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A Comparative Study of the Bending Properties of Dahurian Larch and Japanese Larch Grown in Korea

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Abstract: The bending properties of Dahurian and Japanese larch grown in Korea were comparatively studied to facilitate the effective utilization of both species. The modulus of elasticity (MOE) and modulus of rupture (MOR) of the heartwood and sapwood of both species were observed in the tangential and radial directions using Korean standards. Overall, Dahurain larch showed better bending properties than Japanese larch. In the tangential direction, Dahurian larch had better properties than Japanese larch, but there was no difference in the radial direction between the species. In both species, the bending properties of the heartwood were better than those of the sapwood. In Dahurian larch, the bending properties in the tangential direction were greater than those in the radial direction, but there was no difference in either direction with Japanese larch. The bending properties of both species in both directions were positively correlated with latewood percentage and air-dry density. Bending properties in the radial direction had a negative correlation with the growth ring width, but there was no correlation between the growth ring width and bending properties in the tangential direction for both species. Finally, the MOE of both species was significantly correlated with the MOR.

Keywords: bending properties; Dahurian larch; Japanese larch; MOE; MOR; physical properties; wood quality

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1. Introduction

The members of the *Larix* (Pinaceae) genus are deciduous trees that may be found worldwide, with approximately 10 species in America and Eurasia [1]. In Korea, there are two species: the Dahurian larch (*Larix gmelinii*) and Japanese larch (*Larix kaempferi*). While the Dahurian larch is native to the Korean Peninsula, the Japanese larch is an exotic species from Japan.

The wood of *Larix* species is highly valuable as a wood resource because of its high growth rate at a young age and the mechanical properties of the mature wood [2]. It is used for various purposes, such as building materials, flooring, furniture, decks, and railroad ties [3,4].

Dahurian larch is mainly distributed throughout North Korea and partially in South Korea, such as in the research forest of the Kangwon National University [5]. Furthermore, wood from the Dahurian larch is typically used as a building material because of its excellent durability and straight grain.

Japanese larch was introduced in Korea in 1904, and it is a species that is closely related to Dahurian larch [6]. Currently, Japanese larch is one of the major afforestation species in Korea, and it is widely used for various purposes.

The bending properties of wood—such as the modulus of rupture (MOR) and modulus of elasticity (MOE)—are crucial mechanical properties because, in most structures, wood is subjected to loads that cause it to bend [7].

Thus far, various studies have been performed on the bending properties of the wood of Dahurian larch and Japanese larch. These include research on the effect of the growth ring width on the mechanical properties of Dahurian larch [8]; correlation between MOE and the physical properties of a hybrid between *Larix decidua* and *Larix kaempferi* [9]; sampling method for estimating bending strength distribution in Japanese larch [10]; difference between juvenile and mature wood in Japanese larch and Dahurian larch [11]; distribution characteristics for visual grading of Japanese larch lumber [12]; effect of heartwood extractives on the mechanical properties of Japanese larch [13]; effect of thinning intensity on the mechanical properties of Dahurian larch [14]; effect of the lumber size on the mechanical properties of Dahurian larch [15]; anatomical, physical, and mechanical properties of Dahurian larch and Japanese larch [16]; wood and lumber properties of Dahurian Larch [17]; wood quality and strength properties of old structural members of Dahurian larch [4,5]; and cross laminated timber from Japanese larch [18].

In previous studies, we evaluated the ray properties, radial variation in the ray properties, and physical and mechanical properties of both species as wood identification and quality indices [19,20]. However, to date, there has been no comparative study on the bending properties of both wood species or between the sapwood and heartwood of both species grown in Korea. Moreover, there is no information on the relationship between the bending and physical properties of the wood of Dahurian larch and Japanese larch grown in Korea. Therefore, in this study, the bending properties and the relationship between the bending properties and physical properties of these two species were investigated and compared. This was done to provide basic information that can be used as wood quality indices for the efficient utilization of these tree species.

