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Effect of Growth Ring Width and Latewood Content on Selected Physical and Mechanical Properties of Plantation Japanese Larch Wood

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Abstract: In order to evaluate the physical and mechanical properties of plantation Japanese larch wood, various physical and mechanical indicators were measured with reference to Chinese national standards. The characteristics of the growth ring on the end face of wood samples were captured, with the mean latewood percentage being 21.4% and the mean ring width being 3.24 mm. Relationships between growth ring characteristics, latewood percentages, and the physical and mechanical properties of the plantation Japanese larch wood were investigated. The results revealed that it is most appropriate to use growth ring width to evaluate MOE and MOR, and to use latewood percentage to evaluate air-dry density, radial air-dry shrinkage, IBS and UTS. Regression analysis confirmed that air-dry density (R^2 = 0.99), radial shrinkage (R^2 = 0.97) and UTS (R^2 = 0.96) had significant positive correlations with latewood percentage, while MOE (R^2 = 0.88) and MOR (R^2 = 0.90) had significant negative correlations with RW. IBS was not significantly related to either characteristic. RW can be used to define juvenile wood and mature wood, with the dividing ring width being 4.85 mm. There is a large difference in MOE and MOR between the two wood types.

Keywords: plantation Japanese larch; tree ring analysis; physical properties; mechanical properties

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1. Introduction

Japanese larch has the characteristics of disease resistance, high survival rate, short period to maturity, straight tree trunks and excellent mechanical properties, and can readily be used as building and industrial materials [1–4]. However, the evaluation of its physical and mechanical properties is a key step needed in the process of improving the machining and application of timber from this source.

The structural characteristics of wood are closely related to its mechanical properties, such as the microfibril angle (MFA) of the cellulose within the S2-layer of the wood cell, the tracheid dimensions, and the cell wall thickness [5–7]. Density is generally considered a good indicator and is widely believed to be closely related to material properties [8,9]. However, density can be affected by the content of extracts and inorganic salts; thus, there may be large deviations when using only density to predict the physical and mechanical properties of tree species with high resin or gum content. Growth ring width (RW) and latewood (LW) percentage are also characteristics closely related to wood properties [10–12].

The formation and structure of growth rings are influenced by the environment [13,14]. Earlywood (EW) is formed in the early stage of the growth cycle, when the environment is conducive to active development, the cell wall is thin, the diameter of tracheid is large, and the MFA of S2 layer is high, while LW is formed in the late summer or autumn, with small diameter, tracheid wall thickness and MFA [15,16]. There may also be differences in the radial and tangential variation of cell walls between EW cells and LW cells. Laskowska found that the radial cell wall and tangential cell wall of LW cells have similar thicknesses,

while the thickness of EW cells is only similar in the tangential direction in the sapwood and heartwood zones of *Platycladus orientalis* [17]. Hence, due to the differences in cell structure between EW and LW, growth rings are a potentially powerful feature that can be used to assess the physical and mechanical properties of wood.

The width of a growth ring represents the radial growth of a tree during a growth cycle and can be subjected to considerable natural variation in growth conditions, including climatic conditions, nature of the terrain and silvicultural treatments [18,19].

Wood properties of different stand density but with similar trunk diameters will vary [20,21]. The width of the growth ring can be used to evaluate the physical and mechanical indicators of wood, such as the modulus of elasticity (MOE), the modulus of rupture (MOR), the ultimate tensile stress parallel to the grain (UTS), the specific gravity and the air-dry density [12,21–25]. Growth RW is positively correlated with MFA [26]. MFA is one of the key factors determining wood properties, and has a significant impact on the stiffness, strength and dimensional stability of wood [27–32]. However, the width of growth rings cannot reflect the effect of LW cells on wood properties. The mechanical properties of LW are generally better than those of EW [33–35]. Therefore, wood samples with similar RW but different LW percentage content will have different mechanical properties. Previous studies have focused on evaluating wood properties using the RW or LW percentage, and there are few reports using more complex analyses to evaluate wood physical and mechanical properties.

