Effect of Air Heat Treatment on the Color Change and Weight and Density Loss of Six Korean Oak Woods

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The effects of air heat treatment were evaluated on six Korean oak woods: *Quercus serrata* (*Qs*), *Quercus mongolica* (*Qm*), *Quercus acutissima* (*Qac*), *Quercus aliena* (*Qal*), *Quercus dentata* (*Qd*), and *Quercus variabilis* (*Qv*). Color change (ΔE^*), weight loss, and density loss were examined using flat-sawn heartwood boards before and after treatment at 160 °C, 180 °C, 200 °C, and 220 °C for 2 h. Overall, the ΔE^*, weight loss, and density loss increased with temperature. The properties between temperature and species showed distinct differences. A change to a darker color was observed in all species after treatment at 200 °C. *Qm* and *Qd* exhibited the highest and lowest L^*, a^*, and b^* values after treatment at 220 °C, respectively. The highest ΔE^* values were obtained in *Qd* at 160 °C, *Qs* at 180 °C and 200 °C, and *Qv* at 220 °C. *Qd* and *Qv* exhibited the highest and lowest weight losses at 160 °C, respectively. *Qac* and *Qal* showed the highest and lowest weight losses at 220 °C, respectively. *Qm* showed the highest density loss at all temperatures, whereas *Qs* had the lowest at 160 °C, and *Qac* had the lowest values at 180 °C, 200 °C, and 220 °C.

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INTRODUCTION

The genus *Quercus* L. (oaks, Fagaceae) is the largest tree genus in temperate and subtropical areas of the Northern Hemisphere, with an extensive distribution range (Denk *et al.* 2010), and approximately 400 species in North and Central America, Colombia, Eurasia, and northern Africa (Nixon 1997; Fang *et al.* 2011). Oak wood has high economic value because of its beautiful appearance, superior mechanical properties, and natural durability. Therefore, oak wood is widely used in many applications, including carpentry, construction, furniture, veneers, flooring, charcoal production, and fuelwood (Santos *et al.* 2012). Additionally, it is used in the production of pallets, railway ties, boarded roads, and timber mats (Bumgardner 2017).

In Korea, forests cover 6,348,834 ha, accounting for 63.1% of the total 10,043,185 ha. Six Korean oak species, *Quercus serrata* (*Qs*), *Quercus mongolica* (*Qm*), *Quercus acutissima* (*Qac*), *Quercus aliena* (*Qal*), *Quercus dentata* (*Qd*), and *Quercus variabilis* (*Qv*), are major wood resources, covering 1,037,650 ha, or 16.3% of the forested area, with a total growing stock of 159,261,862 m^3 (Korea Forest Service 2022). These species play crucial roles ecologically and economically in Korea. Historically, these oak species have been used for several purposes. During the late Joseon Dynasty (17th to 20th centuries), Korean oak wood was instrumental in the construction of shrines, fortresses, and palaces (Lee and Bae 2021). However, in modern times, these oaks are primarily used for low-grade applications, including mushroom cultivation, firewood, and charcoal (Kim and Hanna 2006; Fang *et al.* 2011; Han and Chang 2019; Jeon *et al.* 2020; Korea Forest Service 2022).

Air heat treatment is an environment-friendly and simple process that does not require the addition of chemicals for wood modification (Lee *et al.* 2023). In addition, thermally treated wood is used in multiple applications, including windows, claddings, playground equipment, sauna interiors, bathrooms, parquet flooring, and decking (Militz and Altgen 2014). This treatment can alter the color of wood to a darker color, which is preferred by consumers (Hidayat *et al.* 2017; Suri *et al.* 2021), improve dimensional stability and hydrophobicity (Hidayat *et al.* 2015, 2016; Suri *et al.* 2023a), and enhance its durability against fungi (Suri *et al.* 2023b).

Understanding the color properties and weight and density loss of heat-treated wood is essential for ensuring the suitability of wood material for various applications. Several studies have investigated the impact of air heat treatment on the physical properties of oak wood, specifically color change and weight and density loss. Barcík *et al.* (2015) reported on air heat treatment at 160 °C, 180 °C, 210 °C, and 240 °C for 5 h darkened pedunculate oak (*Quercus robur* L.) wood. The L^* (lightness), a^* (red/green chromaticity), and b^* (yellow/blue chromaticity) values, and density decreased with increasing temperature, with the greatest color change (ΔE^*) and the lowest density present at 240 °C. Perçin *et al.* (2016) reported the effects of heat treatment under atmospheric pressure at 150 °C, 170 °C, 210 °C, and 240 °C for 2, 5, and 8 h on the wood properties of *Q. petraea*. The weight and density loss of *Q. petraea* wood increased with temperature and duration, with the most pronounced changes at 210 °C for 8 h. Veizović *et al.* (2018) reported that heat treatment at 180 °C for 4 h in a vacuum oven with a pressure of 100 bar reduced its density from 0.637 g/cm³ to 0.620 g/cm³. Čabalová *et al.* (2018) reported that air heat treatment of *Q. robur* grown in Slovakia at 160 °C, 180 °C, and 200 °C for 3, 6, 9, and 12 h resulted in decreased density, L^* values, and b^* values. The a^* value varied during the heat treatment, with maximum values observed at 160 °C.