2. Materials and Methods

Three trees each of the Dahurian larch and Japanese larch were harvested from the research forest of the Kangwon National University in Chuncheon, Korea (37°77′ N, 127°81′ E). The samples used in assessing the bending properties were collected from the breast height of the trees. The logs were converted into quarter-sawn boards and the boards with straight-grain and free from defects were selected for the experiment. The basic information on the sampled trees is presented in Table 1.

Table 1. Basic information on the sampled trees.

Common Name	Scientific Name	Age (Years)	Height (m)	D.B.H. * (cm)
Dahurian larch	*Larix gmelinii var. olgensis* (A. Henry) Ostenf. and Syrach	71–72	20–22	32–33
Japanese larch	*Larix kaempferi* (Lamb.) Carriere	37–41	20–22	34–36

* D.B.H. is diameter in breast height.

2.1. Measurement of Physical and Bending Properties

Table 2 lists the number of specimens used for each experiment. First, a small clear specimen was chosen with dimensions of 20 (T) × 20 (R) × 300 (L) mm to assess the bending properties of the heartwood and sapwood of Dahurian and Japanese larches, according to the KS F 2208 2020 [21]. Before the measurement, the specimens were stored in a thermo-hygrostat (TH3-PE-65, JEIO TECH, Daejeon, Korea) at 20 ± 2 °C and RH 65 ± 3% until the moisture content of the specimen reached 12%.

Table 2. Number of specimens for each experiment.

Experiments (Standard)		Number of Specimen	
		Dahurian Larch	Japanese Larch
Physical properties	Growth ring width and latewood percentage (KS F 2202; 2016) [22]	40 (heartwood) 40 (sapwood)	40 (heartwood) 40 (sapwood)
	Air-dry density (KS F 2198; 2016) [23]		
MOR and MOE (KS F 2208) [21]	Radial direction	20 (heartwood) 20 (sapwood)	20 (heartwood) 20 (sapwood)
	Tangential direction	20 (heartwood) 20 (sapwood)	20 (heartwood) 20 (sapwood)

The physical properties of the specimens—such as the growth ring width, latewood percentage (KS F 2202; 2016) [22], and air-dry density (KS F 2198; 2016) [23]—were measured following the Korean standard. Additionally, the bending properties in the radial and tangential directions were examined, according to the Korean standard (KS F 2208 2020) [21], using a universal testing machine (no. 4482 Model, Instron, MA, USA) at a load speed of 5.0 mm/min with span length of 280 mm.

2.2. Statistical Analysis

One-way ANOVA tests were performed to analyze the significant differences in bending properties between the hardwood and sapwood of both species, and the force direction. In addition, the relationship between the bending and physical properties was analyzed using correlation and regression tests. Statistical analyses were performed using IBM SPSS Statistics for Windows (version 24.0; IBM Corp., Armonk, NY, USA) and Microsoft Excel 365 (Microsoft Corp., Santa Rosa, CA, USA).

3. Results

3.1. Physical Properties

Table 3 summarizes the physical properties of the Dahurian and Japanese larch specimens. The growth ring width in the heartwood of Dahurian larch was 2.0 mm, and that of Japanese larch was 4.6 mm. In the sapwood, the growth ring was 1.8 mm for the Dahurian larch and 2.6 mm for the Japanese larch. Average values were 1.9 mm in the Dahurian larch and 3.7 mm in Japanese larch. In our previous study [20], the growth ring widths of Dahurian larch and Japanese larch were 2.7 mm and 4.3 mm, respectively. For comparison, Ishiguri et al. (2019) [17] reported that the annual ring width of *Larix gmelinii* grown in Japan was 2.1 mm. In addition, Han et al. (2017) [16] reported that the growth ring widths of Dahurian larch and Japanese larch were 1.02 mm and 2.09 mm, respectively. Moreover, Hwang et al. (2008) [4] reported that the growth ring of Dahurian larch was 0.6–1.5 mm wide.

