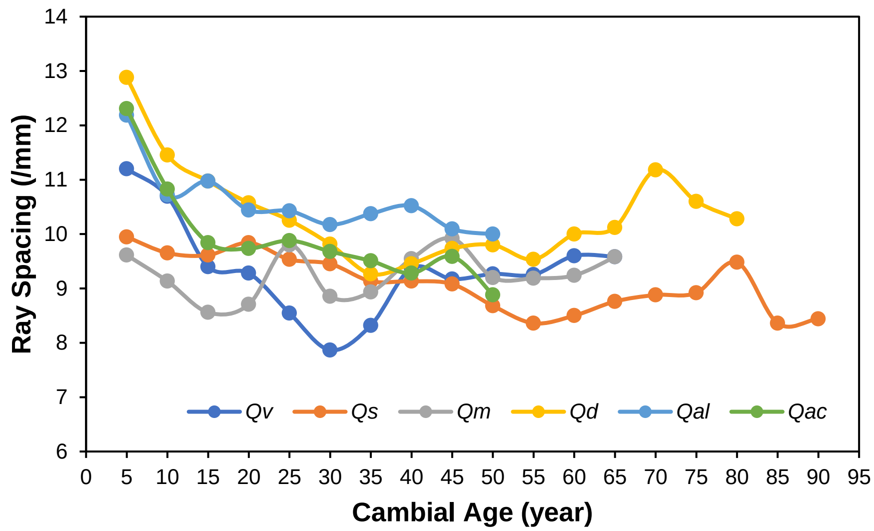

Fig. 5. Uniseriate ray spacing of six Korean oak species

Similar to the uniseriate ray number, the radial variation pattern of the uniseriate ray spacing fit well in the segmented regression model. Table 2 presents the demarcation zones of uniseriate ray spacing, which ranged from 24 to 39 years for the growth rings. This range was slightly higher than the uniseriate ray number but was still comparable. Among the different wood types, the lowest demarcation point was found in *Qac*, whereas the oldest was found in *Qs*. In terms of mature wood proportion, *Qd* exhibited the highest portion at 66%, whereas *Qal* had the lowest at 42%.

There were similar transition points between the radial variation of the uniseriate ray number and spacing to determine the juvenile and mature wood. The demarcation zones for the uniseriate ray number and spacing ranged from 21 to 39 years for growth rings. A comparable result was observed in a previous study by Savero *et al*. (2024), who reported the transition zone for six Korean oak species using fiber length and earlywood vessel diameter ranging from 19 to 44 years of growth. Tsuchiya and Furukawa (2009) identified a demarcation zone for earlywood vessel diameter in *Qs* from Japan, ranging from 11 to 38 years of growth rings. Therefore, we conclude that the uniseriate ray number and spacing in the six Korean oak species can be used to determine the demarcation point between juvenile and mature wood.

Radial Variation and Demarcation Point

Uniseriate ray height

The uniseriate ray height (μm) of six Korean oak species is shown in Table 3. In average values, the highest uniseriate ray height was found in *Qal* with 314.5 μm, while the lowest was in *Qv* with 294.2 μm. In juvenile wood, *Qs* exhibited the highest value at 320.4 μm, while in mature wood, *Qal* had the highest value at 325.3 μm. The lowest uniseriate ray height was observed in both juvenile and mature wood of *Qv*, measuring 289.9 and 296.9 μm, respectively.

Table 3. Uniseriate Ray Characteristics of Six Korean Oak Species

Parameters	Wood	Korean Oak Species						IAWA List
		Qv	*Qs*	*Qm*	*Qd*	*Qal*	*Qac*	
Uniseriate ray height (µm)	Juvenile	289.9^{e} (47.0)	320.4^{a} (46.1)	299.3^{c} (35.9)	294.4^{d} (34.4)	306.5^{b} (36.9)	291.4^{de} (37.3)	-
	Mature	296.9^{c} (43.9)	305.5^{b} (42.3)	305.1^{b} (33.0)	307.9^{b} (32.3)	325.3^{a} (34.3)	298.7^{c} (35.2)	
	Average	294.2^{d} (45.3)	311.9^{b} (44.6)	302.7^{c} (34.3)	302.9^{c} (33.7)	314.5^{a} (37.0)	295.2^{d} (36.4)	
Uniseriate ray height (cells)	Juvenile	15.2^{d} (2.3)	15.9^{b} (1.9)	15.6^{c*} (1.9)	15.6^{c} (1.7)	16.6^{a*} (1.9)	15.3^{d*} (2.0)	-
	Mature	14.9^{d} (2.0)	15.6^{b} (1.9)	15.4^{c*} (1.8)	15.3^{c} (1.7)	16.5^{a*} (1.7)	15.0^{d*} (1.7)	
	Average	15.0^{d} (2.1)	15.8^{b} (1.9)	15.5^{c} (1.9)	15.4^{c} (1.7)	16.6^{a} (1.8)	15.2^{d} (1.8)	
Uniseriate ray number (/mm²)	Juvenile	49.6^{d} (11.8)	45.8^{f} (6.9)	47.3^{e} (4.9)	60.9^{a} (8.9)	53.9^{c} (101)	55.5^{b} (12.0)	-
	Mature	41.4^{e} (5.0)	40.8^{e} (5.6)	45.5^{d} (7.0)	52.3^{a} (7.6)	48.2^{b} (4.5)	46.4^{c} (6.5)	
	Average	44.6^{d} (9.3)	43.0^{e} (6.6)	46.2^{c} (6.2)	55.5^{a} (9.1)	51.5^{b} (8.7)	50.8^{b} (10.6)	
Uniseriate ray spacing (/mm)	Juvenile	9.8^{c} (1.8)	9.6^{c} (1.7)	9.2^{d*} (1.7)	11.1^{a} (1.9)	10.9^{a} (1.7)	10.5^{b} (2.1)	115
	Mature	9.0^{e} (1.7)	8.9^{e} (1.5)	9.3^{d*} (1.7)	9.9^{b} (1.7)	10.2^{a} (1.7)	9.5^{c} (1.6)	
	Average	9.3^{d} (1.7)	9.2^{d} (1.6)	9.2^{d} (1.7)	10.3^{b} (1.9)	10.6^{a} (1.7)	10.0^{c} (1.9)	