Currently, the utilization of six Korean oak woods has diminished to low-grade applications, such as mushroom cultivation, firewood, and charcoal. Thus far, there has been a lack of attempts to improve the quality of domestic oak wood for high-value applications in the Korean wood industry. Wood modification methods, such as air heat treatment, are necessary to improve wood color, dimensional stability, hydrophobicity, surface quality, and fungal durability to align with consumer preferences. This study aimed to determine and compare the effects of air heat treatment on the properties of the six Korean oak woods, including color change, weight loss, and density loss, to facilitate their further effective utilization.

EXPERIMENTAL

Materials

In this study, previously employed samples were examined (Savero *et al.* 2023, 2024). Three trees of each of the six oak species were harvested from the research forest of Kangwon National University, Chuncheon-si, Gangwon-do, Korea (37° 47’ 2.8932” N, 127° 49’ 13.368” E). The wood samples for this study were prepared as follows: 1) the logs were stored in a storage room for 1 year; 2) they were then cut into flat-sawn lumber with dimensions of 1000 to 1500 mm (longitudinal, L) × 200 to 260 mm (tangential, T) × 25 to 30 mm (radial, R) and air-dried in a storage room for 2 months; 3) the flat-sawn lumbers were converted into flat-sawn boards with dimensions of 300 mm (L) × 90 mm (T) × 25 mm (R) from the heartwood of each species; 4) the surface of defect-free flat-sawn boards was sanded using a sanding machine (BSM 6100, 1152 m/min, 1500 W, Topline International, Beijing, China) with AA80 coarse-grit sandpaper (Dae Sung Abrasive Co., Ltd., Incheon, Korea); 5) the boards were placed in a conditioning room with a relative humidity of 65 ± 3% and a temperature of 20 ± 3 °C for 2 weeks. While the wood boards were in the conditioning room, the weight of the samples was measured daily to ensure they stabilized before further testing. Essential information on the six Korean oak trees and wood samples is summarized in Tables 1 and 2, respectively.

Table 1. Essential Information of the Sample Trees

Trade Name	Scientific Name	Tree No.	Breast Height Diameter (cm)	Cambial Age (years)	Location
Jolcham Oak	*Quercus serrata* Murray (*Qs*)	1	22.2	69	Research forest of Kangwon National University, Chuncheon-si, Gangwon-do, Korea (37° 47’ 2.8932” N, 127° 49’ 13.368” E)
		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	
Sawtooth Oak	*Quercus acutissima* Carruth. (*Qac*)	1	15.7	48	
		2	23.6	48	
		3	25.8	48	
Oriental White Oak	*Quercus aliena* Blume (*Qal*)	1	15.5	49	
		2	20.6	44	
		3	25.3	50	
Korean Oak	*Quercus dentata* Thunb. (*Qd*)	1	21.3	82	
		2	21.5	66	
		3	23.7	70	
Oriental Cork Oak	*Quercus variabilis* Blume (*Qv*)	1	21.1	63	
		2	23.8	64	
		3	29.7	61	

Table 2. Wood Sample Information

Test	Sample Dimension (mm)	Species	Air-dry Moisture Content (%)	Temperature (°C)	Sample Number*	Total
Color Change **Density** **Weight loss**	300 (L) × 90 (T) × 25 (R)	*Qs*	11.38 (0.25)	160 180 200 220	$3^{(R)}$ × $6^{(Sp)}$ × $4^{(T)}$	72
		Qm	12.09 (0.22)			
		Qac	11.26 (0.27)			
		Qal	10.88 (0.26)			
		Qd	11.60 (0.30)			
		Qv	11.66 (0.29)			

*Sample number = replication $^{(R)}$ × species $^{(Sp)}$ × temperature $^{(T)}$

Methods

Air heat treatment

Air heat treatment was performed, as described by Hidayat *et al.* (2015, 2016). The wood samples were treated in an electric oven with a programmable controller (L-Series, Jeio TECH Ltd., Daejeon, Korea) under low-oxygen conditions. The heat treatment started at approximately 20 ± 5 °C, and continued to target temperatures of 160 °C, 180 °C, 200 °C, and 220 °C at a heating rate of 2 °C/min. The target temperature was then maintained for 2 h. In the final stage, the oven chamber was allowed to cool naturally until reaching 30 ± 5 °C. Subsequently, the boards were removed and placed in a desiccator filled with silica gel for 1 day. Then, the boards were placed in a conditioning room with a relative humidity of 65 ± 3% and a temperature of 20 ± 3 °C for 2 weeks before further testing.

Measurement of Some Physical Properties Before and After Air Heat Treatment

Color change

To observe the macroscopic color change, the tangential surfaces of the flat-sawn board samples before and after the air heat treatment at different temperatures were scanned using a Samsung printer (SL-M2893FW, color CIS, 1200 DPI, Samsung, Suwon-si, Korea).