The latewood percentage of Dahurian larch was 42.6% in heartwood and 41.7% in sapwood, and the average was 42.2%. For Japanese larch, the latewood percentage was 31.3% in heartwood and 36.5% in sapwood, and the average was 33.7%. Kim et al. (2021) [20] reported that the latewood portion of Dahurian larch was 42%, whereas that of Japanese larch was 35%. Moreover, Han et al. (2017) [16] reported that the latewood percentages of Dahurian larch and Japanese larch were 40.3% and 31.9%, respectively. In addition, as reported by Koizumi et al. (2005) [24], the latewood percentage of Japanese larch was 11%–34%.

Table 3. Physical properties of Dahurian larch and Japanese larch.

	Species	Heartwood	Sapwood	Average
Growth ring width (mm)	Dahurian Larch	2.0 (0.4) * 1.5–3.0	1.8 (0.4) * 1.0–2.8	1.9 (0.4) * 1.0–3.0
	Japanese Larch	4.6 (1.1) * 2.8–7.0	2.6 (0.4) * 2.0–3.4	3.7 (1.3) * 2.0–7.0
Latewood percentage (%)	Dahurian Larch	42.6 (5.0) * 29.3–51.7	41.7 (4.4) * 34.1–50.2	42.2 (4.7) * 29.3–51.7
	Japanese Larch	31.3 (5.1) * 21.5–42.6	36.5 (4.9) * 24.6–46.4	33.7 (5.8) * 21.5–46.4
Air-dry density (g/cm^3)	Dahurian Larch	0.71 (0.05) * 0.63–0.80	0.57 (0.03) * 0.49–0.61	0.65 (0.08) * 0.49–0.80
	Japanese Larch	0.53 (0.04) * 0.43–0.63	0.52 (0.03) * 0.45–0.58	0.53 (0.04) * 0.43–0.63

Note: Numbers in parentheses are standard deviations. *: the range values.

The air-dry density in the sapwood of Dahurian larch was 0.57 g/cm^3, and that of Japanese larch was 0.52 g/cm^3. In heartwood, the air-dry densities of Dahurian larch and Japanese larch were 0.71 g/cm^3 and 0.53 g/cm^3, respectively. In addition, the average air-dry density was 0.65 g/cm^3 in Dahurian larch and 0.53 g/cm^3 in Japanese larch. As reported by Kim et al. (2021b) [20], the air-dry density of Dahurian larch was 0.75 g/cm^3, and that of Japanese larch was 0.58 g/cm^3. Furthermore, Hwang et al. (2008) [4] reported that the air-dry density of Dahurian larch wood was 0.73 g/cm^3; Chong and Park (2008) [6] reported that the air-dry density of Japanese larch wood was 0.61 g/cm^3; and Koizumi et al. (2005) [24] reported the air-dry density of Japanese larch as 546 kg/m^3 in outerwood and 536 kg/m^3 in corewood.

It seems that the difference in air-dry density is related to the latewood portion and extractives between heartwood and sapwood of both species. Ishiguri et al. (2019) [17] reported that basic density of *Larix gmelinii* var. *olgensis* showed significant positive correlation with the latewood portion, while there was no significant correlation between basic density and growth ring width. Additionally, as mentioned by Cáceres et al. (2017) [25], the basic density and oven-dry density of *L. kaempferi* were correlated to the amounts of hot water extractives. Further study is needed for evaluating the relationship between extractive and density of heartwood and sapwood in both species.

3.2. Bending Properties

Table 4 shows the bending properties in radial and tangential direction of Dahurian larch and Japanese larch. The average values of bending properties between both species were slightly different in the radial direction, whereas there were significant differences between both species in the tangential direction. The MOR in the radial direction was 72.8 MPa for Dahurain larch and 70.7 MPa for Japanese larch, and the MOR in the tangential direction of Dahurian and Japanese larch was 87.2 MPa and 72.2 MPa, respectively. The MOE in the radial direction of both species was 7.8 GPa, whereas the MOE in the tangential direction was 8.8 GPa for Dahurian larch and 7.6 GPa for Japanese larch.

