A Comparative Study of the Tracheid and Crystalline Properties of Dahurian Larch (*Larix gmelinii*) and Japanese Larch (*Larix kaempferi*) Wood

Do Hoon Kim,[a] Jong Ho Kim,[a] Byantara Darsan Purusatama,[b] Intan Fajar Suri,[a] Go Un Yang,[a] Fauzi Febrianto,[c] and Nam Hun Kim [a,]*

The tracheid and crystalline properties of earlywood and latewood within the stems of Korean-grown Dahurian and Japanese larches were studied to obtain valuable information for identifying these two species and determining their wood quality. The tracheid length and width were examined *via* optical microscopy, and the relative crystallinity and crystallite widths were examined using the X-ray diffraction method. The tracheid length and width were greater in the Dahurian larch compared to the Japanese larch. In both wood species, the tracheid length and width increased as the growth ring number increased but stabilized at a certain growth ring number. The relative crystallinity was higher in the Japanese larch wood compared to the Dahurian larch wood, while the crystallite width in both species was similar. Neither the relative crystallinity nor the crystallite width displayed a constant trend from pith to bark. The differences in the tracheid properties and the relative crystallinity of both species could be used to identify them and evaluate their wood quality for their effective utilization.

DOI: 10.15376/biores.17.2.2768-2779

Keywords: Crystalline properties; Dahurian larch; Japanese larch; Quality indices; Tracheid length; Tracheid width

*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: Department of Forest Products, Faculty of Forestry, IPB University, Gd. Fahutan Kampus IPB Dramaga, Bogor 16680 Indonesia; *Corresponding author: Nam Hun Kim (kimnh@kangwon.ac.kr)*

INTRODUCTION

Dahurian larch (*Larix gmelinii*) and Japanese larch (*Larix kaempferi*) are distributed throughout the Korean peninsula, which forms part of the Eurasian region. In South Korea, Dahurian larch is only found in a small area in the Gangwon Province, Korea (Hwang and Park 2007). Contrastingly, Japanese larch is widely distributed in the mountains of South Korea and is commonly utilized for various wood products such as wood construction, packaging, plywood, and pulp in present days (Korea Forest Service 2011). However, the two species are often referred to as 'larch' because the tree and wood characteristics are difficult to distinguish from each other (Hwang and Park 2007; Chong and Park 2008). Therefore, further study on the anatomical characteristics is important for wood identification and quality evaluation of both species.

A number of studies have been conducted on the variation of various wood anatomical properties within stems in order to provide wood quality indices, *e.g.*, tracheid length (Herman *et al*. 1998; Gogoi *et al*. 2019), microfibril angle (Senft and Bendtsen 1985; Entwistle and Terrill 2000; Donaldson 2008), and ray properties (Rahman *et al*. 2005; Kim *et al*. 2009; Fonti *et al*. 2015; Kim *et al*. 2021).

In particular, there have been many studies on the radial variation of the tracheid properties of coniferous species, for evaluating wood quality, *e.g.*, studies on *Pinus kesiya* (Burley 1969), *Pinus wallichiana* (Seth 1981), *Picea abies* (Lindström 1997), *Larix kaempferi* (Zhu *et al*. 2000; Rlee and Kim 2005), *Pinus sylvestris* (Mäkinen *et al*. 2015), *Larix decidua*, *Picea abies*, and *Pinus sylvestris* (Fabisiak *et al*. 2020).

Several studies evaluating wood quality have also examined the radial variation of the crystalline properties of coniferous wood species. Wellwood *et al*. (1974) studied the radial variation in cellulose crystallinity in a 500-year-old Douglas fir. Kim and Lee (1998) reported the radial variation in the relative crystallinity and degree of crystallite orientation in *Chamaecyparis obtusa*. Andersson *et al*. (2003) studied radial variation in the crystallinity and crystallite size of *Picea abies*. Eun *et al*. (2008) also reported variations in the fine structure of wood cellulose within the stems of *Pinus densiflora*, *Pinus koraiensis*, and *Pinus rigida*. Ishikura (2017) compared the relative crystallinity between juvenile and mature wood in *Abies sachalinensis*.

Recently, the authors reported the radial variation of the ray properties in Dahurian and Japanese larches as identification and quality indices (Kim *et al*. 2021). In both species, the uniseriate heights increased as the growth ring number increased, and the ray number and ray spacing decreased with age but were stable toward the bark, showing considerable differences in all ray properties between the two species.

Thus far, there have been no comparative studies on the radial variation of the tracheid and crystalline properties of Dahurian and Japanese larches growing in Korea. Therefore, the authors aimed to investigate the tracheid and crystalline properties of Korean-grown Dahurian and Japanese larches to obtain valuable information for wood identification and wood quality indices to evaluate the wood properties.

EXPERIMENTAL

Materials

Three Dahurian larch trees (*Larix gmelinii* var. *olgensis* (A. Henry) Ostenf. and Syrach), approximately 71 years old to 72 years old, and three Japanese larch trees (*Larix kaempferi* (Lamb.) Carriere), approximately 37 years old to 41 years old, were harvested from a plantation site in the research forest at Kangwon National University, South Korea (N 37°77', E 127°81'). The diameter at breast height, the oven-dry density, and the heartwood rate of the sample trees were approximately 347±8 mm, 0.70±0.07 g/cm^3, and 83±3%, respectively, for the Dahurian larch, and 356±8 mm, 0.56±0.10 g/cm^3, and 73±1%, respectively, for the Japanese larch. Detailed information on the sample trees was provided in a previous study (Kim *et al*. 2021).

