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Macroscopic and Microscopic Anatomical Characteristics of Six Korean Oak Species

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Abstract: The macroscopic and microscopic anatomical characteristics of wood impact its utilization. This study investigated and compared the anatomical characteristics of six Korean oak wood species: *Quercus variabilis*, *Quercus serrata*, *Quercus mongolica*, *Quercus dentata*, *Quercus aliena*, and *Quercus acutissima*. Microscopic anatomical characteristics were evaluated according to the International Association of Wood Anatomists' list for hardwood identification. *Q. variabilis* had a corky bark texture, with a color similar to that of *Q. serrata*. Flat ridges and shallow-fissured barks were observed in *Q. serrata* and *Q. mongolica*. The heartwood color was darker than that of sapwood in all species, with color variations. *Q. variabilis* had heartwood–sapwood colors similar to those of *Q. acutissima*, while *Q. mongolica* and *Q. aliena* presented similar heartwood–sapwood colors. Concerning microscopic features, *Q. variabilis* and *Q. acutissima* exhibited similar latewood vessel arrangements, featuring diagonal and/or radial patterns. In contrast, dendritic-to-diagonal patterns of vessels with angular outlines were observed in *Q. serrata*, *Q. mongolica*, *Q. dentata*, and *Q. aliena*. Additionally, *Q. variabilis* and *Q. acutissima* had vasicentric, confluent, and unilateral paratracheal axial parenchyma in the latewood. In summary, bark morphology, bark color, wood color, and latewood vessel characteristics can be used as identification keys for Korean oak species.

Keywords: Korean oak species; macroscopic anatomical characteristics; microscopic anatomical characteristics; wood identification

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1. Introduction

Oak species (*Quercus* spp.) are widely distributed in North America, Europe, Africa, and Asia [1]. In the United States, these species are commonly used as sawn wood in furniture, flooring, framing, and railway ties [2]. In Europe, oak wood is widely used in industrial lumber, railway sleepers, carpentry, boat buildings, packaging, and firewood [3]. This wide range of applications can be attributed to the beautiful figure, excellent mechanical properties, and natural durability of oak [4].

According to the Korea Forest Service [5], Korea has a total land area of 10,043,185 ha with forests covering 6,348,834 ha. These forests are predominantly composed of pine species (*Pinus* spp.) for softwood and oak species (*Quercus* spp.) for hardwood. Thus, Korea has abundant oak resources. Oak tree species cover a forest area of 1,037,650 ha, with a total growing stock of 159,261,862 m^3. Korea is home to six major oak species: *Quercus variabilis*, *Quercus serrata*, *Quercus mongolica*, *Quercus dentata*, *Quercus aliena*, and *Quercus acutissima* [6].

Understanding the macroscopic and microscopic anatomical characteristics of wood is crucial to ensure its quality and optimize the utilization of this valuable resource [7]. Macroscopic anatomical characteristics are recognized as reliable scientific methods for wood identification, offering a fast, cost-effective, and easy-to-apply approach [8].

Several studies have reported on the anatomical characteristics of Oriental oak species. Oh [9] compared the relationship between the anatomical characteristics and bending strength of *Quercus* spp. wood from Korea. Tsuchiya and Furukawa [10] examined the radial variation in axial element size in *Q. serrata* wood from Japan. Eom et al. [11] examined the anatomical characteristics of *Quercus* wood in Korea. Recently, Jeon et al. [12] compared the anatomical characteristics of oak-wilt-damaged *Q. mongolica* wood in South Korea. Wang et al. [13] compared the anatomical characteristics of *Q. acutissima* and *Q. variabilis* from China.

However, to date, there is a lack of comparative studies of the macroscopic and microscopic anatomical characteristics of the six Korean oak species. Therefore, this study aimed to investigate and compare the macroscopic and microscopic anatomical characteristics of the six Korean oak wood species to provide identification keys and quality indices for the effective utilization of these species.

2. Materials and Methods

2.1. Materials

Three trees of each of the six oak wood species were harvested from the research forest of Kangwon National University, Chuncheon, Korea (37°47′2.8932″ N, 127°49′13.368″ E). The disks were extracted at a height of 1.30 m above the ground (diameter at breast height). The bark and wood samples were air-dried at 22 ± 5 °C and a relative humidity of 65 ± 5% until the moisture content reached 12%. Fundamental information on the sampled trees is presented in Table 1.

Table 1. The fundamental information of six Korean oak wood species.

Trade Name	Scientific Name	Diameter (cm) *	Age (Years) *
Oriental Cork Oak	*Quercus variabilis* Blume	24.9 (3.9)	63 (1.5)
Jolcham Oak	*Quercus serrata* Murray	26.7 (3.5)	72 (19.7)
Mongolian Oak	*Quercus mongolica* Fisch. ex Ledeb	23.1 (1.9)	64 (1.0)
Korean Oak	*Quercus dentata* Thunb.	22.2 (1.3)	73 (8.3)
Oriental White Oak	*Quercus aliena* Blume	20.4 (4.3)	48 (3.2)
Sawtooth Oak	*Quercus acutissima* Carruth.	21.7 (4.6)	48 (0.0)

Note: * Diameter and age are the averages of three trees, and the numbers in parentheses represent the standard deviations.

2.2. Methods

2.2.1. Macroscopic Characteristics

Macroscopic anatomical characteristics were observed on the transverse surfaces of the wooden disks. The surfaces were initially sanded using a sanding machine (TW/BD-46, 2070 rpm, 450 W; Rexon Industrial Corp., Ltd., Taichung, Taiwan) equipped with coarse-grit sandpaper (XA167; Deerfos Co., Ltd., Incheon, Republic of Korea). Subsequently, they were manually sanded using fine-grit sandpaper (CC-600 Cw; Daesung Abrasive Co., Ltd., Seoul, Republic of Korea). Images of the transverse surfaces and barks were captured using a mobile phone (iPhone 14 Pro; Apple Inc., Cupertino, CA, USA).