Forty-point measurements on both sides of each sample were performed before and after heat treatment using a chromameter (CR-20 Plus; Konica Minolta, Tokyo, Japan; Fig. 1). The color change was determined using the CIE LAB system and characterized by three parameters: $L*$ (lightness), $a*$ (red/green chromaticity), and $b*$ (yellow/blue chromaticity). The overall color change ($\Delta E*$) was calculated using Eq. 1,

$$\Delta E* = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{\frac{1}{2}} \qquad (1)$$

where $\Delta L*$, $\Delta a*$, $\Delta b*$, and $\Delta E*$ are the changes in lightness, red/green chromaticity, yellow/blue chromaticity, and overall color changes, respectively.

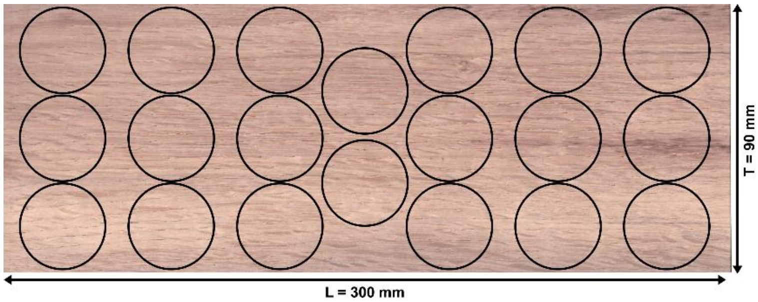

Fig. 1. The measurement of the color properties (black circle) on the tangential surface of the flat-sawn board samples

Weight loss

To determine the weight loss (*WL*) of six Korean oak woods before and after air heat treatment at different temperatures, the weight was measured using a precision balance with external calibration (FX-3000i, 3200 g × 0.01 g, A&D Company, Tokyo, Japan). The *WL* was calculated using Eq. 2,

$$WL = \left(\frac{m_1 - m_2}{m_1}\right) \times 100\ (\%) \qquad (2)$$

where *WL* (%) is the weight loss, m_1 (g) is the weight of the air-dried wood sample before heat treatment, and m_2 (g) is the weight of the wood sample after heat treatment.

Density

To obtain the air-dried density of six Korean oak woods before and after air heat treatment at various temperatures, the weight and volume were measured using a precision balance with external calibration (FX-3000i, 3200 g × 0.01 g, A&D Company, Tokyo, Japan) and an absolute digimatic caliper (CD-45C, 500-500-10, Mitutoyo, Kanagawa, Japan), respectively. The air-dried densities of the untreated and heat-treated samples were determined according to KS F 2198 (2016) using Eq. 3,

$$D_a = \frac{M_a}{V_a}\ (\mathrm{g/cm^3}) \tag{3}$$

where D_a is the density, M_a (g) is the weight, and V_a ($\mathrm{cm^3}$) is the volume of the air-dried wood samples. The density loss (*DL*) was calculated using Eq. 4,

$$DL = \left(\frac{D_1 - D_2}{D_1}\right) \times 100\ (\%) \tag{4}$$

where *DL* (%) is the density loss, D_1 (g) is the density of the air-dried wood samples before heat treatment, and D_2 (g) is the density of the wood samples after heat treatment.

Statistical analysis

Statistical differences in overall color changes and weight and density loss between untreated and heat-treated samples and among species were analyzed using one-way analysis of variance, followed by *post hoc* Tukey's honest significant difference test (SPSS ver. 24, IBM Corp., Armonk, NY, USA).

RESULTS AND DISCUSSION

Color Change

The wooden boards of the six Korean oaks before and after air heat treatment at different temperatures are shown in Fig. 2. The color of the wood darkened with an increase in temperature. Untreated *Qm* wood (Fig. 2 B0) showed the lightest color among the six oak species, whereas untreated *Qal* wood (Fig. 2 D0) showed the darkest color. *Qd* wood appeared darker than the other oaks at 160 °C (Fig. 2. E1). At 180 °C, *Qs* and *Qd* woods showed a darker color among the six oak species (Figs. 2. A2 and E2, respectively). At 200 °C, a noticeable change was observed in all six oak species, particularly in *Qs* (Fig. 2. A3) and *Qd* (Fig. 2. E3) woods. All six oak species (Figs. 2. A4 through F4) showed a completely dark brown color at 220 °C.