The purpose of this study is to explore the relationship between growth ring characteristics and wood properties of Japanese larch, and to provide numerical models that can be used to nondestructively, rapidly and reliably evaluate the properties of Japanese larch.

2. Materials and Methods

2.1. Materials

Plantation Japanese larch (species: *Larix kaempferi* (Lamb.) *Car.*; log diameter: 11~25 cm; initial moisture content: 50%; Age: between 13~25a) was harvested in January 2020 from a plantation in Shaba Town, Longnan City, Gansu Province, China (34°9′8″ N, 106°27′55″ E). The sampling spot is 1736 m above sea level, with an average soil thickness of 60 cm, gravel content less than 25%, and average annual precipitation of 635 mm. A total of 27 logs was collected. The samples were transported to the Chinese Academy of Forestry Sciences in Beijing. After sawing into 40 mm thick lumbers, they were exposed to the atmosphere until they were in an air-dry state (final moisture content: 12.9%, C.V. = 13%). Then, referring to the GB/T 1929-2009 standard [36], they were sawn and processed into small clear specimens, which were free of visible defects, knots, cracks, resin pockets. The reference standards used to determine the specimen specifications are given in Table 1 [36–42].

Table 1. Specimen sizes, quantities and the national *Chinese reference standards* used in their specification.

Properties	Size (R × T × L) (mm)	Quantity	National Reference Standard
Air-dry Density	20 × 20 × 20	109	GB/T1933-2009
Dry Shrinkage	20 × 20 × 20	109	GB/T 1932-2009
Modulus of Elasticity	20 × 20 × 300	196	GB/T 1936.2-2009
Modulus of Rupture	20 × 20 × 300	105	GB/T 1936.1-2009
Impact Bending Strength	20 × 20 × 300	83	GB/T 1940-2009
Longitudinal Tensile Strength	20 × 20 × 370	131	GB/T 1938-2009

2.2. Methods

2.2.1. Determination of Physical and Mechanical Properties

The radial air-drying shrinkage ratio is used to represent the dimensional stability of wood. To estimate this, according to the GB/T 1932-2009 standard [38], the size change of samples from saturated to air-dry and hygroscopic balance, and the weight change from air-dry to absolute drying are recorded.

The radial air-drying shrinkage ratio is calculated as follows:

$$S = (R_1 - R_0)/R_0 \times 100 \quad (1)$$

where R_1 is the radial length of a saturated sample (mm), and R_0 is the radial length of the sample in an air-dry state (mm).

The air-dry density is calculated as follows:

$$D = (W_0 - W_2)/W_2 \quad (2)$$

where W_0 is the weight of a sample in an air-dry state (g) and W_2 is the weight of the sample in a fully dry condition.

Using a universal mechanical testing machine (Model ALL-50KNB, loading speed 3 mm/min) and a pendulum impact testing machine, MOE (static four-point bending with a span of 240 mm), MOR (static three-point bending with a span of 240 mm), impact bending strength (IBS) and UTS of the larch samples were measured according to the corresponding national standards (Table 1).

MOE is calculated as follows:

$$MOE = \frac{23Pl^3}{108bh^3f} \quad (3)$$

where P is load (N); l is the span between two bearings (mm); b is the width of specimen (mm); h is the height of specimen (mm); f is displacement of specimen under load (mm).

MOR is calculated as follows:

$$MOR = \frac{3P_{max}l}{2bh^2} \quad (4)$$

where P_{max} is breaking load (N).

IBS is calculated as follows:

$$IBS = \frac{1000Q}{bh} \quad (5)$$

where Q is the energy absorbed by the sample (J).

UTS is calculated as follows:

$$UTS = \frac{P_{max}}{bt} \quad (6)$$

where t is the thickness of the specimen (mm).