The growth ring width and latewood percentage was measured with a scale loupe (10× magnification, Peak, Tohkai Sangyo Co. Ltd., Tokyo, Japan) from pith to bark in four directions of each disk. The latewood percentage was calculated using the following equation:

$$\text{Latewood Percentage } (\%) = \left(\frac{\text{Latewood width (mm)}}{\text{Growth ring width (mm)}}\right) \times 100$$

Wood–bark proportions and heartwood–sapwood proportions were directly measured using a ruler in four directions for each disk. Furthermore, the bark and wood surface colors were examined with the naked eye and a colorimeter (CR-10 Plus, Φ8 mm, Konica Minolta Inc., Osaka, Japan). The CIELab system was employed to calculate the color parameters, which measure the bark and wood color using a trio of spatial coordinates: L*, a*, and b*. In this context, L* signifies the brightness and measures the point along the black-to-white spectrum (with L = 0 denoting black and L = 100 representing white). Meanwhile, a* denotes chroma and indicates the location on the red-to-green scale (with +100 values indicating red tones and −100 values indicating green tones). Lastly, b* also represents chroma, marking the position on the yellow-to-blue spectrum (with +100 values indicating yellow tones and −100 values indicating blue tones) [14].

2.2.2. Microscopic Characteristics

Microscopic anatomical characteristics were observed using wood block specimens measuring $10 \times 10 \times 10$ mm^3 taken from the sapwood with growth rings aged 40–45 years old for each species. The specimens were softened via boiling in a 50:50 mixture of glycerin and water for 12 h. Slices with a thickness of 15–20 µm in cross, tangential, and radial surfaces were obtained using a sliding microtome (Lab microtome, Swiss Federal Research Institute WSL, Birmensdorf, Switzerland). The slices were stained with 1% safranin and light-green solutions, followed by a series of dehydration reactions using graded alcohol (50%, 70%, 90%, 95%, and 99%) and xylene. Permanent slides were prepared using Canada balsam.

Qualitative anatomical characteristics were examined using an optical microscope (Eclipse E600, Nikon Corp., Tokyo, Japan) connected to an image analysis system (i-Solution Lite, IMT i-Solution Inc., Burnaby, BC, Canada) and evaluated following the International Association of Wood Anatomists (IAWA) list of microscopic features for hardwood identification [15].

2.2.3. Data Analysis

The relationships between bark and wood color, heartwood–sapwood proportions, wood–bark proportions, growth ring width, and latewood percentages between species were analyzed using a one-way analysis of variance. Subsequently, Duncan's test was conducted as a post hoc verification of the analysis of variance test, with the significance level set at 5%. All statistical analyses were performed using SPSS version 26 (IBM Corp., Armonk, NY, USA).

3. Results and Discussion

3.1. Macroscopic Characteristics

3.1.1. Bark Morphology and Color

The bark surfaces of the six Korean oak species are shown in Figure 1. All the species exhibited ridged bark surfaces. *Q. variabilis* had corky, intersecting ridges with round shapes and deep-fissured bark with a greyish-white color on the surface. *Q. serrata* had hard, intersecting ridges with flat and round shapes and shallow-to-deep-fissured bark; the flat surface was greyish-white, whereas the round surface ranged from dark grey to greyish-brown. The bark surface of *Q. mongolica* displayed hard, intersecting ridges with flat and hollow shapes and shallow-to-deep-fissured bark with a color ranging from light greyish-brown to dark brown. *Q. dentata* had hard, intersecting ridges with round shapes and deep-fissured bark with a dark greyish-brown-to-dark-brown bark surface. *Q. aliena* exhibited a bark surface similar to that of *Q. dentata* but with colors ranging from yellowish-white to dark brown. The bark surface of *Q. acutissima* featured hard, intersecting ridges with round shapes and shallow-to-deep-fissured bark with a yellowish-brown-to-dark brown color range.

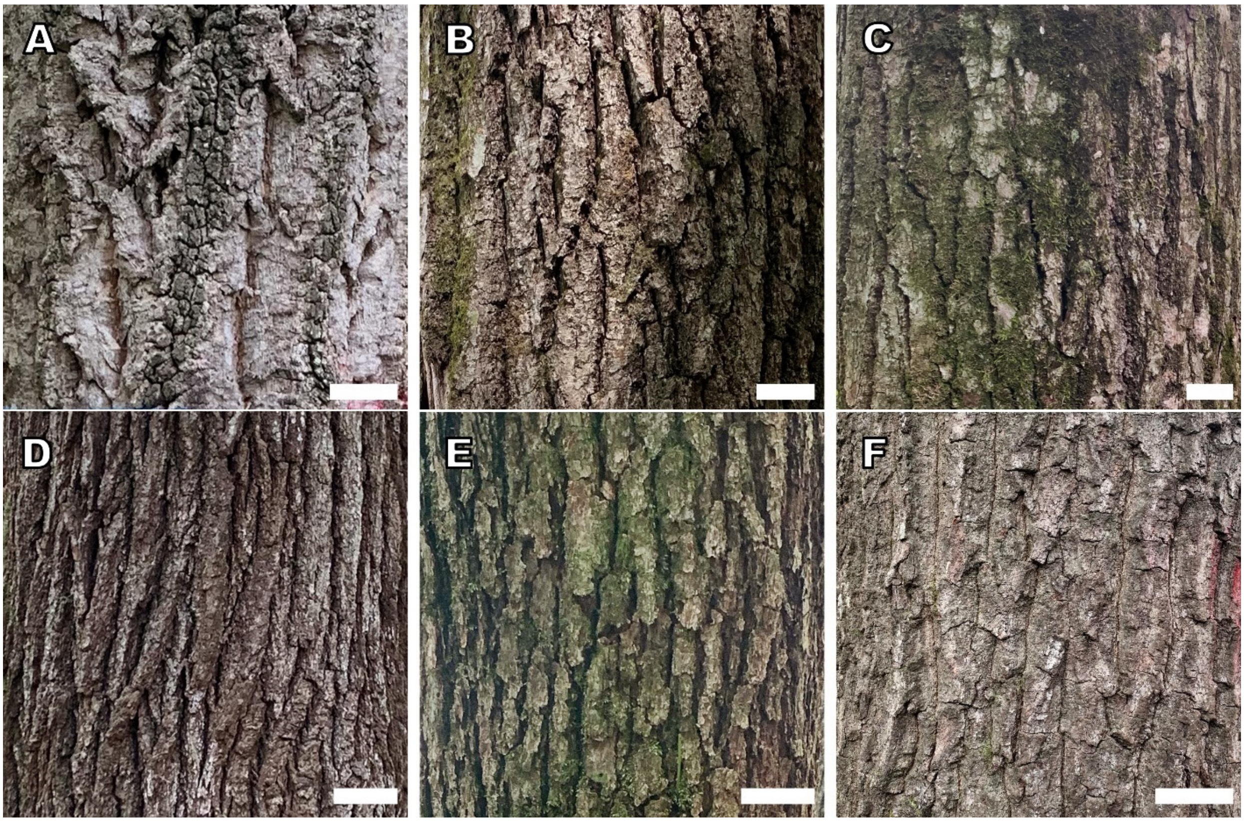


Figure 1. Bark surfaces of (**A**) *Q. variabilis*, (**B**) *Q. serrata*, (**C**) *Q. mongolica*, (**D**) *Q. dentata*, (**E**) *Q. aliena*, and (**F**) *Q. acutissima*. Scale bar: 5 cm.