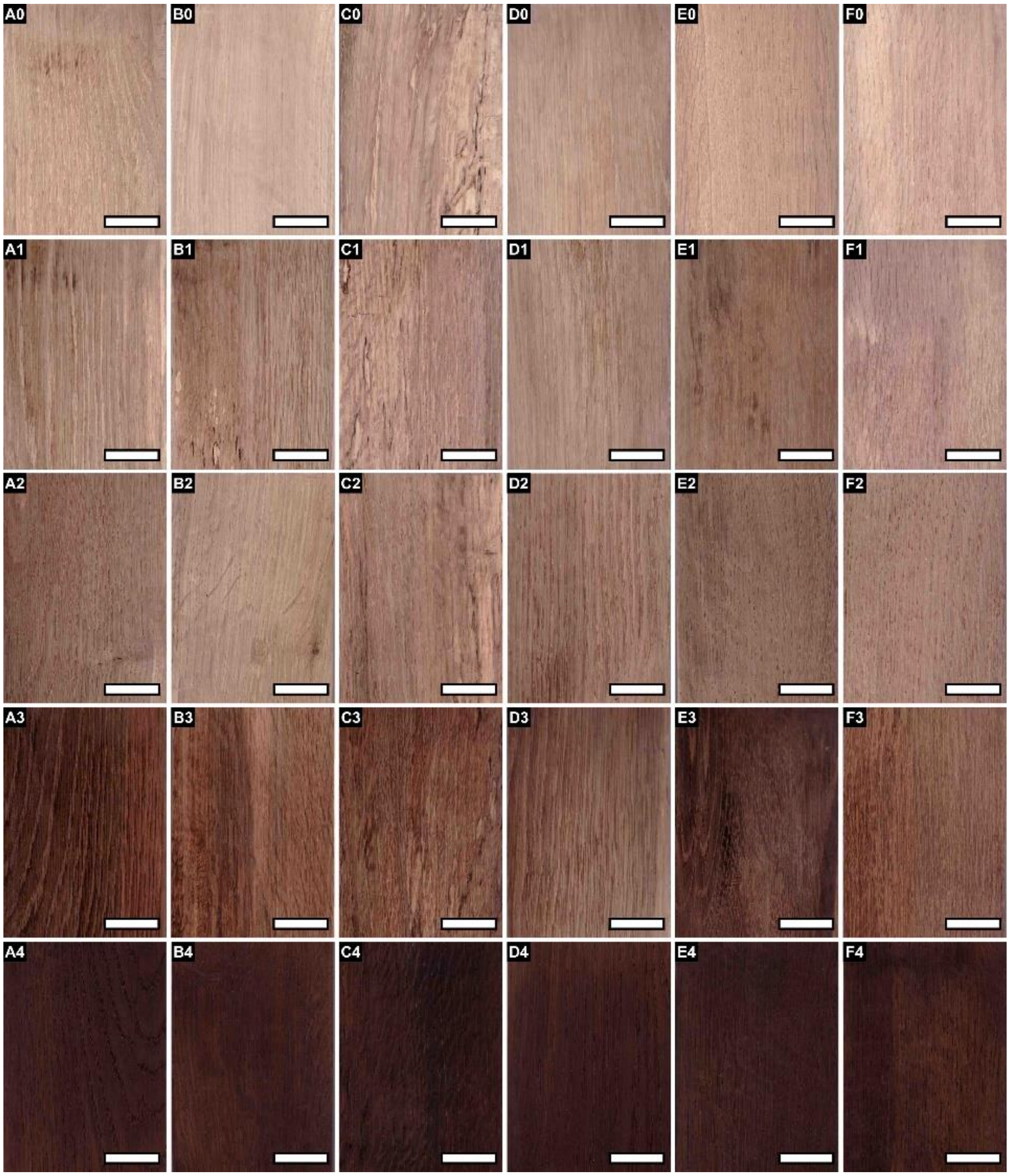

Fig. 2. The appearance of *Qs* (A), *Qm* (B), *Qac* (C), *Qal* (D), *Qd* (E), and *Qv* (F) woods before and after air heat treatment at different temperatures: (0) Untreated, (1) 160 °C, (2) 180 °C, (3) 200 °C, and (4) 220 °C; Scale bars: 3 cm

The *L** (lightness), *a** (red/green chromaticity), and *b** (yellow/blue chromaticity) values of the six untreated and heat-treated Korean oak wood samples are shown in Fig. 3. The average *L** values of the six untreated oak wood samples ranged from 59.3 to 67.7. Untreated *Qm* showed the highest *L** value, whereas untreated *Qd* showed the lowest value. The *L** value decreased considerably in all six Korean oak woods with increasing temperature. It is worth mentioning that *Qd* displayed a different pattern than the other oak species in terms of the change in *L** value. The *L** value in *Qd* decreased significantly at 160 °C, slightly decreased at 180 to 200 °C, and then decreased considerably at 220 °C. *Qm* wood exhibited the highest *L** value at 220 °C, whereas *Qd* exhibited the lowest *L** value.

The average *a** values of the six untreated oak boards ranged from 5.8 to 9.3. Untreated *Qv* had the highest *a** value, whereas untreated *Qac* had the lowest. The *a** value in *Qs*, *Qm*, and *Qac* increased at 160 °C, 180 °C, and 200 °C, and then decreased significantly at 220 °C. In contrast, the *a** values of *Qd* and *Qv* decreased with increasing temperature. Notably, the *a** value of *Qal* decreased at 160 °C, increased from 180 °C to 200 °C, and then decreased significantly at 220 °C. After heat treatment at 220 °C, the *a** value of *Qm* was the highest, whereas that of *Qd* was the lowest.

The *b** values of untreated *Qs*, *Qm*, *Qac*, *Qal*, *Qd*, and *Qv* were 19.4, 19.6, 20.4, 20.6, 22.4, and 19.0, respectively. Untreated *Qd* had the highest *b** value, whereas untreated *Qv* had the lowest. Similar to the *L** values, the *b** values of *Qac*, *Qal*, *Qd*, and *Qv* decreased with increasing temperature. In contrast, the *b** values in *Qs* and *Qm* increased at 160 °C and then decreased from 180 °C to 220 °C. At 220 °C, the *b** value in *Qd* was the lowest, whereas that in *Qm* was the highest.