Specimen Preparation

Wood discs were obtained from the stems of both species at breast height. In the Dahurian larch, the specimens were prepared from every fifth growth ring from pith to bark until the 50th growth ring was reached from four different directions of the discs, and specimens were then prepared from every tenth growth ring from the 50th growth ring. The

Japanese larch specimens were prepared from every fifth growth ring from pith to bark until the 35th growth ring.

Measurement of Tracheid Properties

Matchstick-sized specimens, approximately 1 mm wide and 20 mm to 30 mm in length, were prepared. The specimens were macerated in a heating bath (Thermo bath, ALB128, Korea Science, Korea), according to the Franklin method (Franklin 1945), neutralized using distilled water, acetic acid, and sodium hydroxide, and used to make permanent slides. The tracheid characteristics were observed using an optical microscope (Nikon Eclipse E600, Tokyo, Japan) and analyzed using an image analysis program (IMT I-solution lite, Version 9.1, Vancouver, Canada).

The lengths of the 50 tracheids in the earlywood and latewood from every fifth growth ring from four different directions were measured, and the mean values were recorded. The width of all the tracheids within a growth ring was observed in the earlywood and latewood for the radial section in every fifth growth ring from four different directions.

Measurement of Crystalline Properties

Specimens of approximately 1 mm thickness (*R*), 15 mm width (*T*), and 15 mm length (*L*) were prepared for each growth ring. The specimens were analyzed using an X-ray diffractometer (DMAX2100V, Cu kα, Rigaku, Japan) under operating conditions of 40 kV and 30 mA. The relative crystallinity (CR) and crystallite width (L_{hkl}) were measured using Segal's method (Segal *et al.* 1959) and Scherrer's method (Scherrer 1918), as shown in Eq. 1 and 2, respectively,

$$\mathrm{CR}\ (\%) = \frac{(I_{200} - I_{\mathrm{am}})}{I_{200}} \times 100 \qquad (1)$$

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

$$L_{\mathrm{hkl}} = \frac{K\lambda}{\beta cos\theta} \qquad (2)$$

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

Statistical Analysis

Significant differences in the tracheid and crystalline properties between the wood of the Dahurian and Japanese larches were analyzed using analysis of variance. Correlations among the tracheid properties were analyzed using linear regression analysis and the Pearson coefficient (r) with multivariate analysis (SPSS, version 24, IBM Corporation, Armonk, NY).

RESULTS AND DISCUSSION

Tracheid Properties

The tracheid lengths and widths of both wood species are summarized in Table 1. Dahurian larch had a longer tracheid length compared to Japanese larch, and there were significant differences in the tracheid length between both species (earlywood: p-value less than 0.05; latewood: p-value less than 0.05). The average lengths of the earlywood tracheids in the Dahurian and Japanese larch wood were 2,837± 347 μm and 2,645± 346 μm, respectively. The latewood tracheid lengths in the Dahurian and Japanese larch wood were 2,967±350 μm and 2,735±375 μm, respectively. The tracheid length in the earlywood and latewood of both species was classified as short (IAWA Committee 2004). There was no significant difference in the tracheid length between the earlywood and latewood in either species, with *p*-values of 0.252 and 0.197 for the Dahurian and Japanese larch wood, respectively. Eom (2015) explained that the average tracheid lengths of the Dahurian and Japanese larch wood were 2.95±0.72 and 2.58±0.71 mm, respectively, and that Dahurian larch wood had a longer tracheid length compared to Japanese larch wood. Han *et al.* (2017) also reported an average tracheid length of 2.76±0.66 mm in Dahurian larch wood and 2.82±0.47 mm in Japanese larch wood. Rlee and Kim (2005) reported that the average tracheid length on the north side of the stem of Japanese larch wood was 2.59 (1.68 to 3.04 mm) for earlywood and 3.28 mm (2.14 to 3.98 mm) for latewood; the south side of the stem showed a similar trend, being 2.44 mm (1.59 to 2.92 mm) for earlywood and 3.30 (2.11 to 3.96 mm) for latewood. Fonti *et al.* (2015) concluded that the tracheid length of Dahurian larch trees grown in Siberia ranged between 2273 to 2643 μm. Koizumi *et al.* (2003) reported that the tracheid length for the 20th growth ring of Siberian-grown *Larix sibirica* was 3.1±0.16 mm. As mentioned above, there are some differences in the tracheid lengths denoted in previous studies. These differences could be caused by differences in growing conditions, *e.g.*, soil, temperature, and precipitation.