Table 2 presents the average and standard deviation values of the CIELab color parameters for the bark of six Korean oak species. All species displayed positive values for color parameters, indicating that the bark color of these species was a combination of whiteness (lightness), redness, and yellowness. The L* color parameters for *Q. variabilis*, *Q. serrata*, *Q. mongolica*, *Q. dentata*, *Q. aliena*, and *Q. acutissima* were 43.37, 45.06, 38.77, 33.48, 37.60, and 33.71, respectively. *Q. variabilis* and *Q. serrata* exhibited significantly higher L* values, whereas *Q. dentata* and *Q. acutissima* exhibited significantly lower L*values. There was no significant difference between *Q. variabilis* and *Q. serrata* or between *Q. dentata* and *Q. acutissima*, indicating that *Q. variabilis* and *Q. serrata* had the brightest color, whereas *Q. dentata* and *Q. acutissima* had the darkest color on their bark surfaces.

Table 2. Bark color parameters of six Korean oak species using the CIELab system.

Color Parameter	Species					
	Q. variabilis	***Q. serrata***	***Q. mongolica***	***Q. dentata***	***Q. aliena***	***Q. acutissima***
L*	43.37 [a] (3.33)	45.06 [a] (10.40)	38.77 [b] (4.25)	33.48 [c] (2.04)	37.60 [b] (3.83)	33.71 [c] (2.75)
a*	4.45 [ab] (1.14)	3.62 [a] (1.99)	5.13 [b] (1.44)	6.07 [c] (1.27)	7.66 [d] (1.08)	4.19 [ab] (1.59)
b*	9.87 [ab] (1.50)	9.91 [ab] (1.52)	11.50 [c] (1.42)	10.70 [bc] (1.15)	13.05 [d] (1.53)	9.05 [a] (1.50)

Note: The results are the averages of three trees. Numbers in parentheses are standard deviations. The same superscript letters beside the mean values within columns denote non-significant outcomes at the 5% significance level, using Duncan's test for comparisons between species.

The a* values varied between the oak species: *Q. variabilis*, 4.45; *Q. serrata*, 3.62; *Q. mongolica*, 5.13; *Q. dentata*, 6.07; *Q. aliena*, 7.66; and *Q. acutissima*, 4.19. A significantly higher value of a* was observed for *Q. aliena*, while the lowest was observed for *Q. serrata*. However, *Q. serrata* exhibited no significant differences between *Q. variabilis* and *Q. acutissima*.

The b* values of *Q. variabilis*, *Q. serrata*, *Q. mongolica*, *Q. dentata*, *Q. aliena*, and *Q. acutissima* were 9.87, 9.91, 11.50, 10.70, 13.05, and 9.05, respectively. *Q. aliena* exhibited a significantly higher b* value, whereas *Q. acutissima* exhibited a significantly lower b *value than that of the other species. However, there were no significant differences between *Q. acutissima*, *Q. variabilis*, and *Q. serrata*.

For bark morphology and color, Zhou [16] reported that *Q. variabilis* from China had deeply cracked bark with a greyish-white color. Junikka [17] and Savero et al. [18] reported that bark morphology and color can be used for reliable and rapid identification. Thus, the results of bark morphology and color can be utilized as identification keys to distinguish between these six Korean oak species.

3.1.2. Wood Color

The transverse surfaces of the wood disks from the six Korean oak species are shown in Figure 2. The heartwood and sapwood of all species were distinguishable in color. *Q. variabilis* and *Q. acutissima* presented similar heartwood–sapwood colors, displaying dark reddish-brown heartwood and creamy-to-reddish-white sapwood. However, *Q. variabilis* had a darker heartwood color than *Q. acutissima*. *Q. mongolica* and *Q. aliena* exhibited similar colors, with greyish to greenish-brown heartwood and creamy to yellowish-white sapwood. However, the heartwood of *Q. aliena* was darker than that of *Q. mongolica*. *Q. serrata* displayed greyish-to-olive-brown heartwood and creamy-to-pale white sapwood. *Q. dentata* displayed golden-to-olive-brown heartwood and creamy-to-yellowish-white sapwood.