Significant decreases in *L** values and changes in *a** and *b** values were supported by previous studies. Srinivas and Pandey (2012) reported that the *L** values of silver oak (*Grevillea robusta*) decreased rapidly from 69.3 to 30.4, 24.2, and 23.6 by air heat treatment at 210 °C, 225 °C, and 240 °C for 8 h, respectively, whereas *a** and *b** values initially increased and then decreased with longer exposure at all temperatures. Barcík *et al.* (2015) reported that the *L** value of pedunculate oak (*Q. robur* L.) decreased significantly with increasing temperature. The *a** value of the heat-treated wood of *Q. robur* at 160 °C was comparable to that of untreated wood, and then slightly decreased at 180 °C, increased at 210 °C, and significantly decreased at 240 °C. The *b** values gradually decreased up to 180 °C, slightly increased at 210 °C, and then significantly decreased at 240 °C. The lowest *L**, *a**, and *b** values were identified at 240 °C. Čabalová *et al.* (2018) reported that the *L** value of pedunculate oak (*Q. robur* L.) grown in Slovakia had the most substantial change after heat treatment at 160 °C, 180 °C, and 200 °C. The *a** value increased after heat treatment at 160 °C and 180 °C and decreased at 200 °C, whereas the *b** value decreased with increasing temperature. Todorović *et al.* (2020) reported that the *L**, *a**, and *b** values of heartwood from sessile oak (*Quercus petraea* L.) decreased after heat treatment at 170 °C, 190 °C, and 210 °C for 4 h. The *L** value indicated a significantly greater change compared to *a** and *b** values after heat treatment at 210 °C.

Bourgios *et al.* (1991) reported that the decrease in *L** value of wood during heat treatment is caused by a reduction in hemicellulose content, particularly pentosane. Esteves *et al.* (2008) also explained that the reduction in *L** value of wood due to heat treatment strongly correlated with changes in glucose and hemicellulose contents, with determination coefficients of 0.96 and 0.92, respectively. Additionally, Cirule and Kuka (2015) reported that the different trends in *a** and *b** values of wood during thermal treatment could be attributed to various treatment conditions, durations, and the particular species of wood. These factors lead to the formation of diverse chromophoric systems, which may be due to variations in the chemical composition of different species.