Table 1. Tracheid Properties of Both Larch Woods

Wood Type	Tracheid Length (μm)				Tracheid Width (μm)	
	Earlywood	Latewood	p-value	Average	Earlywood	Latewood
Dahurian larch	2,837 ± 347 (1,891 to 3,308)	2,967 ± 350 (2,388 to 4,005)	0.252	2,931 ± 401 (1891 to 4005)	52.5 ± 13.7 (20.3 to 80.2)	25.8 ± 7.6 (21.3 to 29.5)
Japanese larch	2,645 ± 346 (1,820 to 3,076)	2,735 ± 375 (2,153 to 3,598)	0.197	2,684 ± 365 (1,820 to 3,598)	50.7 ± 12.4 (22.4 to 86.1)	22.3 ± 5.9 (18.6 to 24.9)
p-value	0.044*	0.027*	-	0.030*	0.833	0.007**

Note: Numbers in parentheses indicate the ranges for each property; * denotes statistically significant at a p-value less than 0.05; and ** denotes statistically significant at a p-value less than 0.01

Figure 1 shows the radial variation in the tracheid length in both the earlywood and latewood for the two species. The tracheid length increased as the growth ring number increased in both species but tended to remain constant after a certain growth ring number. As such, it was suggested that the boundary between juvenile and mature wood, according to the tracheid length of the earlywood and latewood, was the 25th growth ring for Dahurian larch and the 20th growth ring for Japanese larch. In coniferous species, the tracheid length is short in the pith region, increases as the growth rings increase, and displays a constant pattern from a certain growth ring (Seth 1981; Yoshizawa *et al*. 1987; Kim and Mishiro 1998; Zhu *et al*. 2000; Saren *et al*. 2001; Fabisiak *et al*. 2020). The width of the earlywood tracheid in the radial direction for the Dahurian and Japanese larches was 52.5±13.7 μm and 50.7±12.4 μm, respectively. The latewood tracheid width was 25.8±7.6 μm for the

Dahurian larch and 22.3± 5.9 µm for the Japanese larch. Dahurian larch exhibited a significantly larger latewood tracheid width compared to the Japanese larch, while there was no significant difference between the earlywood tracheid widths of both species.

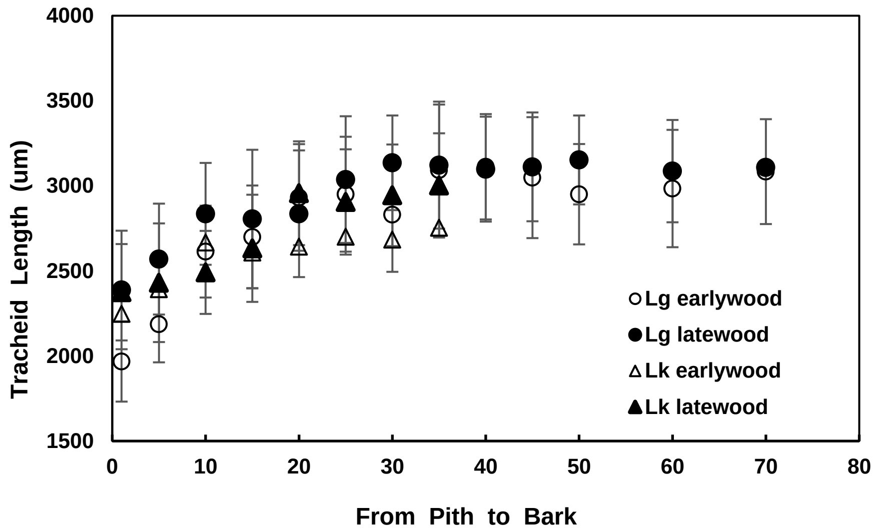

Fig. 1. Radial variation of the tracheid length in the earlywood and latewood of Dahurian (Lg) and Japanese (Lk) larch wood

The tracheid width in this study was similar to the width denoted in some previous studies. Rlee and Kim (2005) reported that the tracheid width of Japanese larch was 54.2 µm (47.2 to 60.4 µm) in earlywood and 36.2 µm (33.4 to 39.4 µm) in latewood. Chong and Park (2008) found that the tracheid width in the radial direction of Japanese larch was 44 µm in earlywood and 26 µm in latewood. Fonti *et al*. (2015) reported that the tangential tracheid width of Dahurian larch was 28 to 30.4 µm.