Note: Numbers in parentheses represent standard deviations. The same superscript letters and asterisks next to the mean values within columns indicate non-significant differences at the 5% significance level, as determined by Duncan's test for comparisons between species and ANOVA for comparisons between juvenile and mature wood, respectively. According to the IAWA lists, the ray per millimeter values are categorized as follows: ≤ 4 /mm (114), 4 to 12 /mm (115), and ≥ 12 /mm (116).

Consistent with uniseriate ray height in µm, the highest average of ray height in cells was 16.6 cells for *Qal*, while the lowest was *Qv* at 15.0 cells, as shown in Table 3. In both juvenile and mature wood, *Qal* exhibited the highest value of the uniseriate ray height (cells), measuring 16.6 cells and 16.5 cells, respectively. The lowest value was observed for *Qv*, at 15.2 cells for juvenile wood and 14.9 cells for mature wood.

The uniseriate ray height (µm) in mature wood exhibited higher values than that in juvenile wood for all species, except *Qs*. In contrast, uniseriate ray height (cells) in mature wood was lower than that in juvenile wood for all species. However, the uniseriate ray height (cell) values of *Qm*, *Qal*, and *Qac* were not significantly different between juvenile and mature wood. Furthermore, both the uniseriate ray height in µm and cells showed no significant difference between *Qv* and *Qac*, as well as between *Qm* and *Qd*. These findings are consistent with those of previous studies showing that mature wood has more cells than juvenile wood (Kozlowski 1971; Tsoumis 1991; Zobel and Sprague 1998; Barbour 2004; Moore and Cown 2017). Therefore, it seems that mature wood had lower uniseriate ray height (cells) values, but higher uniseriate ray height (µm) compared to juvenile wood.

The uniseriate ray height (both µm and cells) in this study was higher than that in previous studies. Leal *et al*. (2006) and Sousa *et al*. (2009) reported that *Q. suber* from Portugal showed uniseriate ray height (µm) averaging 226.5 and 216.3 µm, respectively. Leal *et al*. (2006) reported a uniseriate ray height (cells) with an average of 11.0 cells. Sousa *et al*. (2014) and Han *et al*. (2015) reported that the average heights of the uniseriate rays (cells) in *Q. faginea* from Portugal and *Q. rubra* from Canada were 9.3 cells and 12.7 cells, respectively.

The uniseriate ray height (both µm and cells) from this study differed significantly between species. According to Denk *et al*. (2017) and the World Flora Online (2024), the six Korean oak species are divided into two subgenera and sections. *Qv* and *Qac* belong to *Quercus* subgen. *Cerris* Oerst. sect. *Cerris* Dumort., whereas *Qm*, *Qd*, and *Qal* are categorized under *Quercus* subgen. *Quercus* sect. *Quercus*. In addition, *Qs* do not belong to any specific subgenus or section. Interestingly, *Qal* exhibits significantly different ray height compared to *Qm* and *Qd*, making it a potentially valuable additional identification feature within the *Quercus* subgen. *Quercus* sect. *Quercus*.

These species are grown in the same location, which makes it possible to eliminate the site factor. Therefore, it is suggested that uniseriate ray height (both µm and cells) could be utilized for identifying the six Korean oak species.

Uniseriate ray number and ray spacing

Uniseriate ray numbers varied among species, as presented in Table 3. The average value of the uniseriate ray number showed that *Qd* had the highest value at 55.5/mm², while *Qs* had the lowest at 43.0/mm². In both juvenile and mature wood, *Qd* showed the highest number of uniseriate rays among the species, at 60.9/mm² and 52.3/mm², respectively. In contrast, *Qs* exhibited the lowest values for both juvenile and mature wood, averaging 45.8/mm² and 40.8/mm², respectively.