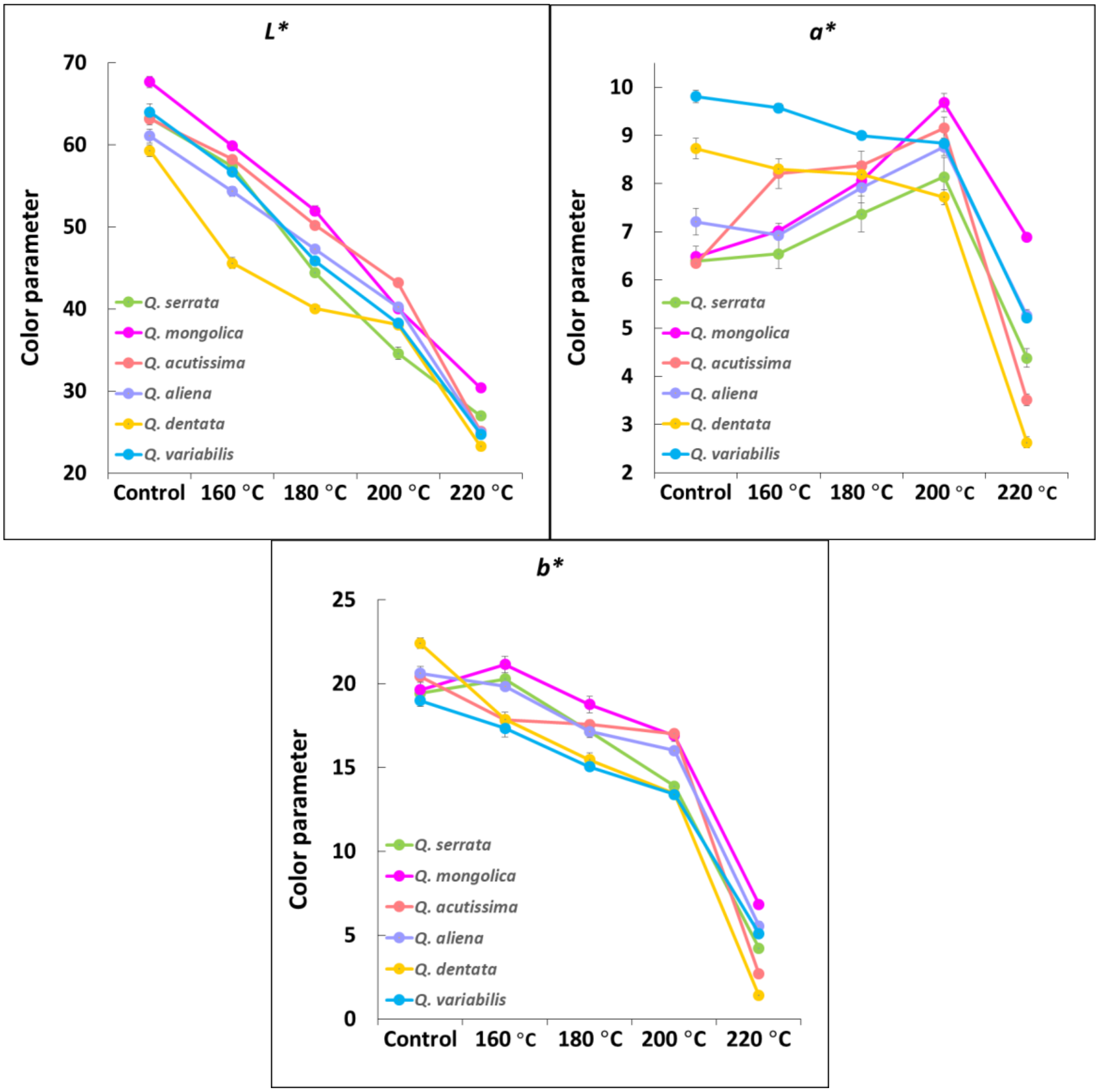

Fig. 3. Effect of treatment temperature on the *L**, *a**, and *b** values of six Korean oak woods

The overall color changes (Δ*E**) of six heat-treated Korean oak woods are depicted in Fig. 4, showing a significant increase with increasing temperature in all six species. In *Qs* wood, the Δ*E** value gradually increased from 160 °C to 220 °C. In *Qm* wood, the Δ*E** value gradually increased from 160 °C to 180 °C, steeply increased from 180 to 200 °C, and then gradually increased from 200 °C to 220 °C. The Δ*E** values in the *Qac*, *Qal*, *Qd*, and *Qv* woods gradually increased from 160 °C to 200 °C, followed by a steep increase from 200 °C to 220 °C.

Moreover, there were noticeable differences in Δ*E** among the species. At 160 °C, *Qd* exhibited the highest Δ*E** value, whereas *Qac* showed the smallest Δ*E** value among the six species. Although there were significant differences in the Δ*E** among the species, the other wood samples showed similar values. At 180 °C, the highest and lowest Δ*E** values were observed for *Qv* and *Qac*, respectively. A significant difference in Δ*E** value was found between *Qv* and the other oak species, except *Qs*. The Δ*E** value in *Qs* was intermediate between *Qv* and *Qd*, and that in *Qal* was intermediate between *Qm* and *Qac*. At 200 °C, *Qs* exhibited the highest Δ*E** value, followed by *Qm*, *Qv*, *Qd*, *Qac*, and *Qal*.

There was a significant difference in Δ*E** between the six oak species, except between *Qac* and *Qal*. At 220 °C, *Qv* exhibited the highest Δ*E** value, followed by *Qd*, *Qs*, *Qac*, *Qm*, and *Qal*. There was a significant difference in Δ*E** value between *Qv* and the other oak species. There were no significant differences between *Qac*, *Qm*, and *Qal* or between *Qd* and *Qs*.

In this study, the wood darkened and Δ*E** increased with increasing temperature, which is consistent with previous studies. Srinivas and Pandey (2012) reported that the wood of *G. robusta* darkened after air heat treatment at 210 °C, 225 °C, and 240 °C for 8 h, and Δ*E** values increased with time and temperature. The maximum change in Δ*E** values of *G. robusta* increased from 40 to 50.4 with increasing temperature from 210 °C to 240 °C. Barcík *et al.* (2015) reported that the Δ*E** value of *Q. robur* increased sharply at 160 to 180 °C, was mitigated at 180 to 210 °C, and rapidly increased again at 210 to 240 °C. Todorović *et al.* (2020) reported that the Δ*E** value of heartwood in *Q. petraea* increased with increasing temperature, as 19.0 at 170 °C, 38.3 at 190 °C, and 46.8 at 210 °C.

Color changes during heat treatment can be attributed to various factors, such as the oxidation of phenolic compounds (Sandoval-Torres *et al.* 2010), the reduction of molecular sugars and amino acids (Sundqvist 2002), the emission of formaldehydes, the formation of quinones, or the caramelization of holocellulose components (Boonstra 2008). Kamperidou *et al.* (2013) also suggested that the darkening of the wood surface might result from the thermal degradation of hemicelluloses and extractives, or potential polymerization reactions of lignin. Oak wood is well-known for its high extractive content, which is extruded onto the wood surface during thermal modification (Barcík *et al.* 2015). Moreover, the degree of discoloration in wood varies based on the wood species, the temperature used, and the duration of the heat treatment (Hill 2006).