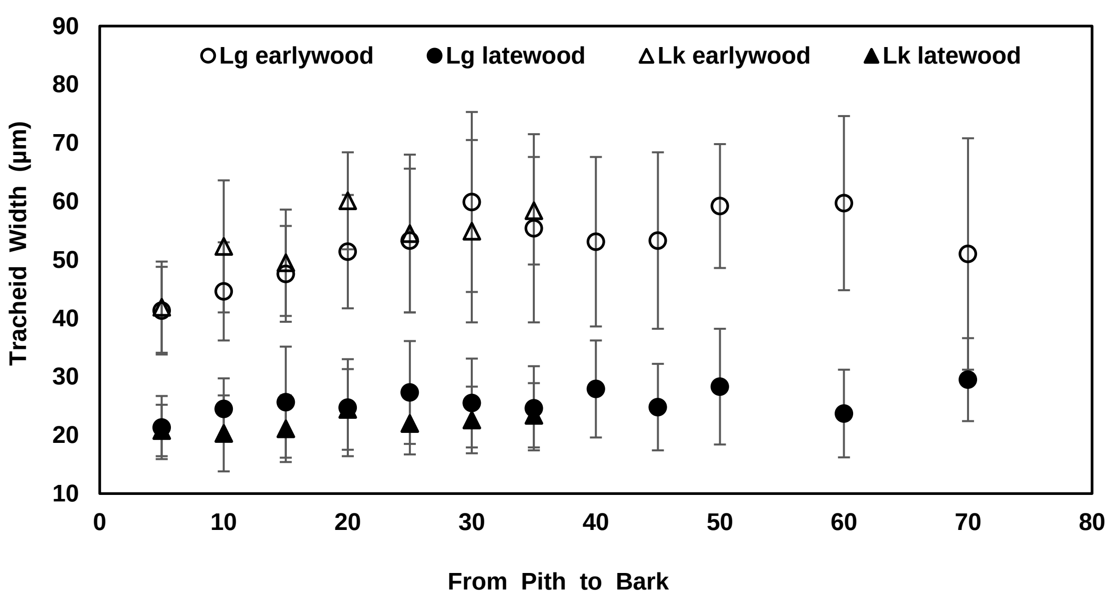

Fig. 2. Radial variation of the tracheid width in the earlywood and latewood of Dahurian (Lg) and Japanese (Lk) larch wood

Figure 2 shows the radial variation of the tracheid width in the earlywood and latewood for both Dahurian and Japanese larch wood. The tracheid width was narrow in the pith region of both species but increased as the growth rings increased. However, it tended to remain constant toward the bark from approximately the 20th growth ring. The tracheid width near the pith increased drastically in earlywood and gradually in latewood. With regards to the radial variation of the tracheid width, the results of this study support many previous studies, in that the tracheid length and diameter increased as the cambial age increased and then stabilized from a certain growth ring (Panshin and Zeeuw 1980; Lindström 1997; Sarén *et al*. 2001).

Figures 3 and 4 show the relationship between the length and width of the tracheids in the earlywood and latewood, respectively. In both species, the tracheid width in the earlywood and latewood tended to increase as the length of the tracheid increased. There was a significant positive correlation between the tracheid length and width in both the earlywood ($r = 0.455$, *p*-value less than or equal to 0.05) and latewood ($r = 0.596$, *p*-value less than or equal to 0.01). Similarly, Bannan (1965) reported that the length to width ratio of the tracheids increased as the mean tracheid length increased in conifer species.

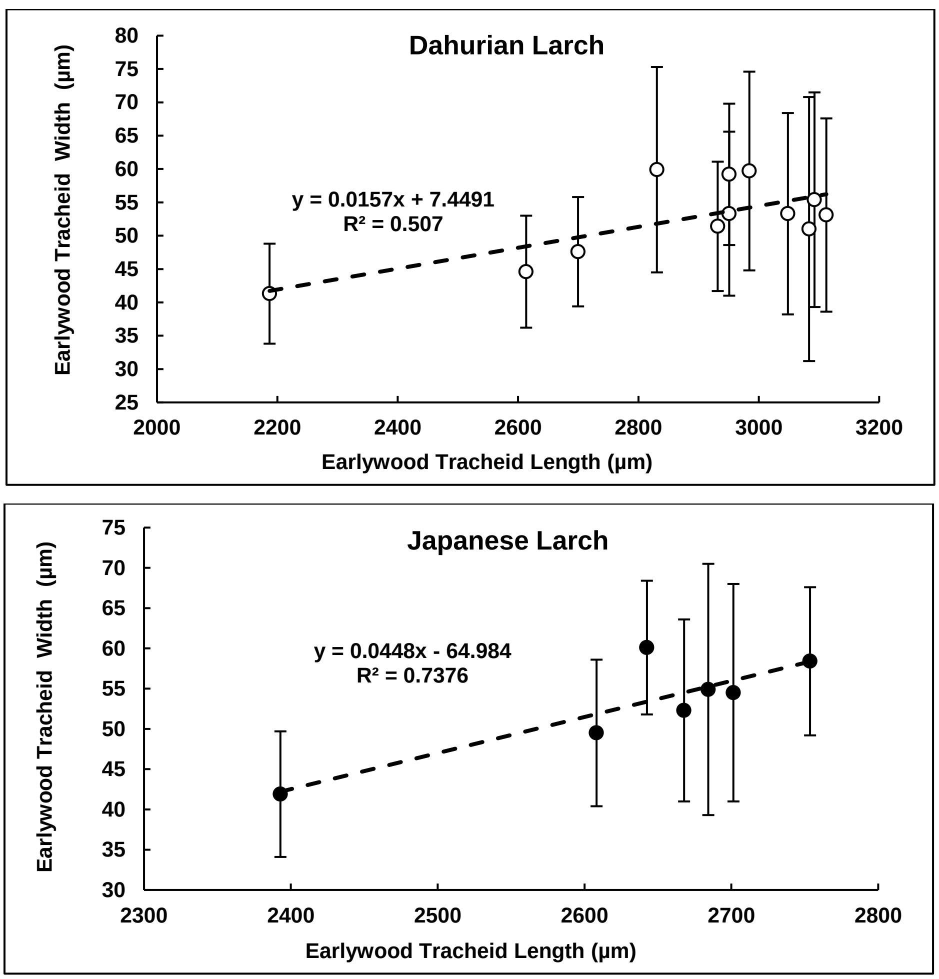

Fig. 3. Relationships between the length and width in earlywood tracheids of Dahurian larch (above) and Japanese larch wood (below)