Table 4. Bending properties of Dahurian larch and Japanese larch.

Directions	Parts	*n*	MOR (MPa) DL	MOR (MPa) JL	*p*-Value	MOE (GPa) DL	MOE (GPa) JL	*p*-Value
Radial	Sapwood	40	62.0 (2.3)	68.0 (5.8)	0.01 *	5.9 (0.7)	7.6 (0.7)	0.00 *
	Heartwood	40	80.6 (3.8)	72.8 (10.4)	0.01 *	9.1 (0.7)	8.0 (1.1)	0.00 *
	p-value		0.00 *	0.18		0.00 *	0.29	
Tangential	Sapwood	40	85.2 (4.4)	62.4 (6.1)	0.00 *	8.3 (1.1)	6.8 (0.4)	0.00 *
	Heartwood	40	88.7 (8.9)	80.0 (5.8)	0.01 *	9.1 (0.8)	8.2 (0.4)	0.00 *
	p-value		0.27	0.00 *		0.07	0.00 *	
Average	Radial	80	72.8 (9.9)	70.7 (8.9)	0.43	7.8 (1.7)	7.8 (1.0)	0.97
	Tangential	80	87.2 (7.4)	72.2 (10.7)	0.00 *	8.8 (1.0)	7.6 (0.8)	0.00 *
	p-value		0.00 *	0.58		0.02 *	0.42	

Notes: Numbers in parentheses are standard deviations. *: The difference was significant at the level of 5%; DL: Dahurian larch; JL: Japanese larch.

The bending properties in the tangential direction of Dahurian larch were higher than those of Japanese larch. The significant differences between the average values of bending properties in radial and tangential direction were only shown in Dahurian larch. In addition, the bending properties in the tangential direction of Dahurian larch were greater than those in the radial direction.

The bending properties of Dahurian larch showed a higher value compared to those of Japanese larch except for sapwood in the radial direction. In the radial direction, the bending properties of Dahurian larch showed significant difference between sapwood and heartwood, but there was no difference between sapwood and heartwood in Japanese larch. In the tangential direction, the bending properties between sapwood and heartwood of both species showed opposite tendency compared to the radial direction. The bending properties of heartwood in both species were higher than those of sapwood.

Many studies have been conducted on the bending properties of *Larix* species. Hwang and Park (2007) [5] reported that the MOR and MOE in the bending test of *Larix gmelinii* wood, which was excavated round pile from old construction, were 84.4 MPa and 9.9 GPa, respectively. Hwang et al. (2008) [4] explained that the MOR and MOE of *Larix gmelinii* wood under air-dry conditions were 98.4 MPa and 12.8 GPa, respectively. In addition, Ishiguri et al. (2019) [17] reported that the MOR and MOE of the bending properties on the radial surface of *Larix gmelinii* var. olgensis were 60.4 MPa and 8.06 GPa. Chong et al. (2014) [14] reported that the MOR and MOE of *Larix kaempferi* wood under air-dry conditions were 107.35 MPa and 10.7 GPa. Han et al. (2017) [16] reported that the MOR and MOE in Dahurian larch was 87.5 MPa and 10.8 GPa, respectively, while those of Japanese larch were 84.1 MPa and 10.1 GPa. Bao et al. (2001) [11] reported that the MOR and MOE of *Larix olgensis* grown in China were 99.5–116.2 MPa and 14.9–18.6 GPa, respectively, while those of *Larix kaempferi* were 90.2–134.5 MPa and 12.9–21.4 GPa, respectively. The bending properties of Dahurian larch in our study were in line with those of previous studies [4,5,16,17]. However, the bending properties of Japanese larch in our study were lower than those reported by Bao et al. (2001) [11], Chong et al. (2014) [14], and Han et al. (2017) [16]. The differences among the studies could be due to the age and growth conditions of the sample trees. Regarding the difference between bending properties in the radial and tangential directions of larch, Borůvka et al. (2020) [26] reported that there were no differences in the bending strength of European larch between the radial and tangential directions, which is in line with the bending properties of Japanese larch observed in our study. In contrast, Güray et al. (2019) [27] revealed that the MOR and MOE of Scotch pine, Black pine, Siberian pine, Stone pine, Nordmann fir, Oriental spruce, and Lebanon cedar were higher in the tangential direction than in the radial direction.