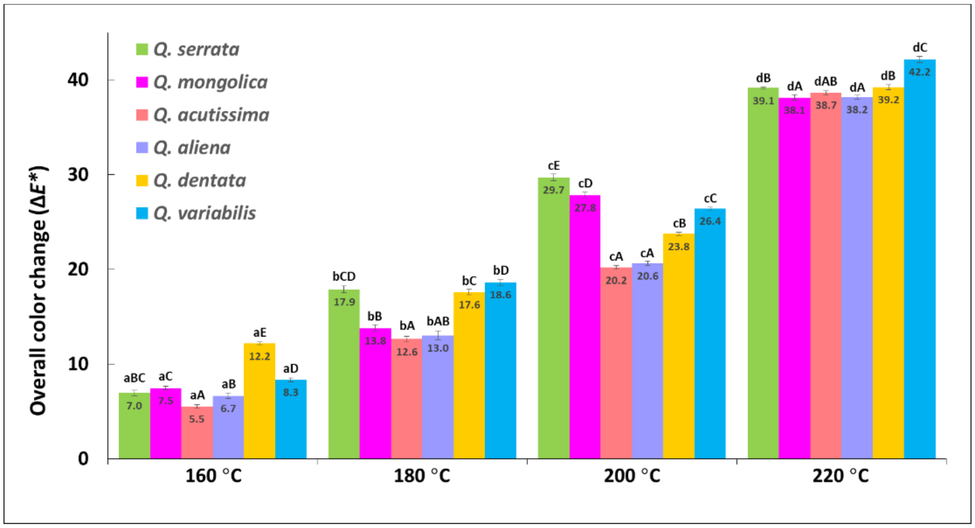

Fig. 4. Effect of air heat treatment on the overall color change (Δ*E**) of six Korean oak woods. Different lowercase and capital letters indicate significant differences at the 5% significance level for comparisons between temperatures and among the species, respectively.

Weight Loss

Table 3 shows the weight loss of the six Korean oak wood species after the air heat treatment. In all species, weight loss significantly increased with increasing temperature.

At 160 °C, *Qd* exhibited the highest weight loss, followed by *Qac*, *Qm*, *Qal*, and *Qs*, whereas *Qv* showed the lowest. Weight loss in *Qd* was significantly higher than that in *Qs* and *Qv*. At 180 °C and 200 °C, weight loss was comparable among the six Korean oak woods. The highest weight loss was 23.59% in *Qac* wood after treatment at 220 °C, followed by *Qv*, *Qm*, *Qd*, and *Qs*, whereas the lowest weight loss was 20.36% in *Qal*. There was a significant difference in the weight loss between *Qac* and *Qal* at 220 °C.

Several studies support these results regarding weight loss during air heat treatment. Srinivas and Pandey (2012) reported that the weight loss of *G. robusta* increased with temperature and treatment duration, observing a maximum weight loss of approximately 18% at 240 °C for 8 h. Korkut and Hiziroglu (2014) reported that the weight loss of *Q. falcate* was 5.8% at 110 °C and 9.27% at 200 °C for 8 h. Perçin *et al.* (2016) reported that the weight loss of *Q. petraea* wood increased with increasing temperature and duration, showing the most pronounced weight loss at the highest temperature of 210 °C for 8 h.

Todorović *et al.* (2020) reported that weight loss due to heat treatment strongly depends on various factors, such as wood species, moisture content, drying step, heating medium, and treatment intensity. Esteves and Pereira (2009), Korkut and Hiziroglu (2014), and Hidayat *et al.* (2016) explained that weight loss after heat treatment is primarily due to the degradation of extractives, hemicelluloses, and cellulose. Additionally, weight loss is attributed to the removal of bound water from the wood (Srinivas and Pandey 2012).

Table 3. Weight Loss of Six Korean Oak Woods Treated at Different Temperatures

Weight Loss (%)						
Treatment	*Qs*	*Qm*	*Qac*	*Qal*	*Qd*	*Qv*
160 °C	10.38^{aAB} (0.28)	10.78^{aABC} (0.23)	11.24^{aBC} (0.46)	10.7^{aABC} (0.17)	11.39^{aC} (0.50)	10.20^{aA} (0.19)
180 °C	12.68^{bA} (0.45)	12.27^{bA} (0.28)	12.77^{bA} (0.46)	12.39^{bA} (0.32)	12.80^{bA} (0.29)	12.42^{bA} (0.37)
200 °C	14.48^{cA} (0.48)	14.36^{cA} (0.32)	14.58^{cA} (0.23)	14.83^{cA} (0.70)	14.56^{cA} (0.18)	14.58^{cA} (0.74)
220 °C	21.19^{dAB} (0.02)	21.96^{dAB} (0.38)	23.59^{dB} (0.38)	20.36^{dA} (1.00)	21.65^{dAB} (0.97)	22.10^{dAB} (0.72)

Numbers within parentheses represent standard deviations. Numbers in the same column with the same superscript lowercase letters indicate non-significant outcomes at the 5% significance level for temperature comparisons. The mean value in the same row followed by the same superscript capital letters indicates non-significant outcomes at the 5% significance level for species comparisons.

Density

The densities and density losses of the six Korean oak wood samples treated at different temperatures are presented in Table 4. The densities of untreated oak woods ranged from 0.78 g/cm^3 in *Qm* to 0.93 g/cm^3 in *Qd*. The densities of all species significantly decreased after air heat treatment. In heat-treated wood, *Qd* exhibited the highest density, followed by *Qv*, *Qac*, *Qal*, and *Qs*, whereas *Qm* had the lowest density. The reduction in densities of the oak woods at 160 °C ranged from 3.9% in *Qs* to 6.3% in *Qm*. The highest density loss was observed at 220 °C, showing a range from 14.7% in *Qac* to 19.9% in *Qm*. *Qm* showed the highest decrease for all temperatures, whereas the lowest density loss was observed in *Qs* at 160 °C and in *Qac* at 180 °C, 200 °C, and 220 °C.