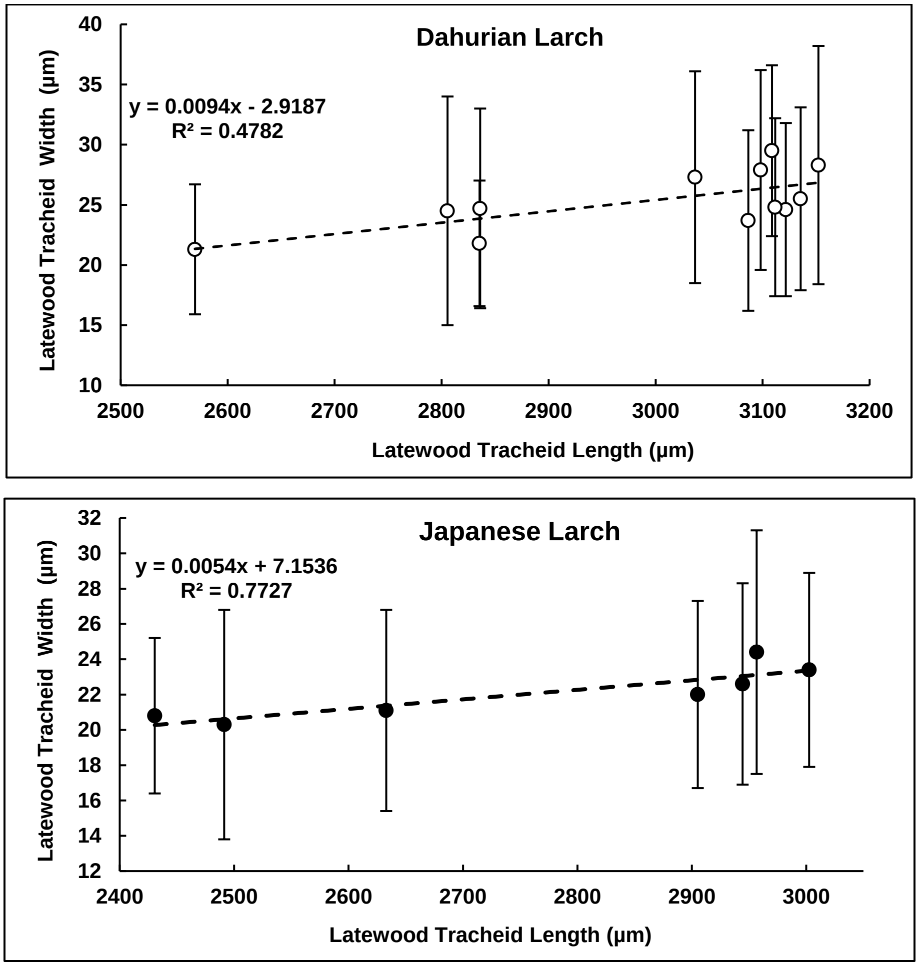

Fig. 4. Relationships between the length and width in the latewood tracheids of Dahurian larch (Lg) and Japanese larch wood (Lk)

Crystalline properties

The relative crystallinity and crystallite width of Dahurian and Japanese larch wood are listed in Table 2.

Table 2. Crystalline Properties of Both Larch Woods

		Dahurian Larch	Japanese Larch	p-value
Relative Crystallinity (%)	Earlywood	61.6 ± 6.1 (52.1 to 71.4)	69.8 ± 5.7 (54.5 to 81.2)	0.004**
	Latewood	64.1 ± 7.4 (48.7 to 73.8)	76.3 ± 4.3 (67.9 to 82.4)	0.000**
	p-value	0.347	0.009**	-
	Average	62.8 ± 6.8 (52.1 to 73.8)	73.1 ± 6.0 (54.5 to 82.4)	0.000**
Crystallite Width (nm)	Earlywood	2.90 ± 0.09 (2.67 to 3.0)	2.84 ± 0.03 (2.79 to 2.89)	0.077
	Latewood	2.88 ± 0.05 (2.80 to 2.97)	2.87 ± 0.08 (2.73 to 3.00)	0.789
	p-value	0.576	0.411	-
	Average	2.89 ± 0.09 (2.67 to 3.00)	2.86 ± 0.05 (2.73 to 3.00)	0.156

Note: Numbers in parentheses indicate the ranges for each property; * denotes statistically significant at a p-value less than 0.05; ** denotes statistically significant at a p-value < 0.01.

The relative crystallinities of Dahurian and Japanese larch wood were 61.6± 6.1% and 69.8± 5.7% in earlywood, respectively, and 64.1± 6.1% and 76.3%± 4.3 in latewood, respectively. Japanese larch wood exhibited a significantly higher relative crystallinity compared to Dahurian larch wood, and the latewood in the Japanese larch showed a significantly higher relative crystallinity compared to the earlywood (p-value less than 0.01). In addition, there was no significant difference in the relative crystallinities of the earlywood and latewood of Dahurian larch wood.

The crystallite width in the earlywood of the Dahurian and Japanese larches was 2.90± 0.09 nm and 2.84± 0.03 nm, respectively, and the crystallite width in the latewood was 2.88± 0.05 nm and 2.87± 0.08 nm, respectively. There was no significant difference in the crystallite width between the two species or between the earlywood and the latewood.

Figures 5 and 6 show the radial variation in the relative crystallinity and crystallite width for both wood species; neither the relative crystallinity nor the crystallite width showed a constant trend as the number of growth rings increased.