For the uniseriate ray spacing of the six Korean oak species, *Qal* had the highest average value of 10.6/mm, whereas the lowest was observed in *Qs* and *Qd* (9.2/mm). In both juvenile and mature wood, *Qal* exhibited significantly greater ray spacing, averaging 10.9/mm and 10.2/mm, respectively. In contrast, the lowest value in juvenile wood was found for *Qm* at 9.2/mm, whereas in mature wood, *Qs* was 8.9/mm. According to the IAWA Committee (1989), the uniseriate ray spacing of six Korean oak species is categorized as anatomical feature number 115, with 4 to 12 rays per mm.

Both the uniseriate ray number and spacing in juvenile wood were significantly higher than those in mature wood, except for *Qm*.

In the present study, the uniseriate ray number was higher compared to *Q. brantii* from Iran, with an average of 30.0/mm² (Soheili *et al*. 2023). In contrast, the present findings regarding uniseriate ray spacing aligned with that of *Q. robur* from Turkey, which was 10.3/mm (Gülsoy *et al*. 2005). However, it was slightly lower than the uniseriate ray spacing observed in *Q. pontica* from Turkey (Yilmaz *et al*. 2008) and *Q. rubra* from Canada (Han *et al*. 2015), which were 11.3/mm and 11.7/mm, respectively.

As mentioned in the previous section, the differences in ray number and spacing between *Qv* and *Qac* from *Quercus* subgen. *Cerris* Oerst. sect. *Cerris* Dumort., as well as between *Qm*, *Qd*, and *Qal* from *Quercus* subgen. *Quercus* sect. *Quercus* might serve as additional information for identifying these species.

Thus, a significant difference in the uniseriate ray number and spacing among all species suggests that these parameters can serve as identification keys for the six Korean oak species.

Relationship Between Uniseriate Ray Characteristics

Figure 6 illustrates the relationship between the uniseriate ray number (Fig. 6A) and spacing (Fig. 6B) to the uniseriate ray height (µm) in six Korean oak species. The correlation between the number of uniseriate rays and their height (µm) significantly differed at 5%, with a Pearson correlation coefficient of -0.28 as shown in Table 4. However, the correlation between uniseriate ray spacing and height (µm) was weak and not significantly different, with a Pearson correlation coefficient of -0.75.

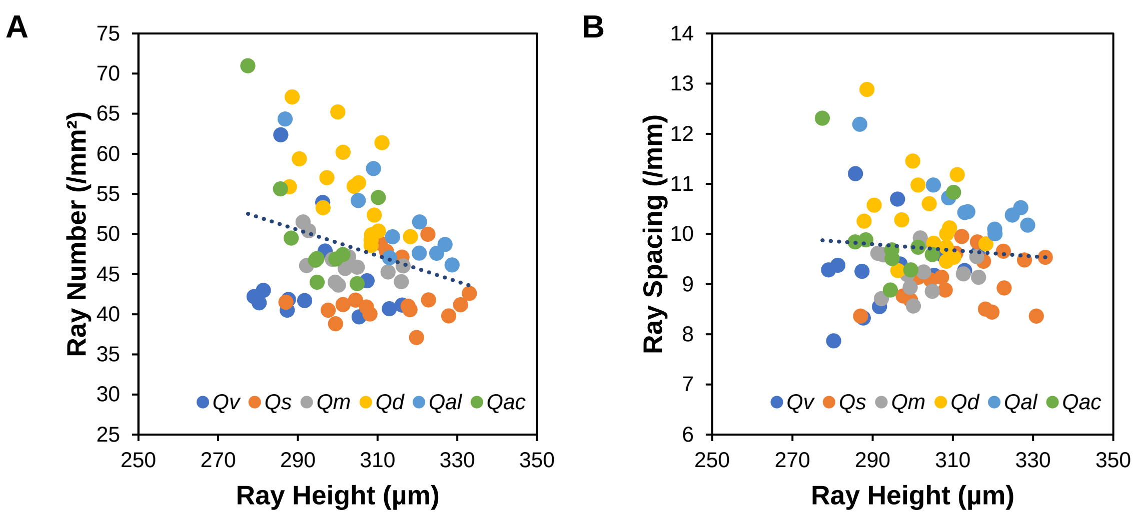

Fig. 6. Relationship between uniseriate ray number (A) and ray spacing (B) to uniseriate ray height (µm) of six Korean oak species.

Table 4. Pearson Correlation Coefficient of Uniseriate Ray Characteristics of Six Korean Oak Species

Parameters	Uniseriate ray height (µm)	Uniseriate ray height (cells)	Uniseriate ray number	Uniseriate ray spacing
Uniseriate ray height (µm)	1	0.41**	-0.28*	-0.75
Uniseriate ray height (cells)	0.41**	1	0.11	0.19
Uniseriate ray number	-0.28*	0.11	1	0.83**
Uniseriate ray spacing	-0.75	0.19	0.83**	1
Note: * Correlation is significant at the 5% significance level (2-tailed). ** Correlation is significant at the 1% significance level (2-tailed).				