3.3. Relationship between the Physical and Bending Properties

The relationships between the bending properties and the growth ring width, latewood percentage, and air-dry density of both species are presented in Figures 1–3, respectively. In addition, the Pearson's correlation coefficient values between the bending properties and physical properties of both species are summarized in Table 5.

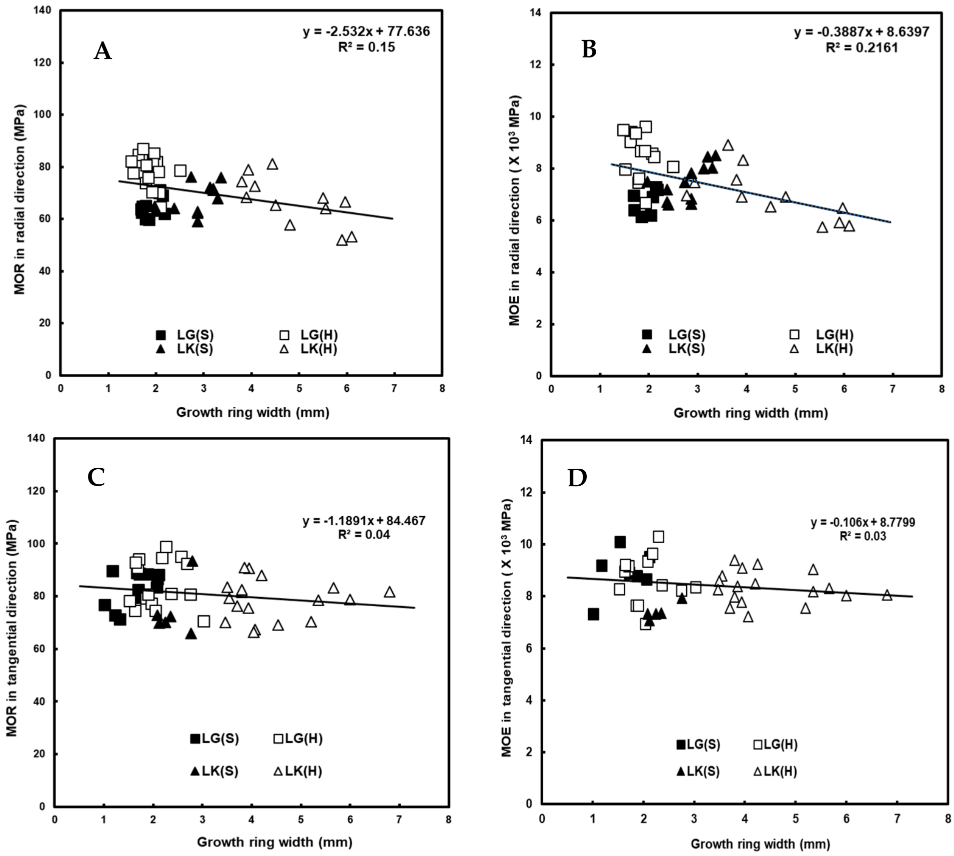

Figure 1. Relationship between growth ring width and bending properties in the radial (**A**,**B**) and tangential directions (**C**,**D**) of the sample species. LG: *Larix gmelinii*; LK: *Larix kaempferi*; S: Sapwood; H: Heartwood.