The properties related to the crystalline and amorphous regions of cellulose play a very important role in the properties of wood. In particular, the relative crystallinity is proposed as a quality index to distinguish between juvenile and mature woods (Wellwood *et al*. 1974; Kim and Lee 1998; Andersson *et al*. 2003; Yeh *et al*. 2006; Eun *et al*. 2008; Esteban *et al*. 2015; Ishikura 2017; Purusatama and Kim 2018).

In this study, the authors found that there was a difference in the relative crystallinity between both species, but no variation in the radial direction was observed. Additionally, there was little difference in the crystallite width between the two species and no variability in the radial direction.

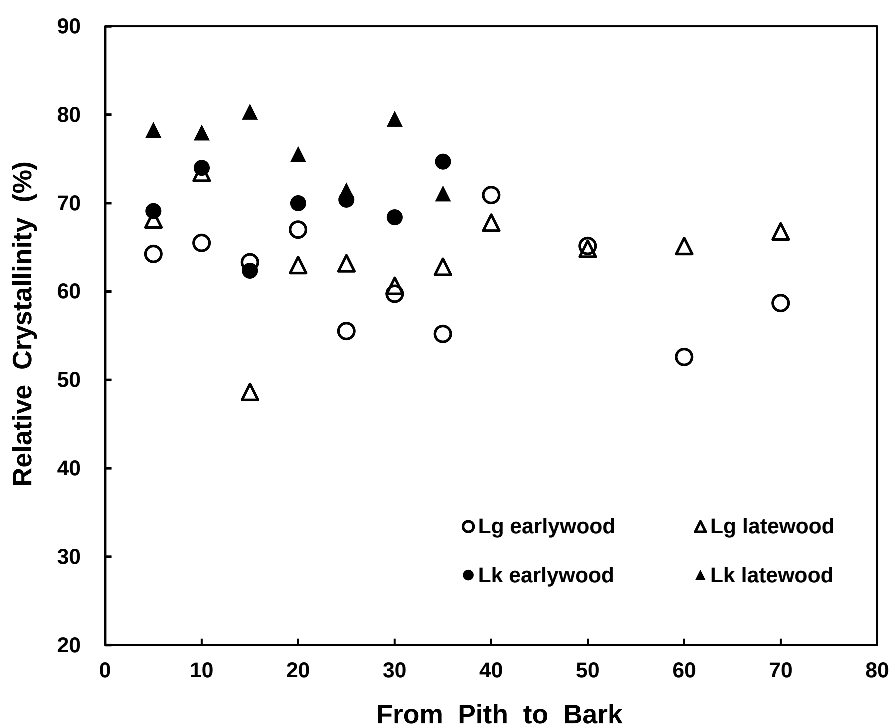

Fig. 5. Radial variation of the relative crystallinity in the earlywood and latewood of Dahurian (Lg) and Japanese (Lk) larch wood

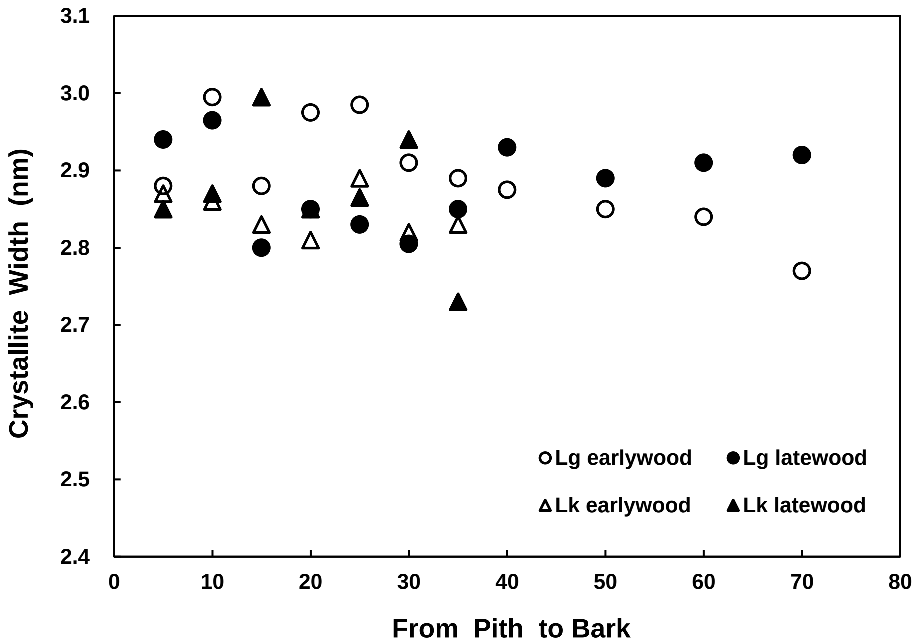

Fig. 6. Radial variation of the crystallite width in the earlywood and latewood of Dahurian (Lg) and Japanese (Lk) larch wood

From this study, it is evident that the relative crystallinity could be used as a species identification index for differentiation between Dahurian and Japanese larch wood, but it is also clear that the crystalline characteristics cannot be used as a quality index for determining the boundary of juvenile and mature wood.