In contrast, a positive correlation was observed among uniseriate ray number (Fig. 7A), spacing (Fig. 7B), and uniseriate ray height (cells). However, the correlation was not statistically significant. Table 4 shows that the uniseriate ray number and height (cells) exhibited a weaker correlation, with a Pearson correlation coefficient of 0.11, compared to the relationship between uniseriate ray spacing and height (cells), with a Pearson correlation coefficient of 0.19.

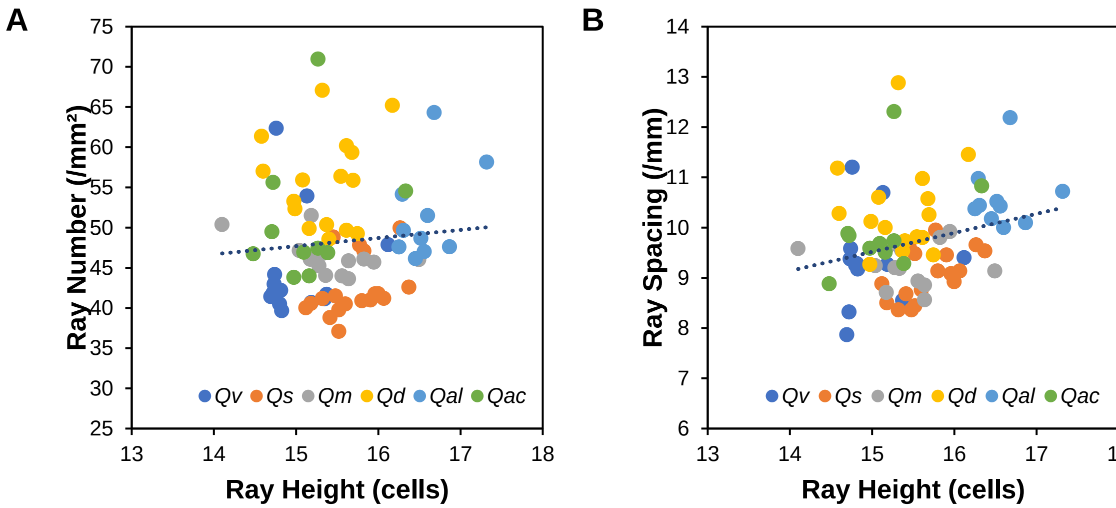

Fig. 7. Relationship between uniseriate ray number (A) and ray spacing (B) to uniseriate ray height (µm) of six Korean oak species.

A positive correlation was also found between uniseriate ray height in µm and cells (Fig. 8A), as well as between uniseriate ray number and spacing (Fig. 8B). Both relationships were statistically significant at the 1% level, as indicated in Table 4. A strong correlation was observed between the uniseriate ray number and the spacing, with a Pearson's correlation coefficient of 0.83. In contrast, the relationship between uniseriate ray height in µm and cells exhibited a weaker correlation, with a Pearson correlation coefficient of 0.41. Compared to the previous study reported by Leal *et al*. (2006), the relationship between uniseriate ray height in µm and cells exhibited a positive correlation.

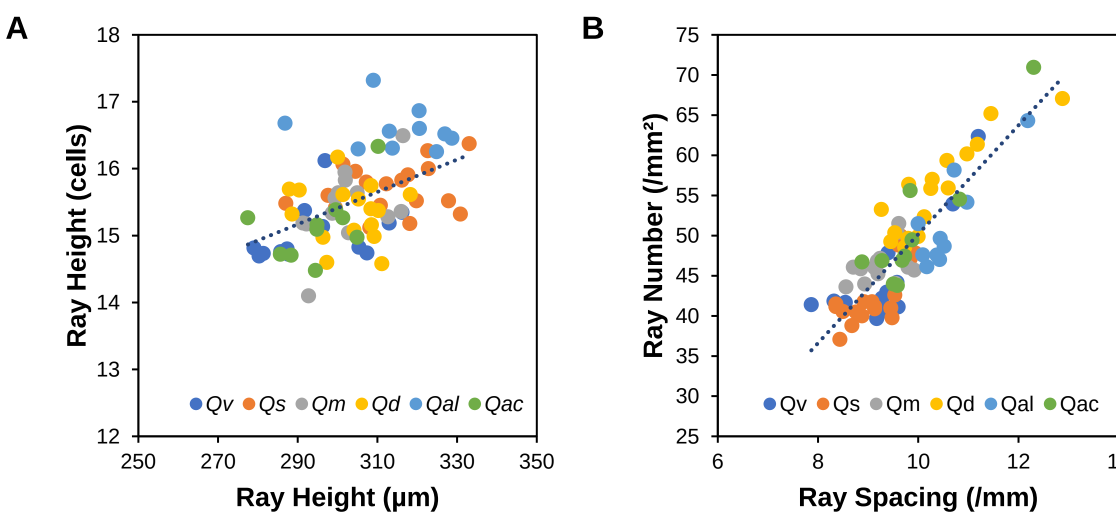

Fig. 8. Relationship between uniseriate ray number (A) and ray spacing (B) to uniseriate ray height (µm) of six Korean oak species