2.2.2. Determination of Latewood Rate and Growth Ring Width

Photographs of the two end faces of a processed specimen were used to record growth ring characteristics. The images were imported into the ImageJ 1.53k, and the end face area was estimated. The LW area was manually extracted and recorded. The ratio of LW area to end face area is the LW percentage. Incomplete growth rings on the end face of the specimen were excluded, and the number of complete growth rings in the radial direction were counted. The distance from the first complete growth ring EW to the LW of the last complete growth ring was measured in the radial direction. Three measurements were taken at equal intervals apart, and the average value was then used. The ratio of this distance to the number of complete rings is the average RW. The end face image processing process is summarized in Figure 1.

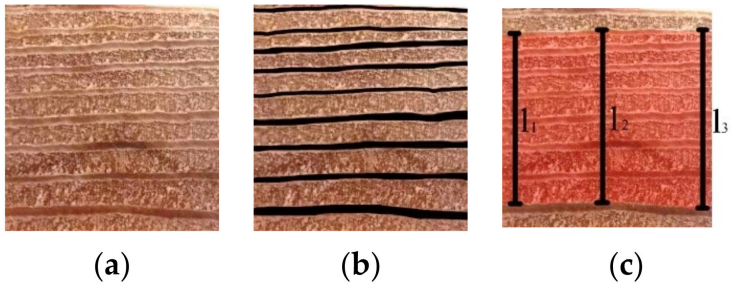


Figure 1. Three stages in the process used to record growth ring characteristics: (**a**) initial sample end face photograph; (**b**) manual extraction of latewood area; (**c**) three measurements of overall width of radial growth rings.

In order to facilitate the analysis of the relationship between growth rings and physical and mechanical properties, the samples were grouped according to their RW values and their LW percentages. The grouping criteria aimed, as much as possible, to make the number in each group approximately equal. The five resulting groups using RW were: RW <2.3 mm (R1); RW 2.3–3.3 mm (R2); RW 3.3–4.3 mm (R3); RW 4.3–5.3 mm (R4); RW >5.3mm (R5). The five resulting groups using LW percentage were: <17% (L1); 17–21% (L2); 21–25% (L3); 25–29% (L4); >29% (L5).

3. Results and Discussion

3.1. Relationship between Growth Ring Width and Latewood Percentage

Juvenile wood and mature wood that both form in suitable climates are the result of fast growth. The RW of juvenile wood is wider than that of mature wood. LW percentage decreased with RW (Figure 2), suggesting that the increase in RW was mainly because the increase in the growth of EW and the width of LW in most years was stable.

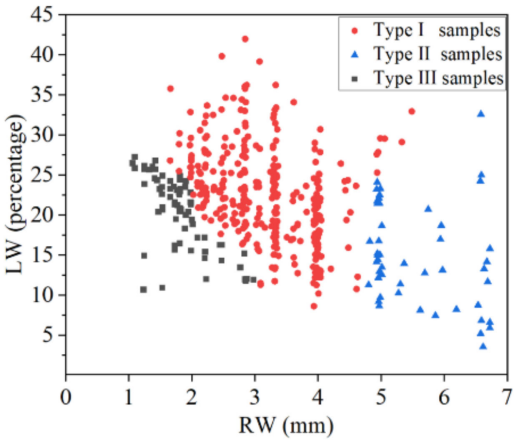


Figure 2. The relationship between latewood (LW) percentage and ring width (RW).

According to the relationship between the RW and the LW percentage (Figure 2), the samples can be roughly divided into three categories: Type I samples had a moderate RW and a high LW percentage, and the samples were mostly mature wood; Type II samples had a large RW and a small LW percentage, indicating that the proportion of juvenile wood in the samples was relatively high; Type III samples had small RW values and the percentage of LW was also small. Figure 3 presents typical cross-sectional images of type I, II, and III samples.