CONCLUSIONS

1. The tracheid length and width in both the earlywood and latewood of Dahurian larch were higher than the tracheid length and width of Japanese larch, and they tended to increase toward the bark until stabilization.
2. There was a significant positive correlation between the tracheid length and tracheid width in the earlywood and latewood of both species.
3. The relative crystallinity in the earlywood and latewood of Japanese larch was higher than the relative crystallinity in Dahurian larch, and there was no difference in the crystallite width between the two species. There was no radial variation in the crystalline properties of either species.
4. In conclusion, the tracheid properties and relative crystallinity can be used as indices for wood quality evaluation and wood identification in both species.

ACKNOWLEDGMENTS

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF), which is funded by the Ministry of Education (Grant No. NRF-2016R1D1A1B01008339 and Grant No. NRF-2018R1A6A1A03025582) and the Science and Technology Support Program through the NRF, which is funded by the Ministry of Science and ICT (Grant No. NRF-2019K1A3A9A01000018). In addition, the authors would like to thank Editage (www.editage.co.kr) for English language editing.

REFERENCES CITED

Andersson, S., Serimaa, R., Paakkari, T., Saranpää, P., and Pesonen, E. (2003). "Crystallinity of wood and the size of cellulose crystallites in Norway spruce (*Picea abies*)," *Journal of Wood Science* 49(6), 531-537. DOI: 10.1007/s10086-003-0518-x

Bannan, M. W. (1965). "The length, tangential diameter, and length/width ratio of conifer tracheids," *Canadian Journal of Botany* 43(8), 967-984. DOI: 10.1139/b65-109

Burley, J. (1969). "Tracheid length variation in a single tree of *Pinus kesiya* Royle ex Gord," *Wood Science and Technology* 3(2), 109-116. DOI: 10.1007/BF00639635

Chong, S. H., and Park, B. S. (2008). *Wood Properties of the Useful Tree Species Grown in Korea*, Korea Forest Research Institute, Seoul, Korea.

Donaldson, L. (2008). "Microfibril angle: Measurement, variation and relationships – A review," *IAWA Journal* 29(4), 345-386. DOI: 10.1163/22941932-90000192

Entwistle, K. M., and Terrill, N. J. (2000). "The measurement of the micro-fibril angle in soft-wood," *Journal of Materials Science* 35(7), 1675-1684. DOI: 10.1023/A:1004755913978

Eom Y. G. (2015). "Wood anatomy of Korean species," *IAWA Journal* 36(4), 465. DOI: 10.1163/22941932-90001669.

Esteban, L. G., Simón, C., Fernández, F. G., Palacios, P. d., Martín-Sampedro, R., Eugenio, M. E., and Hosseinpourpia, R. (2015). "Juvenile and mature wood of *Abies pinsapo* Boissier: Sorption and thermodynamic properties," *Wood Science and Technology* 49(4), 725-738. DOI: 10.1007/s00226-015-0730-z

Eun, D.-J., Kwon, S.-M., and Kim, N.-H. (2008). "Variation of fine structure of wood cellulose within stems of 3 commercial softwood species grown in Korea," *Journal of the Korean Wood Science and Technology* 36(1), 12-20. DOI: 10.5658/WOOD.2008.36.1.012

Fabisiak, E., Fabisiak, B., and Krauss, A. (2020). "Radial variation in tracheid lengths in dominant trees of selected coniferous species," *BioResources* 15(4), 7330-7341. DOI: 10.15376/biores.15.4.7330-7341

Fonti, P., Tabakova, M. A., Kirdyanov, A. V., Bryukhanova, M. V., and Arx, G. v. (2015). "Variability of ray anatomy of *Larix gmelinii* along a forest productivity gradient in Siberia," *Trees* 29(4), 1165-1175. DOI: 10.1007/s00468-015-1197-0

Franklin, G. L. (1945). "Preparation of thin sections of synthetic resins and wood-resin composites, and a new macerating method for wood," *Nature* 155(3924), 51. DOI: 10.1038/155051a0

Gogoi, B. R., Sharma, M., and Sharma, C. L. (2019). "Tracheid length variation in *Pinus kesiya* Royle ex Gord. as affected by age, distance from pith, growth rate and ring width," *Journal of Tree Sciences* 37(2), 55-61. DOI: 10.5958/2455-7129.2018.00017.1

Han, Y., Kim, M.-J., Lee, H.-M., Kang, J.-T., and Eom, C.-D. (2017). "Comparison of cellular anatomical, physical and mechanical properties between Dahurian larch and Japanese larch," *Journal of the Korean Wood Science and Technology* 45(5), 525-534. DOI: 10.5658/WOOD.2017.45.5.525

Herman, M., Dutilleul, P., and Avella-Shaw, T. (1998). "Intra-ring and inter-ring variations of tracheid length in fast-grown versus slow-grown Norway spruces (*Picea abies*)," *IAWA Journal* 19(1), 3-23. DOI: 10.1163/22941932-90000648

Hwang, K., and Park, B.-S. (2007). "Strength properties of old Korean larch pile," *Journal of the Korean Wood Science and Technology* 35(6), 23-30.

IAWA Committee (2004). *IAWA List of Microscopic Features for Softwood Identification*, Leiden, Netherlands. DOI: 10.1163/22941932-90000349

Ishikura, Y. (2017). "Structural and bending properties of juvenile and mature softwood," *Cellulose Chemistry and Technology* 51(9-10), 879-887.