Relationship Between Uniseriate Ray Characteristics

In the introduction it was discussed that ray characteristics impact wood quality, including physical and mechanical properties (Reiterer *et al*. 2002; Elaieb *et al*. 2019). Barbe and Keller (1996) attributed this impact to the higher proportion of rays in the anatomical elements of wood, which typically ranges from 3% to 30% of the total wood volume. Elaieb *et al*. (2019) observed that ray numbers correlate positively with tangential and radial shrinkage of wood. Additionally, De la Paz *et al*. (2005) reported that uniseriate ray characteristics, particularly uniseriate ray spacing, are positively associated with compression perpendicular to the grain. Rahman *et al*. (2005) also noted a positive correlation between ray volume and specific gravity, as well as radial compression strength. Furthermore, it is essential to recognize that juvenile and mature wood also play a role in overall wood quality (Zobel and van Buijtenen 1989; Bao *et al*. 2001; Bhat *et al*. 2001; Passialis and Kiriazakos 2004; Alteyrac *et al*. 2006; Rulliaty 2008; Dünisch *et al*. 2010; Moya *et al*. 2017; Shmulsky and Jones 2019).

The present results indicate that *Qal* exhibits higher uniseriate ray characteristics than other species. Ozden and Ennos (2014) reported that the hexagonal shape of ray cells contributed to giving greater strength, stiffness, and toughness to the wood. Thus, wood with higher values of ray height, density, and spacing resulted in higher mechanical properties. Additionally, *Qal* showed a younger transition age compared to *Qs* and *Qd*, but an older transition age compared to *Qv* and *Qac*. Wood with younger transition age produced a higher mature wood portion in the same age, the mature wood had a better overall quality than juvenile wood (Zobel and van Buijtenen 1989; Bao *et al*. 2001; Bhat *et al*. 2001; Passialis and Kiriazakos 2004; Alteyrac *et al*. 2006; Rulliaty 2008; Dünisch *et al*. 2010; Moya *et al*. 2017; Shmulsky and Jones 2019). According to Oh (1999), *Qal* has higher bending strength than *Qs*, *Qm*, and *Qac*, although it is lower than *Qv*. Furthermore, a previous study by Savero *et al*. (2024) suggests that *Qv* may have the best quality among the species based on vessel and fiber properties. Therefore, the present findings indicate that *Qal* may have better quality than *Qs*, *Qm*, *Qd*, and *Qac*.

CONCLUSIONS

1. The radial variation patterns of uniseriate ray height in µm and numbers of cells exhibited a similar fluctuating pattern for all species. All species followed a similar trend in uniseriate ray number and spacing, gradually decreasing from the pith to near the bark. The segmented regression model fitted well with the uniseriate ray number and spacing, resulting in a transition zone for the six Korean oak species, ranging from the 21^{st} to 39^{th} growth rings.
2. The highest average uniseriate ray height (µm and cells) and spacing were observed in *Quercus aliena* Blume (*Qal*) and *Quercus dentata* Thunb. (*Qd*) exhibited the highest average uniseriate ray number. *Quercus variabilis* Blume (*Qv*) showed the lowest average uniseriate ray height (µm and cells), whereas *Quercus serrata* Murray (*Qs*) had the lowest average in both uniseriate ray number and spacing. Across all species, uniseriate ray height (cells), number, and spacing were higher in juveniles than in mature wood. In contrast, mature wood of all species displayed higher uniseriate ray height (µm) than juvenile wood, except for *Qs*.

3. A positive correlation was observed between uniseriate ray characteristics. However, a negative correlation was observed between the uniseriate ray number and spacing to the uniseriate ray height (µm). The strongest correlation was observed between the uniseriate ray number and ray spacing.
4. The most reliable parameters for estimating the demarcation point between juvenile and mature wood were the radial variation in the uniseriate ray number and spacing. Uniseriate ray characteristics might also be used to identify the six Korean oak species, along with other qualitative and quantitative anatomical characteristics, for more accurate wood identification. Additionally, the results could be useful for silvicultural management and determining the optimal harvesting times to produce the best quality wood from the six Korean oak species. To fully understand the wood quality of these species, future research should explore their physical, mechanical, and chemical properties and natural durability.

ACKNOWLEDGMENTS

This research was supported by the Science and Technology Support Program through the National Research Foundation of Korea (NRF), funded by the Ministry of Science and ICT (MSIT) (No. 2022R1A2C1006470), the Basic Science Research Program through the NRF, funded by the Ministry of Education (No. 2018R1A6A1A03025582), and the R&D Program for Forest Science Technology (No. 2021350C10-2323-AC03) provided by the Korea Forest Service (Korea Forestry Promotion Institute).

REFERENCES CITED

Alteyrac, J., Cloutier, A., and Zhang, S. Y. (2006). "Characterization of juvenile wood to mature wood transition age in black spruce (*Picea mariana* (Mill.) B.S.P.) at different stand densities and sampling heights," *Wood Sci. Technol.* 40, 124-138. DOI: 10.1007/s00226-005-0047-4.