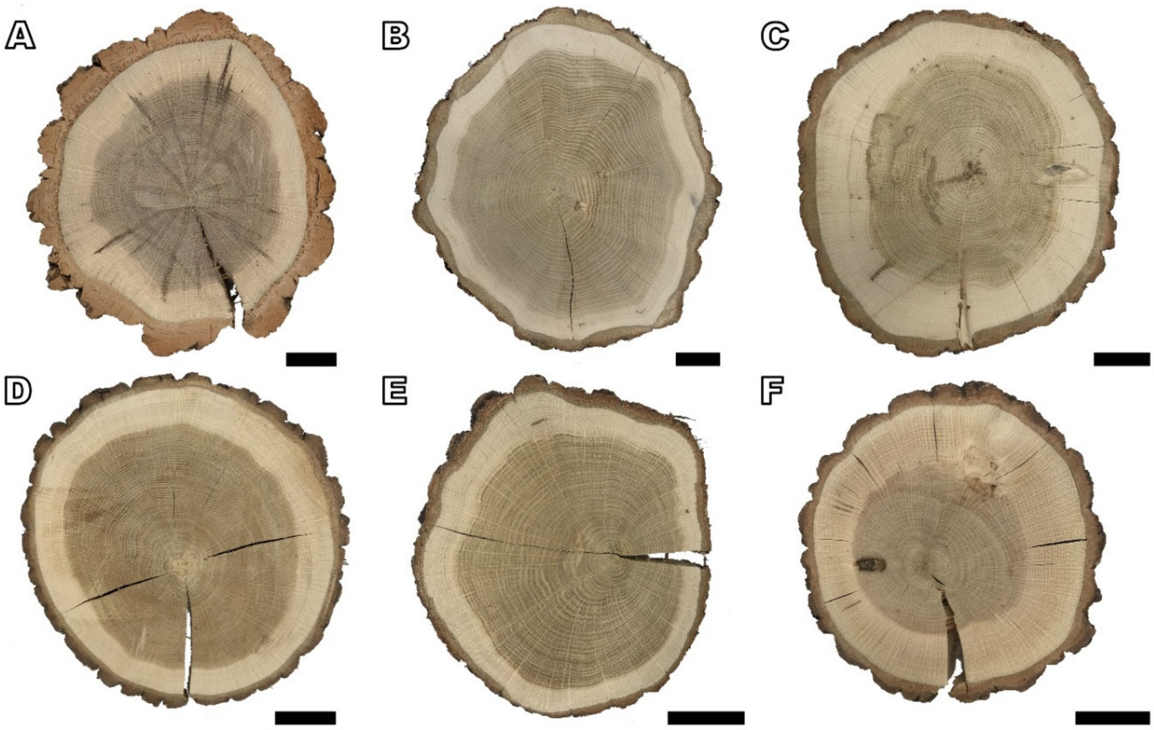


Figure 2. Wood disks of (**A**) *Q. variabilis*, (**B**) *Q. serrata*, (**C**) *Q. mongolica*, (**D**) *Q. dentata*, (**E**) *Q. aliena*, and (**F**) *Q. acutissima*. Scale bar: 5 cm.

The CIELab color parameters of the heartwood and sapwood of six Korean oak species are presented in Table 3. Similar to the bark color parameters, heartwood and sapwood colors exhibited positive values in all species. The heartwood and sapwood L* values differed across various oak species, with averages of 56.92 and 67.78 for *Q. variabilis*, 62.19 and 74.67 for *Q. serrata*, 59.21 and 72.56 for *Q. mongolica*, 55.06 and 69.57 for *Q. dentata*, 58.44 and 71.88 for *Q. aliena*, and 58.70 and 67.31 for *Q. acutissima*. The heartwood and sapwood of *Q. serrata* exhibited significantly higher L* values, whereas *Q. dentata* had significantly lower values, and *Q. acutissima* had the lowest values for sapwood. The sapwood of *Q. acutissima* did not significantly differ from that of *Q. variabilis*.

Table 3. Heartwood and sapwood color parameters of six Korean oak species devised using the CIELab system.

Wood	Color Parameter	Species					
		Q. variabilis	*Q. serrata*	*Q. mongolica*	*Q. dentata*	*Q. aliena*	*Q. acutissima*
Heartwood	L*	56.92 ^{a} (1.53)	62.19 ^{b} (2.14)	59.21 ^{c} (3.87)	55.06 ^{d} (2.53)	58.44 ^{c} (2.56)	58.70 ^{c} (1.96)
	a*	7.88 ^{a} (1.04)	6.29 ^{b} (0.66)	6.41 ^{b*} (0.37)	7.93 ^{a} (0.71)	6.57 ^{b} (0.46)	7.95 ^{a} (0.92)
	b*	12.37 ^{a} (1.33)	14.92 ^{b*} (1.02)	16.04 ^{c} (1.22)	16.57 ^{c*} (1.52)	16.59 ^{c*} (2.13)	13.01 ^{a} (0.68)
Sapwood	L*	67.78 ^{a} (1.95)	74.67 ^{b} (2.19)	72.56 ^{c} (3.22)	69.57 ^{d} (2.46)	71.88 ^{c} (2.01)	67.31 ^{a} (2.49)
	a*	8.94 ^{a} (0.66)	5.51 ^{b} (0.47)	6.20 ^{c*} (0.72)	6.45 ^{c} (0.50)	5.65 ^{b} (0.46)	9.19 ^{a} (1.44)
	b*	16.24 ^{a} (1.14)	14.88 ^{b*} (0.89)	15.24 ^{b} (1.27)	16.52 ^{a*} (0.84)	16.15 ^{a*} (1.09)	16.42 ^{a} (1.29)

Note: The results are the averages of three trees. The numbers in parentheses are standard deviations. The same superscript letters and asterisks beside the mean values within columns denote non-significant outcomes at the 5% significance level, using Duncan's test for comparisons between species and non-significant outcomes at the 5% significance level and the analysis of variance test for comparisons between heartwood and sapwood, respectively.

The a* values of heartwood and sapwood varied between the different oak species: *Q. variabilis*, 7.88 and 8.94; *Q. serrata*, 6.29 and 5.51; *Q. mongolica*, 6.41 and 6.20; *Q. dentata*, 7.93 and 6.45; *Q. aliena*, 6.57 and 5.65; and *Q. acutissima*, 7.95 and 9.19. *Q. acutissima* showed significantly higher a* values in both heartwood and sapwood, whereas *Q. serrata* had the lowest values. In the heartwood, the a* values of *Q. serrata* did not significantly differ from those of *Q. mongolica* and *Q. aliena*. Additionally, in the sapwood, *Q. serrata* showed no significant difference from *Q. aliena*. The a* value of *Q. mongolica* did not differ significantly between the heartwood and sapwood.

The b* values of heartwood and sapwood were 12.37 and 16.24 for *Q. variabilis*, 14.92 and 14.88 for *Q. serrata*, 16.04 and 15.24 for *Q. mongolica*, 16.57 and 16.52 for *Q. dentata*, 16.59 and 16.15 for *Q. aliena*, and 13.01 and 16.42 for *Q. acutissima*. The heartwood b* values were significantly higher in *Q. aliena*, whereas the sapwood b* values were significantly higher in *Q. dentata*. However, the heartwood of *Q. aliena* did not significantly differ from *Q. mongolica* and *Q. dentata*, and this was also true for the sapwood of *Q. dentata*, *Q. variabilis*, *Q. aliena*, and *Q. acutissima*. In addition, the heartwood b* values of *Q. serrata*, *Q. dentata*, and *Q. aliena* did not significantly differ from the sapwood b* values.

The CIELab color parameters exhibited similar color values between *Q. variabilis* and *Q. acutissima* and between *Q. mongolica* and *Q. aliena*. Naked-eye observation confirmed these results. The heartwood colors of *Q. variabilis* and *Q. acutissima* in this study were consistent with those reported by Wang et al. [13], who described a light reddish-brown color. In addition, Vetter et al. [19], Wheeler and Baas [20], and Bernal et al. [21] reported that wood color is an important characteristic for species identification. Therefore, the wood color results of this study may be useful for the identification of these six Korean oak species.