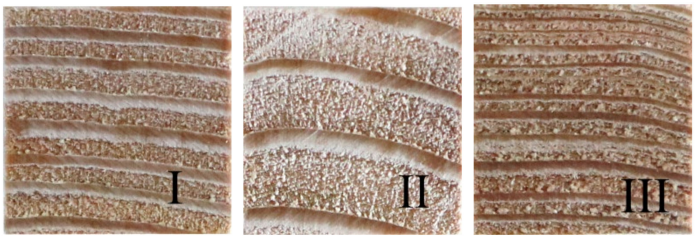


Figure 3. End face images of samples from three categories of larch wood: Type I (moderate ring width (RW), high latewood (LW) percentage); Type II (large RW, small LW percentage); Type III (small RW, small LW percentage).

3.2. The Relationship between Growth Rings and Physical Properties

The density and shrinkage were fitted with RW and LW percentage. It can be seen from Figure 4a that the radial air-drying shrinkage rate and air-dry density have a linear relationship with the LW percentage, with R^2 values of 0.99 and 0.97, respectively (Supplementary Materials Tables S1, S3, and S4), and the regression coefficients are −0.007 and 0.002, respectively. Radial air-drying shrinkage fluctuates with RW (Figure 4b), indicating that air-drying shrinkage is mainly related to the content of LW cells, and is less affected by RW. In our samples, air-dry density first decreased and then increased with the RW (Figure 4b), and the R^2 using a quadratic function fitting was 0.99 (Supplementary Materials Tables S1, S2 and S4), which is higher than the R^2 of fitting equation of LW percentage and density. LW lumens are smaller, and their cell walls are thicker [15]; hence, the density increases with LW percentage. Density is also affected by extractive content, lignin and other factors [43]. Generally, RW tends to decrease from the pith to the bark. From Table 2, it can be seen that the MOE and MOR decreased rapidly after an RW value of about 4.85 mm, indicating that this RW size is located in the transition area between juvenile wood and mature wood. The lignin content of juvenile wood is higher than that of mature wood, and the extract content is higher [15]; hence, the density increased when RW was greater than 4.85 mm. Since the RW can distinguish juvenile wood from mature wood, the use of RW can better reflect the influence of extract on density when evaluating density.

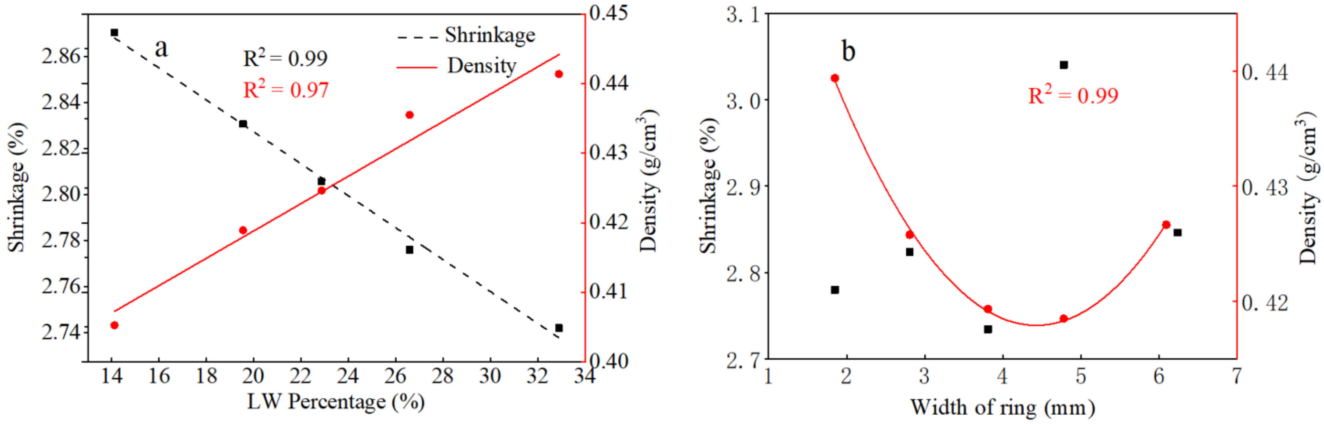


Figure 4. Influence of (**a**) latewood (LW) percentage and (**b**) ring width (RW) on shrinkage and density.