Bao, F. C., Jiang, Z. H., Jiang, X. M., Lu, X. X., Luo, X. Q., and Zhang, S. Y. (2001). "Differences in wood properties between juvenile wood and mature wood in 10 species grown in China," *Wood Sci. Technol.* 35, 363-375. DOI: 10.1007/s002260100099.

Barbe, C., and Keller, R. (1996). "Les rayons ligneux et le matériau bois," *Revue Forestière Française* 48, 63-68. DOI: 10.4267/2042/26729. [in French]

Barbour, J. (2004). "Wood formation and properties: Wood Quality," in: *Encyclopedia of Forest Sciences*, J. Burley, J. Evans, and J. A. Youngquist (eds.), Elsevier, London, UK, pp. 1840-1846; ISBN 978-0-121-45160-8. DOI: 10.1016/B0-12-145160-7/00039-9.

Bhat, K. M., Priya, P. B., and Rugmini, P. (2001). "Characterisation of juvenile wood in teak," *Wood Sci. Technol.* 34, 517-532. DOI: 10.1007/s002260000067.

Bumgardner, M. (2019). "Overview of oak markets and marketing," in: *Proceedings of the Oak Symposium: Sustaining Oak Forests in the 21st Century through Science-Based Management*, Knoxville, TN, USA, pp. 113-115. DOI: 10.2737/SRS-GTR-237.

Butterfield, B. G. (2003). “Wood anatomy in relation to wood quality,” in: *Wood Quality and Its Biological Basis*, J. R. Barnett, and G. Jeronimidis (eds.), Blackwell Publishing Ltd., Oxford, UK, pp. 30-49, ISBN 1-84127-319-8.

Darmawan, W., Nandika, D., Sari, R. K., Sitompul, A., Rahayu, I., and Gardner, D. (2015). “Juvenile and mature wood characteristics of short and long rotation teak in Java,” *IAWA J.* 36, 428-442. DOI: 10.1163/22941932-20150112.

De la Paz Pérez-Olvera, C., Dávalos Sotelo, R., and Quintanar-Isaías, A. (2005). “Influencia de los radios en algunas propiedades físicas y mecánicas de la madera de ocho encinos (*Quercus*) de Durango, México,” *Madera y Bosques* 11, 49-68. DOI: 10.21829/myb.2005.1121256. [in Spanish]

Denk, T., Grimm, G. W., Manos, P. S., Deng, M., and Hipp, A. L. (2017). “An updated infrageneric classification of the oaks: Review of previous taxonomic schemes and synthesis of evolutionary patterns,” in: *Oaks Physiological Ecology. Exploring the Functional Diversity of Genus Quercus L. Tree Physiology Volume 7,* E. Gil-Pelegrín, J. Peguero-Pina, and D. Sancho-Knapik (eds.), Springer, Cham, Switzerland, pp. 13-38, ISBN: 978-3-319-69099-5. DOI: 10.1007/978-3-319-69099-5_2.

Dünisch, O., Richter, H.-G., and Koch, G. (2010). “Wood properties of juvenile and mature heartwood in *Robinia pseudoacacia* L.,” *Wood Sci. Technol.* 44, 301-313. DOI: 10.1007/s00226-009-0275-0.

Elaieb, M. T., Shel, F., Jalleli, M., Langbour, P., and Candelier, K. (2019). “Physical properties of four ring-porous hardwood species: influence of wood rays on tangential and radial wood shrinkage,” *Madera y bosques* 25, article 12521695. DOI: 10.21829/myb.2019.2521695.

Eom, Y. G. (2015). *Wood Anatomy of Korean Species*, Media Wood Ltd., Seoul, Republic of Korea, ISBN: 978-89-97450-98-5-93480.

Gülsoy, S. K., Eroğlu, H., and Merev, N. (2005). “Chemical and wood anatomical properties of tumorous wood in a Turkish white oak (*Quercus robur* subsp. *robur*),” *IAWA J.* 26, 469-476. DOI: 10.1163/22941932-90000128.

Han, M.-S., Lee, J.-R., Kim, J.-S., Shin, S.-J., and Kim, B.-R. (2015). “Studies on wood quality and growth of *Quercus rubra* in Korea: anatomical properties,” *J. Korean Wood Sci. Technol.* 43, 421-428. DOI: 10.5658/WOOD.2015.43.4.421. (In Korean)

Helińska-Raczkowska, L., and Fabisiak, E. (1991). “Radial variation and growth rate in the length of the axial elements of sessile oak wood,” *IAWA Bull.* 12, 257-262. DOI: 10.1163/22941932-90001254.

IAWA Committee. (1989). “IAWA list of microscopic features for hardwood identification,” *IAWA Bull.* 10, 219-332.

Jozsa, L. A., and Middleton, G. R. (1994). *A Discussion of Wood Quality Attributes and Their Practical Implications*, Forintek Canada Corp., Vancouver, BC, Canada, ISSN 0824-2119.

Kim, N.-H., Kwon, S.-M., and Chun, K.-W. (2009). “Radial variation of rays in two commercial softwoods grown in Korea,” *Wood Fiber Sci*. 41, 138-144.