3.1.3. Heartwood–Sapwood Proportion

The heartwood–sapwood proportions of the six Korean oak species are shown in Figure 3. The heartwood and sapwood portions differed between the various oak species, with averages of 69.94% and 30.06% for *Q. variabilis*, 85.47% and 14.53% for *Q. serrata*, 79.51% and 20.49% for *Q. mongolica*, 80.13% and 19.87% for *Q. dentata*, 76.78% and 23.22% for *Q. aliena*, and 64.58% and 35.42% for *Q. acutissima*. *Q. serrata* exhibited a significantly higher proportion of heartwood, whereas *Q. acutissima* exhibited the lowest proportion.

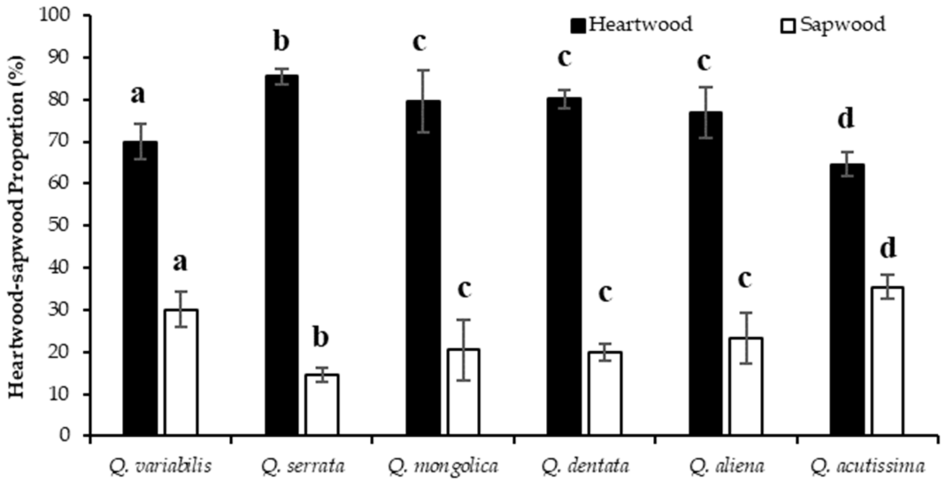


Figure 3. Heartwood–sapwood proportion of six Korean oak species. The results are the averages of three trees. The same superscript letters on the columnar top denote non-significant outcomes at the 5% significance level, using Duncan's test for comparisons between species.

Arisandi et al. [22] reported that the heartwood proportion is directly influenced by tree variations (position in the tree, age, growth rate, and species), growing conditions (location and environmental factors), and silvicultural treatments (spacing, thinning, pruning, fertilization, and irrigation). Moreover, tree variations have a greater impact on the heartwood proportion than environmental conditions, and the heartwood proportion is more affected by wood species than age. According to Savero et al. [23], heartwood proportion is indicative of wood durability, with a higher proportion of heartwood indicating greater durability and, consequently, a longer service life. Natural variations in heartwood proportions are influenced by both species and tree age.

3.1.4. Wood-Bark Proportion

Figure 4 shows the wood–bark proportion of six Korean oak species. The average proportions of wood, inner bark, and outer bark of these species were 82.64%, 5.87%, and 11.48% for *Q. variabilis*; 90.83%, 5.08%, and 4.09% for *Q. serrata*; 90.29%, 5.92%, and 3.79% for *Q. mongolica*; 90.29%, 4.15%, and 5.57% for *Q. dentata*; 91.79%, 3.02%, and 5.20% for *Q. aliena*; and 89.97%, 5.93%, and 4.10% for *Q. acutissima*, respectively. The wood and outer bark proportions of *Q. variabilis* were significantly higher than those of the other species. The largest outer bark portion of *Q. variabilis* was due to its thick cork layer. In the inner bark, *Q. aliena* had a significantly lower proportion than the other species. Additionally, *Q. serrata*, *Q. mongolica*, *Q. dentata*, *Q. aliena*, and *Q. acutissima* showed no significant differences in wood portions.

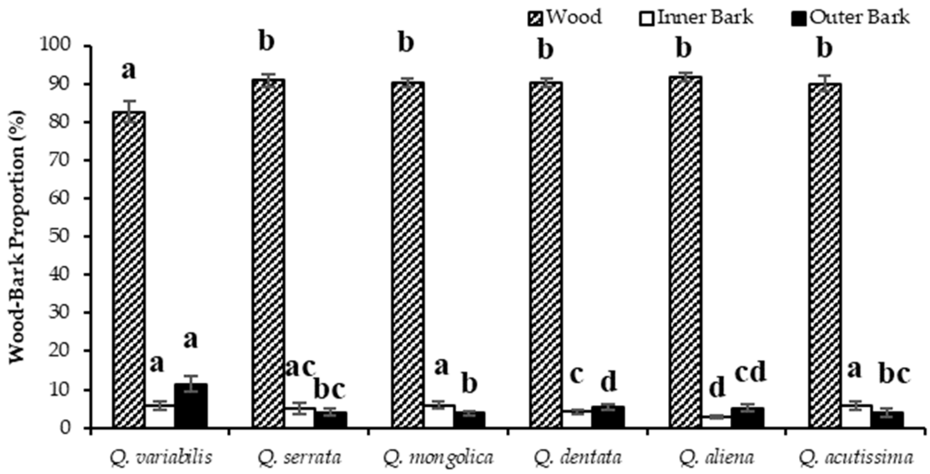
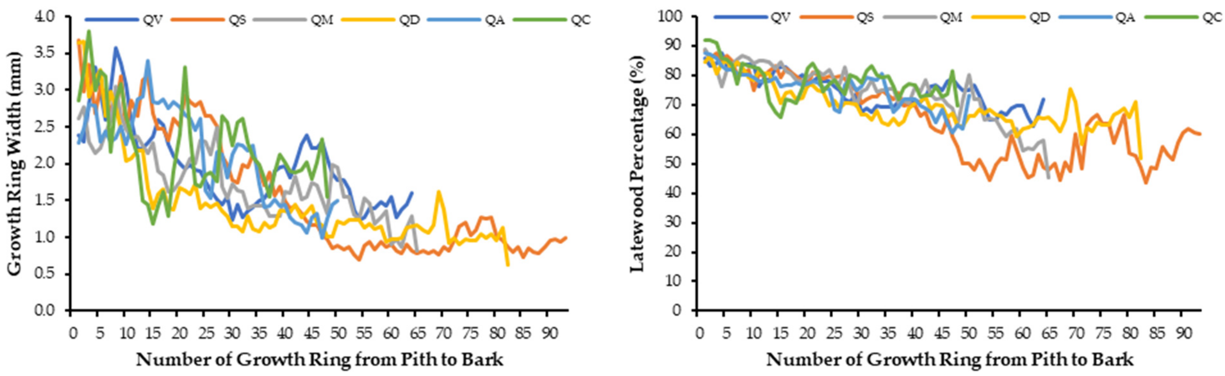


Figure 4. Wood–bark proportion of six Korean oak species. The results are the averages of three trees. The same superscript letters on the columnar top denote non-significant outcomes at the 5% significance level, using Duncan's test for comparisons between species.