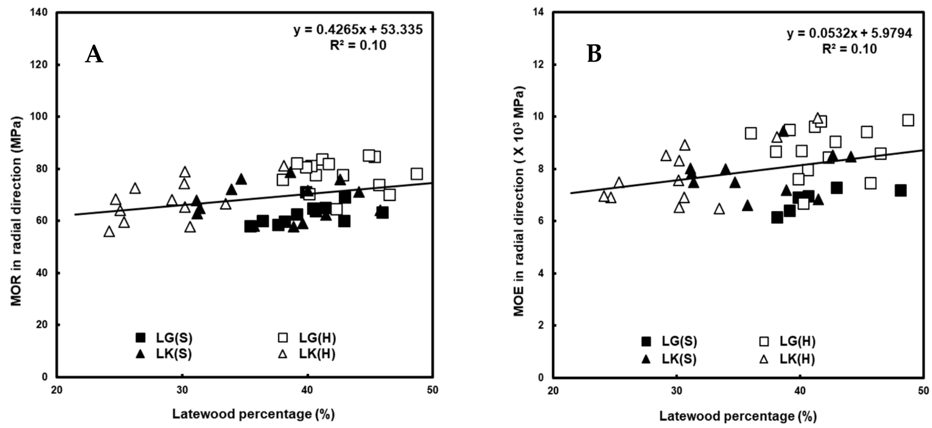

Figure 2. *Cont.*

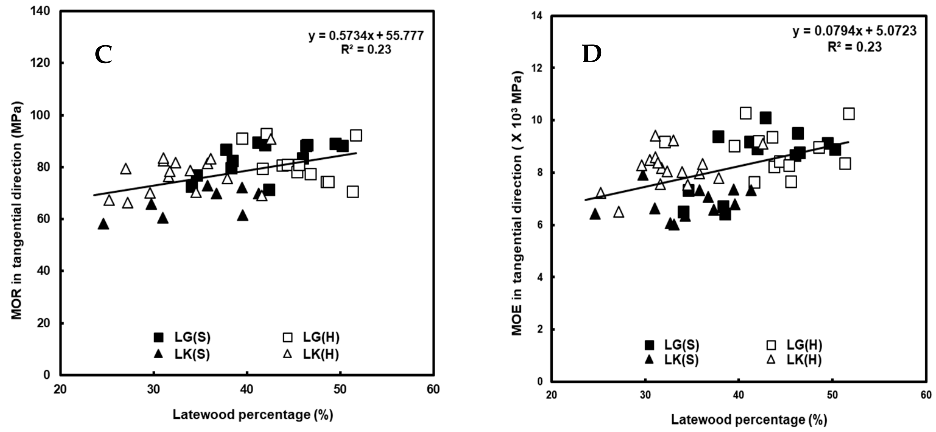

Figure 2. Relationship between latewood percentage and bending properties in the radial (**A**,**B**) and tangential directions (**C**,**D**) of the sample species. LG: *Larix gmelinii*; LK: *Larix kaempferi*; S: Sapwood; H: Heartwood.