Table 2. Mechanical properties of Japanese larch for the five classifications of RW (R1 to R5) and of LW percentage (L1 to L5). See text for classification definitions. MOE: modulus of elasticity; MOR: modulus of rupture; IBS: impact bending strength; UTS: ultimate tensile stress parallel to the grain; CV: coefficient of variation.

Group		MOE				MOR				IBS				UTS			
		RW (mm)	Quantity	Mean (MPa)	CV (%)	RW (mm)	Quantity	Mean (Mpa)	CV(%)	RW (mm)	Quantity	Mean (kJ/m^2)	CV (%)	RW (mm)	Quantity	Mean (Mpa)	CV (%)
RW class	R1	1.80	49	12.92	17.18	1.83	23	93.85	14.50	1.83	26	57.55	27.28	1.87	34	107.58	23.48
	R2	2.76	52	11.53	18.75	2.81	33	83.53	17.12	2.75	15	42.17	28.94	2.86	38	99.02	33.17
	R3	3.72	60	11.92	18.67	3.77	27	83.63	13.14	3.71	29	49.93	49.23	3.71	43	109.40	31.15
	R4	4.85	20	11.02	25.86	4.85	12	86.15	39.53	4.84	8	37.71	51.98	4.89	11	89.54	33.80
	R5	6.14	11	8.83	18.29	6.00	8	65.11	15.95	6.50	3	46.16	67.37	6.33	5	92.55	30.88
LW Percentage class	L1	12.91	53	10.34	22.74	12.22	33	75.39	29.93	14.06	20	42.94	55.56	13.36	36	91.62	27.44
	L2	19.12	38	11.91	17.21	19.19	22	86.95	12.85	19.12	12	46.75	36.30	19.20	38	98.12	28.22
	L3	22.96	59	12.57	17.20	22.92	28	89.99	16.44	22.99	31	51.28	43.31	22.79	39	108.42	30.07
	L4	26.97	27	12.50	17.74	26.53	13	89.37	17.97	27.37	14	56.45	23.59	26.64	13	120.74	24.42
	L5	32.91	19	12.27	22.24	32.06	9	92.29	6.76	31.90	6	52.72	26.53	32.29	5	149.42	23.37

3.3. The Relationship between Growth Rings and Mechanical Properties

Table 2 presents the mechanical properties of Japanese larch for the five classes of RW and for the five classes of LW percentage (Supplementary Materials Tables S5–S8). The data were analyzed with ANOVA, and the results showed that MOE, MOR and UTS had significant relationships with RW and LW percentage, while IBS had no significant relationship with growth ring parameters (Supplementary Materials Table S9). MOE showed a strong relationship to RW and decreased with increasing RW. The MOE of samples from the R1, R2, R3 and R4 classes (mean 11.98 MPa) was significantly differently from that of samples in the R5 class (8.83 MPa). The R5 class (i.e., RW greater than 5.3 mm) specimens were mostly juvenile wood, which led to a significant decrease in MOE [44].

The modulus of the L1 class was significantly smaller than that of the other classes, and the difference between the other classes was small, which is mainly due to the fact that the L1 class contains juvenile wood with wide rings and low LW percentages and that type III specimens have fine growth rings and low LW percentage. The MFA is negatively correlated with mechanical strength, and the MFA of juvenile wood near pith is usually higher than mature wood [45,46].Therefore, type III samples and juvenile wood have significant MOE differences but cannot be distinguished according to their LW percentage; hence, it is better to evaluate MOE using RW.