3.1.5. Growth Ring Width and Latewood Percentage

The growth ring widths of all the species exhibited similar patterns, as shown in Figure 5A. They increased sharply in the first five growth rings and then gradually decreased, eventually stabilizing near the bark.



(**A**) (**B**)

Figure 5. Radial variation in (**A**) growth ring width and (**B**) latewood percentage of *Q. variabilis* (QV), *Q. serrata* (QS), *Q. mongolica* (QM), *Q. dentata* (QD), *Q. aliena* (QA), and *Q. acutissima* (QC). The results are the averages of three trees.

Growth ring width varied among the different oak species, as shown in Table 4. *Q. variabilis* was 1.98 mm, *Q. serrata* was 1.62 mm, *Q. mongolica* was 1.77 mm, *Q. dentata* was 1.47 mm, *Q. aliena* was 2.10 mm, and *Q. acutissima* was 2.20 mm. *Q. acutissima* had a significantly wider growth ring than the other species, while *Q. dentata* had the narrowest growth ring. Nevertheless, there was no significant difference in growth ring width between *Q. acutissima*, *Q. variabilis*, and *Q. aliena* or between *Q. dentata* and *Q. serrata*.

The percentage of latewood in all species followed a similar pattern, as illustrated in Figure 5B, with a slight decrease from the pith to the bark. The latewood percentages of *Q. variabilis*, *Q. serrata*, *Q. mongolica*, *Q. dentata*, *Q. aliena*, and *Q. acutissima* were 75.01%, 65.10%, 74.13%, 69.63%, 75.11%, and 78.16%, respectively (Table 4). A significantly greater percentage of latewood was found in *Q. acutissima*, whereas *Q. serrata* exhibited a significantly smaller percentage. No significant differences were observed between *Q. acutissima*, *Q. variabilis*, and *Q. aliena*.

Table 4. Growth ring widths and latewood percentages of six Korean oak species.

Parameter	Species					
	Q. variabilis	*Q. serrata*	*Q. mongolica*	*Q. dentata*	*Q. aliena*	*Q. acutissima*
Growth ring width (mm)	1.98 ^{ab} (0.57)	1.62 ^{bc} (0.85)	1.77 ^{b} (0.50)	1.47 ^{c} (0.64)	2.10 ^{a} (0.63)	2.20 ^{a} (0.60)
Latewood percentage (%)	75.01 ^{ac} (6.13)	65.10 ^{b} (13.23)	74.13 ^{c} (9.54)	69.63 ^{d} (7.11)	75.11 ^{ac} (6.44)	78.16 ^{a} (5.96)

Note: The results are the averages of three trees. The numbers in parentheses are standard deviations. The same superscript letters beside the mean values within columns denote non-significant outcomes at the 5% significance level, using Duncan's test for comparisons between species.

These findings were consistent with Wang et al. [13], who reported similar radial variations in the growth ring width and latewood percentage in *Q. variabilis* and *Q. acutissima* from China. Additionally, Ivković et al. [24] and Zubizarreta-Gerendiain et al. [25] reported that growth ring width is influenced by cambial age and climate. The growth ring width decreases with increasing age and has a positive correlation with rainfall and temperature. Moreover, the growth ring width affects wood density. According to Zhang [26] and Sousa et al. [27], the growth ring and latewood percentages of European oak wood can affect wood density. Konukcu et al. [28] found that a higher percentage of latewood in American red oak resulted in better mechanical properties (fracture toughness) than in southern yellow pine.

3.2. Microscopic Characteristics

3.2.1. Cross-Section

Optical micrographs of the cross-sections of the six Korean oak species are shown in Figure 6. All species exhibited distinct growth ring boundaries composed of ring porous wood with solitary vessels. Tyloses were present in the vessels of all species. Regarding the arrangement of the latewood vessels, *Q. variabilis* and *Q. acutissima* displayed a similar diagonal pattern, whereas *Q. serrata*, *Q. mongolica*, *Q. dentata*, and *Q. aliena* exhibited diagonal-to-dendritic patterns with an angular outline of solitary vessels. The axial parenchyma arrangements in all the species were classed as diffuse, diffuse-in-aggregates, and narrow bands. *Q. variabilis* and *Q. acutissima* displayed vasicentric, confluent, and unilateral paratracheal axial parenchyma.