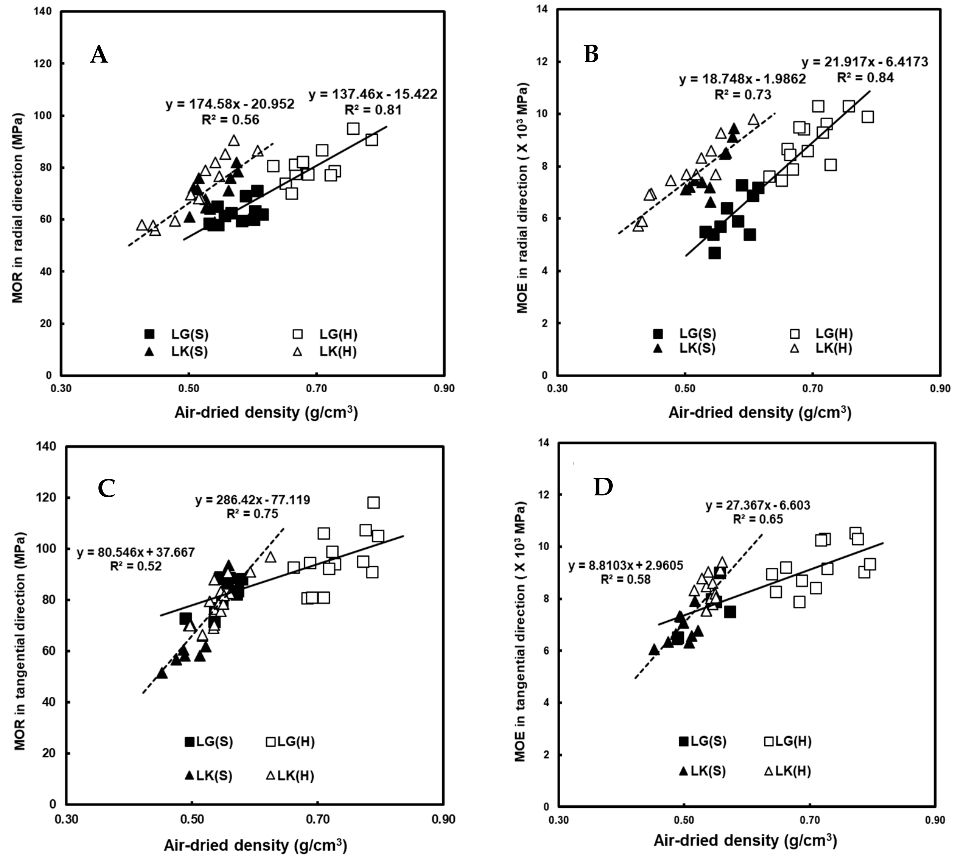

Figure 3. Relationship between air-dry density and bending properties in the radial (**A**,**B**) and tangential directions (**C**,**D**) of the sample species. LG: *Larix gmelinii*; LK: *Larix kaempferi*; S: Sapwood; H: Heartwood.

There was a negative relationship between the growth ring width and the bending properties in the radial and tangential directions. The correlation coefficient between the growth ring width and the bending properties in the radial direction was higher than that in the tangential direction. Notably, the relationship between the bending properties in the tangential direction and growth ring width was insignificant. It might be caused by differences in the arrangement and orientation of cell components between radial and tangential direction. Further study is needed to evaluate the correlation between the anatomical characteristics and bending properties in radial and tangential direction.

Table 5. Pearson's correlation coefficient between bending and physical properties.

Bending Properties	Direction	Growth RingWidth	Latewood Percentage	Air-Dry Density	
				Dahurian Larch	Japanese Larch
MOR	Radial	−0.393 *	0.319 *	0.902 *	0.747 *
	Tangential	−0.181	0.475 *	0.719 *	0.861 *
MOE	Radial	−0.477 *	0.330 *	0.918 *	0.848 *
	Tangential	−0.182	0.482 *	0.757 *	0.806 *

* Correlation is significant at the 0.01 level (two-tailed).

The bending properties of both species showed a positive relationship with the latewood percentage and air-dry density. In addition, the relationship between the latewood percentage and the bending properties in the radial direction showed a higher correlation coefficient than that in the tangential direction. Furthermore, the relationship between the air-dry density and bending properties in the radial direction had a higher correlation coefficient than that in the tangential direction. The density showed the highest correlation coefficient with the bending properties among the physical properties.

There are many studies on the relationship between the bending and physical properties of larch species that support our results. As reported by Zhang (1995) [8], the bending properties of *Larix gmelini* were negatively correlated with the growth rate; however, the correlation was not significant, and the bending properties were strongly influenced by the specific gravity. Ishiguri et al. (2019) [17] reported that the bending properties of Dahurian larch showed a positive correlation with the latewood percentage, and the bending properties had a negative relationship with the annual ring width. Leban and Haines (1998) [9] reported that the MOE of a hybrid between *Larix decidua* and *Larix kaempferi* increased with a decreasing number of growth rings per centimeter, whereas the MOE showed a positive correlation with air-dry density and age. As reported by Koizumi et al. (2005) [24], the air-dry density of Japanese larch had a positive relationship with the latewood percentage, and the density and latewood percentage showed a negative correlation with the growth ring width. In addition, the authors mentioned that the density was consistent with the bending properties. Koizumi et al. (2003) [2] reported that the growth ring width of *Larix sibirica* showed a negative correlation with the bending properties and density, and the bending properties showed a positive correlation with density.