In this study, the density loss of six Korean oak woods after air heat treatment increased with increasing temperature. Several studies support these results regarding the density loss of *Quercus* spp. during heat treatment (Korkut and Hiziroglu 2014; Barcík *et al.* 2015; Martinka *et al.* 2016; Perçin *et al.* 2016; Čabalová *et al.* 2018). In contrast, Aydin (2020) reported that the density of *Q. petraea* wood grown in Türkiye decreased insignificantly after air heat treatment in an oven at 120 °C, 150 °C, and 180 °C for 2, 5, and 8 h, whereas the density showed a significant decrease at 210 °C for 8 h.

Regarding the reasons for density loss in wood due to heat treatment, Barcík *et al.* (2015) explained that density loss was caused by moisture loss during thermal modification, thereby reducing the volume of wood, and by the degradation of its structure. Boonstra *et al.* (2007) and Esteves and Pereira (2009) reported that a decrease in density could be attributed to the degradation of hemicellulose into volatile substances. In addition, the evaporation of moisture and extractives during heat treatment reduce the density of wood exposed to heat (Korkut *et al.* 2008; Gunduz *et al.* 2009).

Table 4. Air-dry Density (D_a) and Density Loss (*DL*) of Six Korean Oak Woods Treated at Different Temperatures

Air-dry Density (g/cm^3) and Density Loss (%)												
Treatment	*Qs*		*Qm*		*Qac*		*Qal*		*Qd*		*Qv*	
	D_a	*DL*	D_a	*DL*	D_a	*DL*	D_a	*DL*	D_a	*DL*	D_a	*DL*
Untreated	0.79^{dA} (0.009)	-	0.78^{dA} (0.011)	-	0.84^{dBC} (0.026)	-	0.81^{dAB} (0.014)	-	0.93^{dD} (0.027)	-	0.87^{dC} (0.020)	-
160 °C	0.76^{cB} (0.014)	3.9	0.73^{cA} (0.021)	6.3	0.80^{cC} (0.006)	4.8	0.76^{cB} (0.005)	6.2	0.88^{cE} (0.014)	5.2	0.83^{cD} (0.005)	5.2
180 °C	0.73^{cB} (0.012)	7.4	0.70^{bcA} (0.007)	9.6	0.78^{bcC} (0.007)	7.0	0.74^{bcB} (0.004)	8.6	0.86^{cE} (0.012)	7.5	0.80^{bcD} (0.006)	8.4
200 °C	0.69^{bA} (0.010)	12.3	0.68^{bA} (0.005)	13.1	0.75^{bC} (0.006)	9.9	0.72^{bB} (0.007)	10.6	0.81^{bE} (0.001)	12.8	0.78^{bD} (0.008)	10.6
220 °C	0.64^{aA} (0.005)	19.0	0.62^{aA} (0.012)	19.9	0.70^{aB} (0.005)	14.7	0.68^{aB} (0.005)	16.6	0.77^{aD} (0.006)	17.6	0.74^{aC} (0.006)	14.8

Numbers within parentheses represent standard deviations. Numbers in the same column with the same superscript lowercase letters indicate non-significant outcomes at the 5% significance level for temperature comparisons. The mean value in the same row followed by the same superscript capital letters indicates non-significant outcomes at the 5% significance level for species comparisons.

CONCLUSIONS

1. A change to a darker color was observed in all six oak species after air heat treatment at 200 °C, particularly in *Qs* and *Qd*. The ΔE^* value and weight and density loss increased with increasing temperature.
2. The L^* values decreased with increasing temperature in all six Korean oak species. The a^* value of *Qal* decreased at 160 °C, and then increased from 180 °C to 200 °C. Additionally, the a^* value in all species decreased significantly at 220 °C. The b^* value in *Qac*, *Qal*, *Qd*, and *Qv* decreased with increasing temperature, whereas that in *Qs* and *Qm* increased at 160 °C and then decreased from 180 °C to 220 °C. *Qm* exhibited the highest L^*, a^*, and b^* values at 220 °C, whereas *Qd* exhibited the lowest. *Qd*, *Qs*, and *Qv* had the highest ΔE^* values at 160 °C, 180 °C and 200 °C, and 220 °C, respectively. *Qac* showed the smallest ΔE^* valued at 160 °C, 180 °C, and 200 °C. The lowest ΔE^* value at 220 °C was observed in *Qm*.

3. *Qd* exhibited the highest weight loss at 160 °C, whereas *Qv* exhibited the lowest. Weight loss was comparable among the six oak species at 180 °C and 200 °C. At 220 °C, *Qac* exhibited the highest weight loss, whereas *Qal* exhibited the lowest.
4. *Qm* showed the highest density loss for all temperatures, whereas the lowest density losses were observed in *Qs* at 160 °C and in *Qac* at 180 °C, 200 °C, and 220 °C.

In conclusion, air heat treatment significantly affected color change, as well as weight and density loss in six Korean oak woods. These findings may provide valuable information for understanding the effects of air heat treatment on the wood properties of six oak species for further utilization.

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