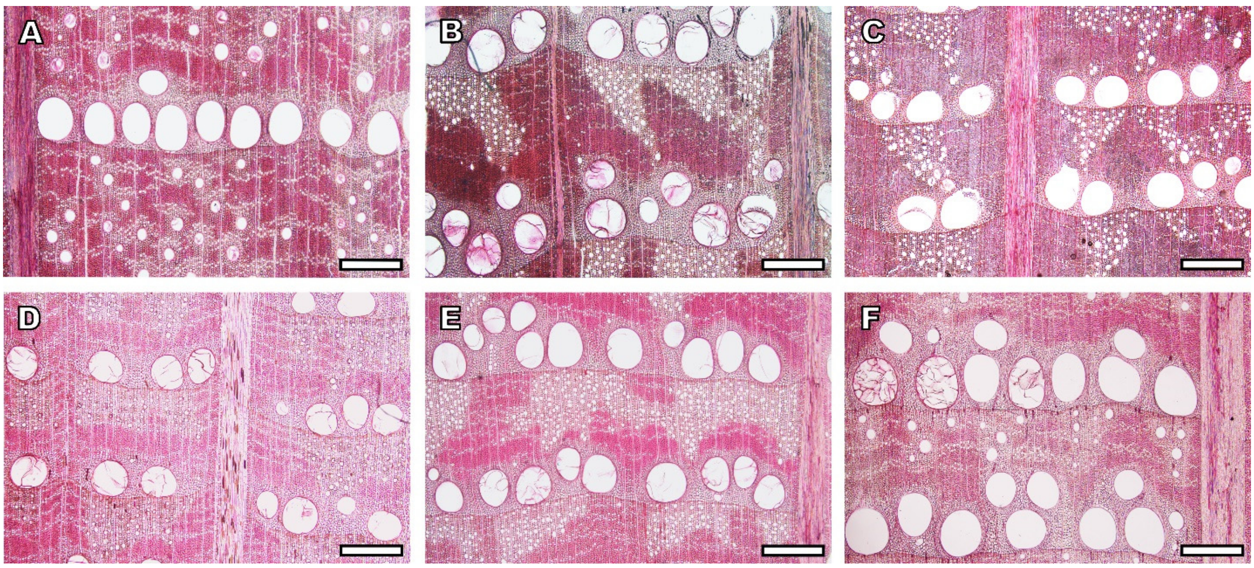


Figure 6. Optical micrographs of the cross-sections of (**A**) *Q. variabilis*, (**B**) *Q. serrata*, (**C**) *Q. mongolica*, (**D**) *Q. dentata*, (**E**) *Q. aliena*, and (**F**) *Q. acutissima*. Scale bar: 500 µm.

Eom [11] reported that *Quercus* spp. from Korea exhibits distinct growth ring boundaries with ring-porous wood. The vessels were exclusively solitary, and tyloses were observed in the vessels of all species. *Q. variabilis* and *Q. acutissima* exhibited a diagonal pattern of latewood vessel arrangement, whereas *Q. serrata*, *Q. mongolica*, *Q. dentata*, and *Q. aliena* exhibited diagonal-to-dendritic patterns. The axial parenchyma in all species was diffuse, with diffuse-in-aggregates and narrow bands. Similarly, Wang et al. [13] reported that *Q. variabilis* and *Q. acutissima* from China have ring-porous wood with distinct growth in ring boundaries. These two species exclusively have solitary vessels arranged in radial or diagonal patterns, and tyloses are abundant in the heartwood vessels.

The six Korean oak species exhibited differences in latewood vessel arrangement, solitary vessel outlines, and paratracheal axial parenchyma. Thus, these parameters could be used as identification keys for these species.

3.2.2. Radial Section

Figure 7 displays an optical micrograph of the radial sections for all species, showing similar characteristics. The rays consisted entirely of procumbent ray cells, and the perforation plates were simple. The vessel ray pits had much-reduced borders to apparently simple (pits ranged from rounded to angular or horizontal to vertical). Vasicentric tracheids were found near the earlywood vessels. In addition, all species contained prismatic crystals in their axial parenchyma, procumbent rays, and enlarged cells.

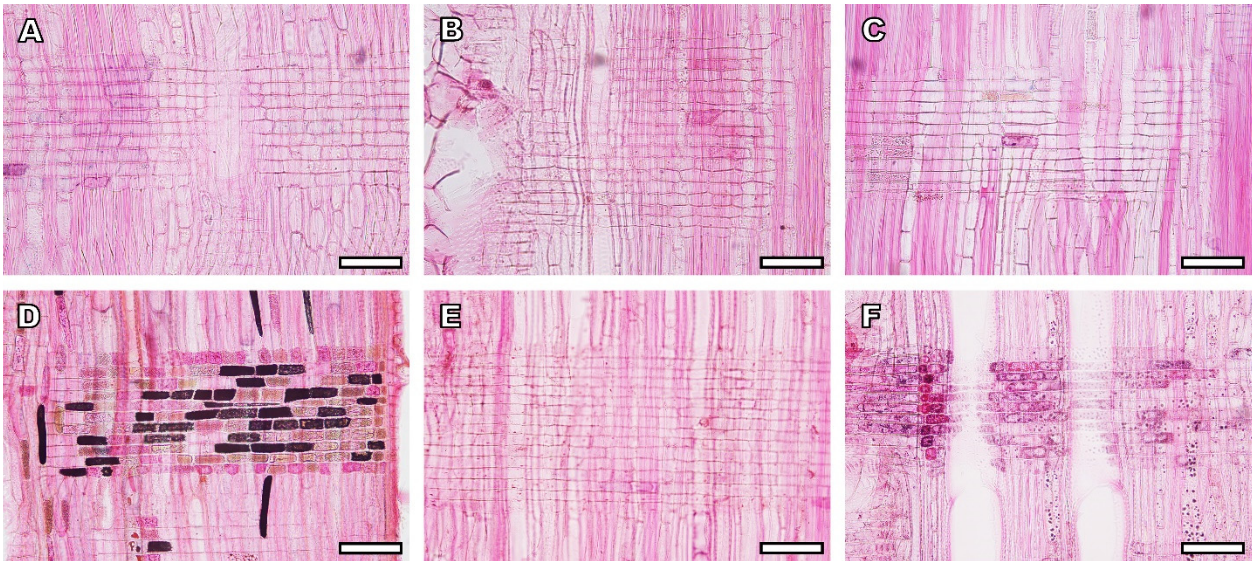


Figure 7. Optical micrographs of the radial sections of (**A**) *Q. variabilis*, (**B**) *Q. serrata*, (**C**) *Q. mongolica*, (**D**) *Q. dentata*, (**E**) *Q. aliena*, and (**F**) *Q. acutissima*. Scale bar: 100 µm.

Eom et al. [11] reported that *Quercus* spp. in Korea have simple perforation plates. The rays were composed of procumbent cells. Vessel ray pitting was much-reduced borders to apparently simple pits (pits rounded to angular or horizontal to vertical). Prismatic crystals were observed in the chambered axial parenchyma and ray cells.

3.2.3. Tangential Section

In the tangential sections, all species exhibited similar characteristics, as shown in Figure 8. The rays were of two distinct sizes: uniseriate and multiseriate. The larger rays typically consisted of more than 10 seriate cells and had heights exceeding 1 mm. Non-septate fibers with simple-to-minutely bordered pits were observed. Furthermore, all species displayed alternate intervessel pits.