The MOR of the R5 class (65.11 MPa) was significantly lower than that of the other four groups (average value is 86.39 MPa), indicating that the MOR of juvenile wood is significantly lower than that of mature wood. The MOR of the R5 class was also significantly lower than that of the L1 class, indicating that the L1 class contains type III samples (small LW percentage, small RW), which makes the MOR values of the L1 and the R5 classes differ considerably. The difference can be confirmed by two other aspects: (1) The coefficient of variation of the L1 class was greater than that of the R5 class, which indicates that juvenile wood and type III samples in L1 have low content of LW but the MOR of them are quite different. (2) The MOR of the R1 class was significantly higher than that of the R2, R3, and R4 classes, indicating that MOR is significantly increased when the RW is smaller than a certain threshold, which is similar to the RW of type III specimens. Therefore, when the MOR is grouped according to the RW, the samples can be divided into three sub-groups, i.e., juvenile wood samples, type III samples, and other groups of samples. These three sub-groups have average MOR values of 65.11, 93.85 and 84.01 MPa, respectively. In summary, and as was found for MOE, LW percentage cannot be used to distinguish juvenile wood samples from type III samples that exhibit large differences in MOR; hence, it is more appropriate to evaluate MOR using RW.

It can be seen from Table 2 that IBS fluctuated with RW. It is not as obvious, but IBS was also positively correlated with LW percentage. However, the IBS of the L5 class does not fit this trend, as it was lower than that of the L4 class, and it is speculated that there may be deviations in the value due to the small number of test samples used in the analysis. Compared with RW, LW percentage is more suitable for evaluating IBS, but due to the large variability of IBS in wood, this conclusion needs to be further verified.

UTS values fluctuated with RW with poor regularity (Table 2), while LW percentage showed a strong linear relationship with UTS, indicating that tensile strength along the grain is less affected by the growth rate of the wood and is affected more by the LW in the material. Michaela's micro-tensile test results on single tracheids also showed that there is a significant difference in tensile stiffness between early and late wood cells [47]. The difference in UTS in early and late wood cells can be attributed to the difference in density and MFA between them [32]. Hence, it is better to use the LW percentage to evaluate UTS.

The MOE, MOR, IBS and UTS were linearly fitted with RW and LW percentage, respectively, and the results are presented in Table 3.

Table 3. The results of linear fits of mechanical properties of plantation Japanese larch (i.e., MOE, MOR, UTS) to ring width (w) and latewood percentage (l).

Properties	Linear Fitting Equation	R^2
MOE	$y = -0.85w + 14.46$	0.88
	$y = 0.52l + 75.92$	0.56
MOR	$y = -6.33w + 105.22$	0.90
	$y = 0.58l + 37.35$	0.80
UTS	$y = -0.77w + 114.31$	0.59
	$y = 3.12l + 42.74$	0.96

MOE: modulus of elasticity; MOR: modulus of rupture; UTS: ultimate tensile stress parallel to the grain.

RW was negatively correlated with all three mechanical properties, while LW percentage was positively correlated with all three. Although the overall LW percentage was negatively correlated with RW, it can be affected by tree species, the environment, stress and other factors. As well as the radial and axial wood property variation of trees, the relationship between RW and LW percentage is not absolute [11]. Hence, for some mechanical properties, analyzing from the perspective of RW and LW percentage may produce contradictory results. In order to avoid this contradiction and obtain the most accurate evaluation results, it is necessary to know which LW percentage and RW has a greater impact on each mechanical indicator, and whether the correlation is sufficient such that it can be used in an evaluation.

From the R^2 of each fitting model obtained here (Table 3), it can be seen that the correlation of MOE, MOR with RW was relatively high, while the R^2 value of the UTS fitting to the LW percentage was high. This is consistent with the results discussed above. However, from the absolute value of R^2, the fitting degree of UTS is the best, and the fitting degree of the flexural performance is good. The fitting degree of the IBS is extremely poor (Supplementary Materials, Table S10). This indicates that growth ring parameters are reasonable to evaluate MOE, MOR and UTS but cannot be used to evaluate IBS.