Figure 4 shows the relationship between the MOE and MOR of the Dahurian larch and Japanese larch in both directions. In both wood species, there was a high positive correlation between the MOE and MOR in the radial and tangential directions. The results of this study are consistent with those of many previous studies. Takeda and Hashizume (2000) [10] reported that the relationship between the MOR and MOE of *Larix kaempferi* showed a high correlation. Chong et al. (2014) [14] reported that the MOE of the bending properties of *Larix kaempferi* was positively correlated with the MOR. Hwang et al. (2008) [4] also reported a high positive correlation between the MOR and MOE of *Larix gmelinii*. Koizumi et al. (2003) [2] reported that the MOE of *Larix sibirica* obtained from bending tests showed a positive correlation with the MOR. Pearson and Ross (1984) [28] proposed that the MOR of loblolly pine showed an extremely high correlation with the MOE. Horáček et al. (2012) [29] reported that the MOE of Scotch pine was highly correlated with the MOR. Finally, Borůvka et al. (2020) [26] demonstrated the strong dependence between bending strength and static MOE in various wood species.

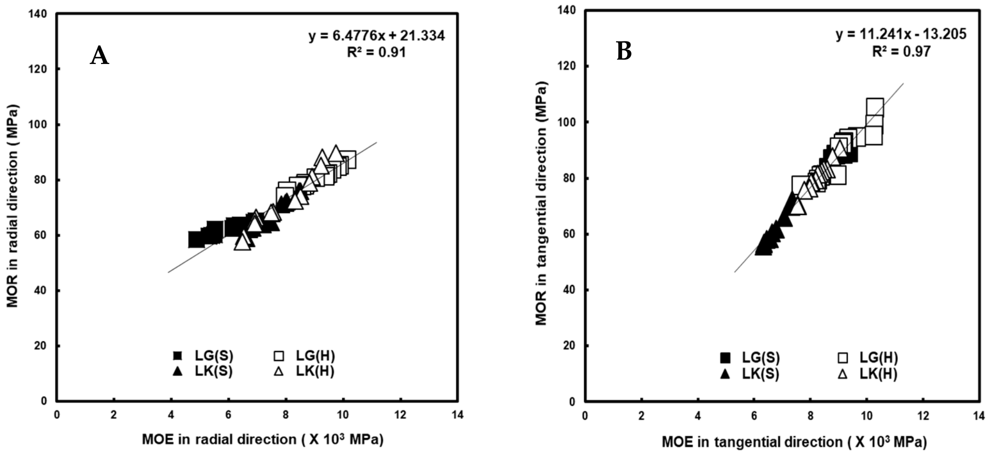

Figure 4. Relationship between the modulus of elasticity (MOE) and modulus of rupture (MOR) in the radial (**A**) and tangential (**B**) directions of the sample species. LG: *Larix gmelinii*; LK: *Larix kaempferi*; S: Sapwood; H: Heartwood.

4. Conclusions

The bending properties of Dahurian larch were significantly better than those of Japanese larch. The MOE and MOR in the tangential direction of the Dahurian larch were higher than those of the Japanese larch, and there was no significant difference between the MOR and MOE in the radial direction of both species.

In the Dahurian larch, the bending properties in the tangential direction were higher than those in the radial direction, but the bending properties were similar in the radial and tangential directions of the Japanese larch. In both species, the bending properties of the heartwood were better than those of sapwood.

The bending properties in the radial and tangential directions of both species were positively correlated with latewood percentage and air-dry density. The growth ring width had a significantly negative correlation with bending properties in the radial direction, but the correlation was insignificant in the tangential direction. The MOE of both species was significantly correlated with the MOR.

In conclusion, the differences in the bending properties of Dahurian larch and Japanese larch were revealed, and the results can be used as valuable information for the effective utilization of both wood species.

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Conflicts of Interest: The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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