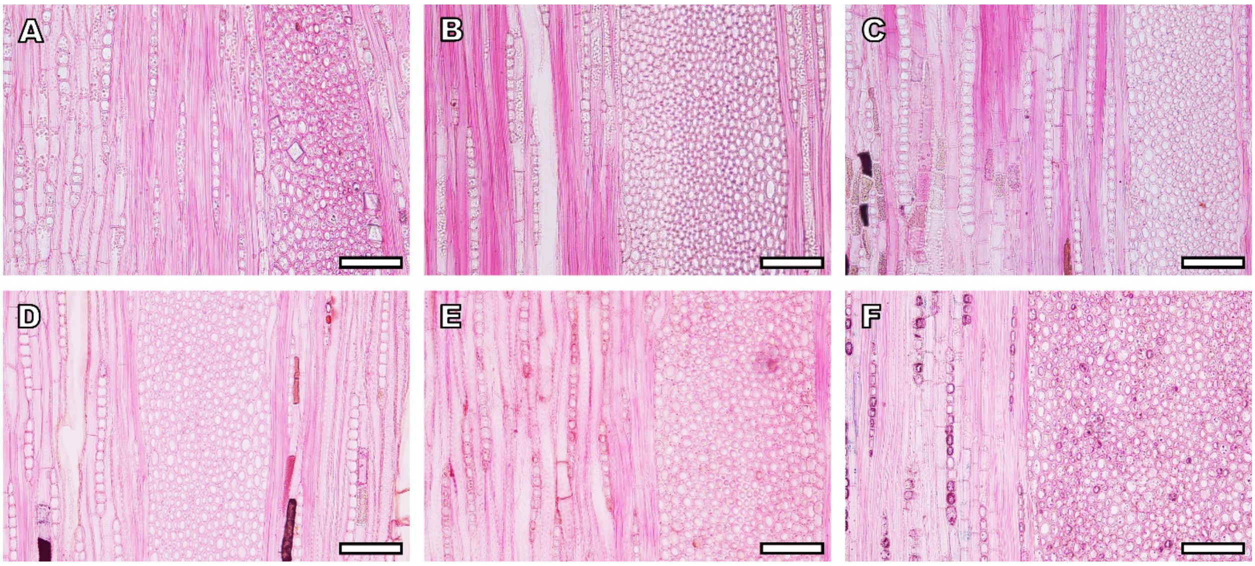


Figure 8. Optical micrographs of the tangential sections of (**A**) *Q. variabilis*, (**B**) *Q. serrata*, (**C**) *Q. mongolica*, (**D**) *Q. dentata*, (**E**) *Q. aliena*, and (**F**) *Q. acutissima*. Scale bar: 100 µm.

According to Eom [11], *Quercus* spp. exhibited alternate intervessel pits, with all species exhibiting two distinct ray sizes and the fibers being non-septate with simple-to-minutely bordered pits.

3.3. Summary of Anatomical Characteristics

The anatomical characteristics of the six Korean oak wood species based on the IAWA feature lists are presented in Table 5.

Table 5. The anatomical characteristics of six Korean oak wood species based on IAWA feature lists.

Parameter	Species					
	Q. variabilis	*Q. serrata*	*Q. mongolica*	*Q. dentata*	*Q. aliena*	*Q. acutissima*
Growth ring	Distinct (1)					
Porosity	Wood ring-porous (3)					
* Latewood vessel arrangement	**Diagonal** pattern (7)	**Dendritic** pattern (8)				**Diagonal** pattern (7)
* Latewood solitary vessel outline	**Round**	**Angular** (12)				**Round**
Vessel groupings	Exclusively solitary (9)					
Perforation plates	Simple (13)					
Intervessel pits	Alternate (22)					
Vestured pits	Absent					
Vessel-ray pitting	Much reduced borders, pits rounded or angular (31), pits horizontal (scalariform, gash-like) to vertical (palisade) (32)					
Tyloses	Present (56)					
Tracheids	Vasicentric tracheids are present (60)					
Fibers pits	Simple to minutely bordered pits (61)					
Septate fibers	Non-septate (66)					
Apotracheal axial parenchyma	Diffuse (76) and diffuse-in-aggregates (77)					
* Paratracheal axial parenchyma in latewood	**Vasicentric** (79), **confluent** (83), and **unilateral paratracheal** (84)	**Absent**				**Vasicentric** (79), **confluent** (83), and **unilateral paratracheal** (84)
Banded parenchyma	In narrow bands or lines up to three cells wide (86)					
Ray width	Exclusively uniseriate (96) and larger rays commonly > 10-seriate (99)					

Table 5. *Cont.*

Parameter	Species					
	Q. variabilis	***Q. serrata***	***Q. mongolica***	***Q. dentata***	***Q. aliena***	***Q. acutissima***
Rays of two distinct sizes	Present (103)					
Ray composition	All cells procumbent (104)					
Prismatic crystals	Present (136), in procumbent ray cells (138), and in chambered axial parenchyma cells (142)					
Other diagnostic crystal features	Crystals in enlarged cells (156)					

Note: the numbers in parentheses denote the IAWA feature list for hardwood identification. * Bold letters indicate distinct characteristics.

4. Conclusions

Macroscopically, all species exhibited distinct characteristics. The bark surfaces of all the species displayed intersecting ridges with varying textures and colors. A corky texture of the bark was only observed in *Q. variabilis*, which had a bark color similar to *Q. serrata*. Regarding the shape of ridges, *Q. serrata* and *Q. mongolica* had a flat shape. Shallow-fissured bark was observed in *Q. serrata*, *Q. mongolica*, and *Q. acutissima*. The heartwood color was consistently darker than that of the sapwood in all species, with color variations. *Q. variabilis* had heartwood–sapwood colors similar to those of *Q. acutissima*, while *Q. mongolica* and *Q. aliena* presented similar heartwood–sapwood colors. *Q. serrata* showed the highest proportion of heartwood. *Q. variabilis* had the lowest proportion of wood but the highest proportion of outer bark. In terms of growth ring width and latewood percentage, *Q. variabilis*, *Q. aliena*, and *Q. acutissima* exhibited the highest latewood percentage.

Microscopically, *Q. variabilis* and *Q. acutissima* exhibited similar latewood vessel arrangements, featuring diagonal and/or radial patterns. In contrast, dendritic-to-diagonal patterns of vessels with angular outlines were observed in *Q. serrata*, *Q. mongolica*, *Q. dentata*, and *Q. aliena*. Additionally, *Q. variabilis* and *Q. acutissima* had vasicentric, confluent, and unilateral paratracheal axial parenchyma in latewood.

Our results showed that bark morphology, color, wood color, and latewood vessel characteristics can be used as identification keys for the six Korean oak species.

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

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

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