Kim, D. H., Kim, S. H., Jo, J. I., Kim, J. H., Purusatama, B. D., Lee, S. H., and Kim, N. H. (2021). “Ray properties in the stems of Dahurian larch (*Larix gmelinii*) and Japanese larch (*Larix kaempferi*),” *IAWA J.* 42, 134-142. DOI: 10.1163/22941932-bja10031.

Korea Forest Service. (2022). *Statistical Yearbook of Forestry*, Department of Forest Resources in Korea Forest Service, Daejeon, Republic of Korea. (In Korean)

Kozlowski, T. T. (1971). *Growth and Development of Trees, Volume II*, Academic Press, Inc., London, UK, Volume 2.

Kweon, D., and Comeau, P. G. (2021). "Climate, site conditions, and stand characteristics influence maximum size-density relationships in Korean red pine (*Pinus densiflora*) and Mongolian oak (*Quercus mongolica*) stands, South Korea," *For. Ecol. Manag.* 502, article 119272. DOI: 10.1016/j.foreco.2021.119727.

Leal, S., Sousa, V. B., and Pereira, H. (2006). "Within and between-tree variation in the biometry of wood rays and fibres in cork oak (*Quercus suber* L.)," *Wood Sci. Technol.* 40, 585-597. DOI: 10.1007/s00226-006-0073-x.

Lee, H. M., and Bae, J. S. (2021). "Major species and anatomical characteristics of the wood used for national use specified in Yeonggeon-Uigwes of the late Joseon Dynasty period," *J. Korean Wood Sci. Technol.* 49, 462-470. DOI: 10.5658/WOOD.2021.49.5.462.

Lee, D., Kang, H., Koo, C., Kwon, K., Kim, G., Kim, H., Combalicer, M.S., Batkhuu, N., Park, B., Park, Y., *et al*. (2012). *Ecological Management of Forests*, Seoul National University Press, Seoul, Republic of Korea.

Lee, S.-H., Kwon, S.-M., Lee, S.-J., Lee, U., Kim, M.-J., and Kim, N.-H. (2009). "Radial variation of anatomical characteristics of chestnut wood (*Castanea crenata*) grown in Korea—Vessel element and ray," *J. Korean Wood Sci. Technol.* 37, 19-28. (in Korean)

Lei, H., Milota, M. R., and Gartner, B. L. (1996). "Between- and within-tree variation in the anatomy and specific gravity of wood in Oregon white oak (*Quercus garryana* Dougl.)," *IAWA J.* 17, 445-461. DOI: 10.1163/22941932-90000642.

Moore, J. R., and Cown, D.J. (2017). "Corewood (juvenile wood) and its impact on wood utilization," *Curr. For. Rep.* 3, 107-118. DOI: 10.1007/s40725-017-0055-2.

Moya, R., Berrocal, A., Rodriguez-Solis, M., and Muñoz, F. (2017). "Effect of steam-drying treatment on moisture content, drying rate, color, and drying defects in juvenile wood of *Tectona grandis* from fast-growth plantations," *Drying Technol.* 35, 1832-1842. DOI: 10.1080/07373937.2017.1280503.

Nixon, K. C. (2006). "Global and neotropical distribution and diversity of oak (genus *Quercus*) and oak forests," in: *Ecology and Conservation of Neotropical Montane Oak Forests*, M. Kappelle (ed.), Springer, Berlin/Heidelberg, Germany, pp. 3-13, ISBN 978-3-540-28909-8. DOI: 10.1007/3-540-28909-7.

Oh, S.-W. (1999). "The relationship between anatomical characteristics and bending strength in major species of Korean Lepidobalanus," *J. Korean Wood Sci.* 27, 9-17.

Ozden, S., and Ennos, A. R. (2014). "Understanding the function of rays and wood density on transverse fracture behaviour of green wood in three species," *J. Agr. Sci. Technol.* 4, 731-743. DOI: 10.17265/2161-6264/2014.09.006.

Panshin, A. J., and de Zeeuw, C. (1964). *Textbook of Wood Technology, 3rd Ed.*, McGraw-Hill Inc., New York, NY, USA, ISBN 07-048440-6.

Passialis, C., and Kiriazakos, A. (2004). "Juvenile and mature wood properties of naturally-grown fir trees," *Holz Roh Werkst.* 62, 476-478. DOI: 10.1007/s00107-004-0525-7.

Pasta, S., de Rigo, D., and Caudullo, G. (2016). "*Quercus pubescens* in Europe: Distribution, habitat, usage and threats," in: *European Atlas of Forest Tree Species*, J. San-Miguel-Ayanz, D. de Rigo, G. Caudullo, T. Houston Durrant, and A. Mauri (eds.), Publication Office of European Union, Luxembourg, pp. 156-157, ISBN 978-92-76-17290-1. DOI: 10.2760/776635.