Kim, N.-H., and Lee, K.-Y. (1998). "Variation of crystalline state in a stem of *Chamaecyparis obtusa* E," *Journal of the Korean Wood Science and Technology* 26(4), 20-25.

Kim, B.-R., and Mishiro, A. (1998). "Studies on variability of wood properties in stem of *Pinus koraiensis* (II) - Differences in tracheid length, microfibril angle, and compression strength in south and north sides of stem," *Journal of the Korean Wood Science and Technology* 26(2), 45-50.

Kim, N.-H., Kwon, S.-M., and Chun, K.-W. (2009). "Radial variation of rays in two commercial softwoods grown in Korea," *Wood and Fiber Science* 41(2), 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 Journal* 42(2), 134-142. DOI: 10.1163/22941932-bja10031

Koizumi, A., Takata, K., Yamashita, K., and Nakada, R. (2003). "Anatomical characteristics and mechanical properties of *Larix sibirica* grown in south-central Siberia," *IAWA Journal* 24(4), 355-370. DOI: 10.1163/22941932-90000341

Lindström, H. (2007). "Fiber length, tracheid diameter, and latewood percentage in Norway spruce: Development from pith outward," *Wood and Fiber Science* 29(1), 21-34.

Mäkinen, H., Hynynen, J., and Penttilä, T. (2015). "Effect of thinning on wood density and tracheid properties of Scots pine on drained peatland stands," *Forestry: An International Journal of Forest Research* 88(3), 359-367. DOI: 10.1093/forestry/cpv006

Panshin, A. J., and Zeeuw, C. (1980). *Textbook of Wood Technology*, McGraw-Hill, New York, NY.

Purusatama, B. D., and Kim, N. H. (2018). "Quantitative anatomical characteristics of compression wood, lateral wood, and opposite wood in the stem wood of *Ginkgo biloba* L.," *BioResources* 13(4), 8076-8088. DOI: 10.15376/biores.13.4.8076-8088

Rahman, M. M., Fujiwara, S., and Kanagawa, Y. (2005). "Variations in volume and dimensions of rays and their effect on wood properties of teak," *Wood and Fiber Science* 37(3), 497-504.

Rlee, S.-M., and Kim, B.-R. (2005). "Studies on variability of wood properties within stem of *Larix kaempferi* (II) - Difference in tracheid length and width, microfibril

angle, and strength in south and north sides of stem," *Journal of the Korean Wood Science and Technology* 33(1), 21-28.
Sarén, M.-P., Serimaa, R., Andersson, S., Paakkari, T., Saranpää, P., and Pesonen, E. (2001). "Structural variation of tracheids in Norway spruce (*Picea abies* [L.] Karst.)," *Journal of Structural Biology* 136(2), 101-109. DOI: 10.1006/jsbi.2001.4434
Scherrer, P. (1918). "Determination of the size and internal structure of colloidal particles using X-rays," *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen* 17, 98-100.
Segal, L., Creely, J. J., Martin Jr., A. E., and Conrad, C. M. (1959). "An empirical method for estimating the degree of crystallinity of native cellulose using the X-ray diffractometer," *Textile Research Journal* 29(10), 786-794. DOI: 10.1177/004051755902901003
Senft, J. F., and Bendtsen, B. A. (1985). "Measuring microfibrillar angles using light microscopy," *Wood and Fiber Science* 17(4), 564-567.
Seth, M. K. (1981). "Variation in tracheid length in Blue pine (*Pinus wallichiana* A. B. Jackson)," *Wood Science and Technology* 15(4), 275-286. DOI: 10.1007/BF00350945
Wellwood, R. W., Sastry, C. B. R., Micko, M. M., and Paszner, L. (1974). "On some possible specific gravity, holo-and α-cellulose, tracheid weight/length and cellulose crystallinity relationships in a 500-year-old Douglas-fir tree," *Holzforschung* 28(3), 91-94. DOI: 10.1515/hfsg.1974.28.3.91
Yeh, T.-F., Braun, J. L., Goldfarb, B., Chang, H., and Kadla, J. F. (2006). "Morphological and chemical variations between juvenile wood, mature wood, and compression wood of loblolly pine (*Pinus taeda* L.)," *Holzforschung* 60(1), 1-8. DOI: 10.1515/HF.2006.001
Yoshizawa, N., Kiyomiya, M., and Idei, T. (1987). "Variations in tracheid length and morphological changes in tracheid tips associated with the development of compression wood," *Wood Science and Technology* 21(1), 1-10. DOI: 10.1007/BF00349713
Zhu, J., Nakano, T., and Hirakawa, Y. (1998). "Effect of growth on wood properties for Japanese larch (*Larix kaempferi*): Differences of annual ring structure between corewood and outerwood," *Journal of Wood Science* 44(5), 392-396. DOI: 10.1007/BF01130453
Zhu, J., Nakano, T., and Hirakawa, Y. (2000). "Effects of radial growth rate on selected indices for juvenile and mature wood of the Japanese larch," *Journal of Wood Science* 46(6), 417-422. DOI: 10.1007/BF00765798

Article submitted: November 19, 2021; Peer review completed: December 19, 2021; Revised version received and accepted: March 7, 2022; Published: March 29, 2022.
DOI: 10.15376/biores.17.2.2768-2779