The bending properties of wood are often affected by many factors. Alteyrac performed measurements on growth ring samples of Scots Pine. Bending properties of early wood and latewood were investigated with respect to their MFA, density and RW. A correlation of −0.47 was found between RW and MOE, while −0.42 was found between RW and MOR. This is consistent with the results shown in Table 3. The study found that, compared with the RW, the MFA and the growth ring density had a greater impact on the MOR, and MFA had a greater impact on MOE [10]. Majid also found that there were strong relationships between density and MOR but MOE showed weak correlations [48]. Ekiza measured the physical and mechanical properties of Scots Pine from diverse genetic origins and showed that the origin of the wood had a significant influence on wood density, MOR and MOE [49]. Therefore, RW can be used to assess the mechanical properties of larch without damage, but further evaluation of wood properties requires a combined analysis of all relevant indicators.

IBS is one of the most important properties for dynamic loading. The fitting equation showed that IBS was positively correlated with RW, and LW was negatively correlated, but due to the low value of R^2, it was not recommended to use the fitting equation to evaluate IBS (Supplementary Materials, Table S10). The IBS of wood is affected by many factors, including tree species, sample thickness, density and moisture content [50,51]. Almeida assessed the apparent density and IBS of thirty-six Brazilian tropical woods species by using linear, quadratic, and cubic polynomial regression models. The cubic polynomial model was found to be the most efficient tool to estimate wood IBS, with R^2 = 77.77% [52]. Pazos studied the IBS of test wood, with a density of 0.62 g/cm^3, in air-dry and green states and found that the IBS of the air-dry state was about 11.98% higher than that of the green state [51]. Therefore, it may be necessary to introduce moisture content and density to further evaluate IBS of Japanese larch.

4. Conclusions

In this study, MOR, MOE, IBS, UTS, air-dry density and dry shrinkage rate of Japanese larch were measured in accordance with Chinese national standards. The relationships between the characteristics of rings and the physical and mechanical properties of Japanese larch were explored. In summary:

(1) The LW percentage can be used to evaluate the air-drying shrinkage rate. The radial air-drying shrinkage rate (R^2 = 0.99) has a linear relationship with LW percentage. The RW has more advantages in density evaluation than LW percentage. Air-dry density first decreases and then increases with RW, and the R^2 of a quadratic fitting function was found to be 0.99.

(2) RW is more suitable for evaluating MOR and MOE than LW percentage. However, LW percentage is more suitable for evaluating UTS. The resulting fitting models can be used for accurate evaluations of Japanese larch wood properties. The RW and LW percentage of wood do not directly affect its impact resistance.

(3) The demarcation ring width between juvenile wood and mature wood would be about 4.85 mm, and the MOE and MOR of them are quite different.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13050797/s1, Table S1. Physical properties of plantation Japanese larch for ring width and latewood percentage; Table S2. Physical properties of plantation Japanese larch for ring width; Table S3. Physical properties of plantation Japanese larch for latewood percentage; Table S4. The results of fits of physical properties of plantation Japanese larch to ring width (w) and latewood percentage (l); Table S5. The modulus of elasticity of plantation Japanese larch for ring width and latewood percentage; Table S6. The modulus of rupture of plantation Japanese larch for ring width and latewood percentage; Table S7. The ultimate tensile stress of plantation Japanese larch for ring width and latewood percentage; Table S8. The impact bending strength of plantation Japanese larch for ring width and latewood percentage; Table S9. Anova table of growth ring parameter and physical and mechanical properties; Table S10. The results of linear fits of impact bending strength of plantation Japanese larch to ring width (w) and latewood percentage (l).

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

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