Rahayu, I., Darmawan, W., Nugroho, N., Nandika, D., and Marchal, R. (2014). "Demarcation point between juvenile and mature wood in sengon (*Falcataria moluccana*) and jabon (*Antocephalus cadamba*)," *J. Trop. For. Sci.* 26, 331-339.

Rahman, Md. M., Fujiwara, S., and Kanagawa, Y. (2005). "Variations in volume and dimensions of rays and their effect on wood properties of teak," *Wood Fiber Sci.* 37, 497-504.

Reiterer, A., Burgert, I., Sinn, G., and Tschegg, S. (2002). "The radial reinforcement of the wood structure and its implication on mechanical and fracture mechanical properties—A comparison between two tree species," *J. Mater. Sci.* 37, 935-940. DOI: 10.1023/A:1014339612423.

Rulliaty, S. (2008). "Characteristics of juvenile wood in Mangium (*Acacia mangium* Willd.) and its drying qualities," *J. For. Prod. Res.* 26, 117-128. (in Indonesian; Abstract in English)

Santos, J. A., Carvalho, J. P. F., and Santos, J. (2012). "Oak wood," in: *Oak: Ecology, Types and Management*, C. A. Chuteira, and A. B. Grão (eds.), Nova Science Publishers Inc., New York, NY, USA, pp. 119-150, ISBN 978-1-61942-492-0.

Savero, A. M., Kim, J.-H., Purusatama, B. D., Prasetia, D., Wahyudi, I., Iswanto, A. H., Lee, S.-H., Kim, N.-H. (2024). "Radial variation of wood anatomical characteristics and maturation ages of six Korean oak species," *Forests* 15, article 433. DOI: 10.3390/f15030433.

Savero, A. M., Kim, J.-H., Purusatama, B. D., Prasetia, D., Wahyudi, I., Iswanto, A. H., Park, B.-H., Lee, S.-H., and Kim, N.-H. (2023). "Macroscopic and microscopic anatomical characteristics of six Korean oak species," *Forests* 14, article 2449. DOI: 10.3390/f14122449.

Shmulsky, R., and Jones, P. D. (2019). *Forest Products and Wood Science: An Introduction, Seventh Edition*, John Wiley & Sons Ltd, Hoboken, NJ, USA, ISBN 978-1-119-42636-3.

Soheili, F., Abdul-Hamid, H., Almasi, I., Heydari, M., Tongo, A., Woodward, S., and Naji, H.R. (2023). "How tree decline varies the anatomical features in *Quercus brantii*," *Plants* 12, article 377. DOI: 10.3390/plants12020377.

Son, Y., Park, I. H., Yi, M. J., Jin, H. O., Kim, D. Y., Kim, R. H., and Hwang, J. O. (2004). "Biomass, production and nutrient distribution of a natural oak forest in central Korea," *Ecol. Res.*19, 21-28. DOI: 10.1111/j.1440-1703.2003.00617.x.

Sousa, V. B., Cardoso, S., and Pereira, H. (2014). "Age trends in the wood anatomy of *Quercus faginea*," *IAWA J.* 35, 293-306. DOI: 10.1163/22941932-00000067.

Sousa, V. B., Leal, S., Quilhó, T., and Pereira, H. (2009). "Characterization of cork oak (*Quercus suber*) wood anatomy," *IAWA J.* 30, 149-161. DOI: 10.1163/22941932-90000210.

Tsoumis, G. (1991). *Science and Technology of Wood: Structure, Properties, Utilization*, Van Nostrand Reinhold, New York, NY, USA, ISBN 0-442-23985-8.

Tsuchiya, R., and Furukawa, I. (2009). "Radial variation in the size of axial elements in relation to stem increment in *Quercus serrata*," *IAWA J.* 30, 15-26. DOI: 10.1163/22941932-90000199.

Tulik, M. (2014). "The anatomical traits of trunk wood and their relevance to oak (*Quercus robur* L.) vitality," *Eur. J. For. Res.* 133, 845-855. DOI: 10.1007/s10342-014-0801-y.

World Floral Online (WFO). (2024). "*Quercus* L Taxonomy," (http://www.worldfloraonline.org/taxon/wfo-4000032377), accessed 11 May 2024.

Yilmaz, M., Serdar, B., Altun, L., and Usta, A. (2008). "Relationships between environmental variables and wood anatomy of *Quercus pontica* C. Koch (Fagaceae)," *Fresenius Environ. Bull.* 17, 902-910.
Zobel, B. J., and Sprague, J. R. (1998). *Juvenile Wood in Forest Trees*, Springer, Berlin/Heidelberg, Germany, ISBN 978-3-642-72126-7. DOI: 10.1007/978-3-642-72126-7.
Zobel, B. J., and van Buijtenen, J. P. (1989). *Wood Variation: Its Causes and Control*, Springer, Berlin/Heidelberg, Germany, ISBN 978-3-642-74069-5. DOI: 10.1007/978-3-642-74069-5.

Article submitted: June 4, 2024; Peer review completed: June 30, 2024; Revised version received: August 1, 2024; Accepted: August 2, 2024; Published: August 12, 2024.
DOI: 10.15376/biores.19.4.7102-7119