TECHNICAL NOTE

Preliminary Evaluation of Bending Properties in Dimension Lumber of *Paulownia tomentosa* as a Fast-Growing Tree Species in Japan

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Abstract

The aim of this study is to evaluate the possibility of re-establishment of the *Paulownia tomentosa* (Thunb.) Steud. forestry and wood industry for sustainable wood production in Japan. Bending properties were preliminarily investigated for dimension lumber (2 by 4, 38 by 89 mm in transverse section) and small-clear specimens of this species. The severe slope of grain in lumber reduced the modulus of rupture (MOR) and disturbed the relationship between the modulus of elasticity (MOE) and MOR. Preliminary studies determined a 5 percent lower tolerance limit with a 75 percent confidence level in MOR of lumber was 12.1 MPa. The value exceeded the characteristic value of MOR of 2 by 4 lumber in structural grade Western redcedar (*Thuja plicata*).

Forestry using fast-growing tree species has been promoted for both preventing global warming by reducing the carbon dioxide concentration in the atmosphere, and efficiency of wood production in the world. The wood from fast-growing tree species is mainly used for producing chips as raw material for pulp and paper industries and substitutional fuel instead of fossil fuel for power generation. However, the price of chips only sometimes meets the desired price for maintaining sustainable forestry. Therefore, to strengthen sustainability, fast-growing plantations should produce not only chips but also solid wood, which is relatively more expensive than chips.

Paulownia species were originally distributed in East Asia, and they have been extensively cultivated in Asia, Africa, North America, South America, Europe, and Australia as fast-growing tree species (Olson et al. 1989, Koman and Feher 2020, Young and Lundgren 2022, Fos et al. 2023). Among *Paulownia* species, *Paulownia tomentosa* (Thunb.) Steud. is planted in many places in Japan to obtain wood for traditional furniture (such as chests of drawers), musical instruments (such as Koto, Japanese harp), and other traditional goods in Japan (Kumakura 1957). In Japan, the historical background of the *P. tomentosa* tree have led to it being regarded not as a 'forestry species' but as a 'special purpose tree species.' The Forest Agency, Ministry of Agriculture, Forestry, and Fishery, Japan treats wood from this species as 'special forest products' in official statistics. Many famous provenances of *P. tomentosa* wood production have recently declined as a result of reduced demand for *P. tomentosa* wood products in modern Japanese life. If *P. tomentosa* can be utilized as forestry species to produce wood for construction and interior use as well as biomass for fuel, both sustainable wood production and succession of the traditional culture of *Paulownia* wood may be achieved. To utilize wood from *P. tomentosa*, scientific data on wood properties are needed. However, scientific data on wood properties have not been

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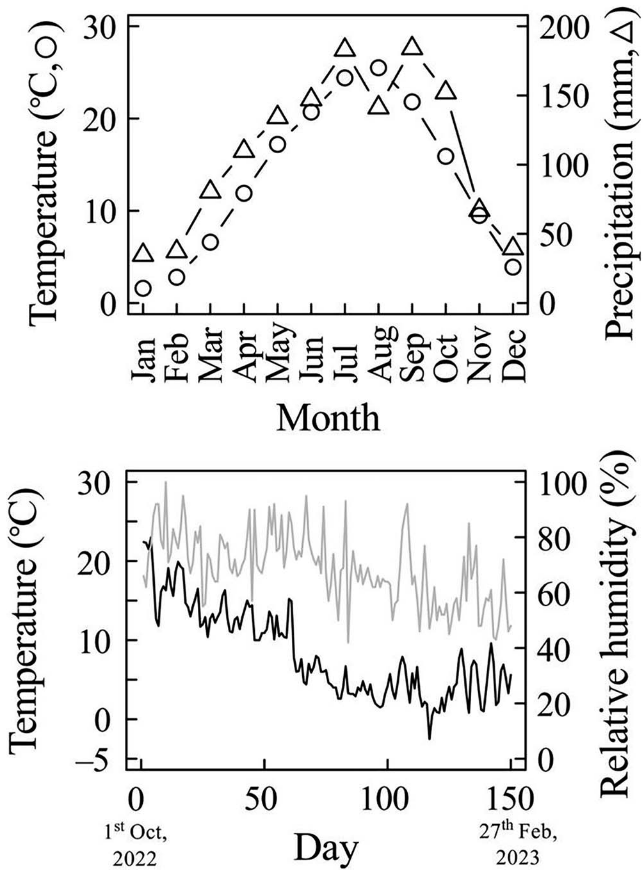

Figure 1.—Climatic conditions of the sampling site (upper graph) and experiment site for air-drying (lower graph). Note: Upper graph, monthly mean temperature (open circles) and mean monthly precipitation (open triangles) from 1991 to 2001 in Moka, Tochigi, Japan (36°28.6′ N, 139°59.2′ E, the nearest meteorological station of the Japan Meteorological Agency from the sampling site); lower graph, daily mean temperature (black line) and mean relative humidity (gray line) in Utsunomiya meteorological station of the Japan Meteorological Agency (36°32.9′ N and 139°52.1′ E). All climatic data were obtained from the Web site of the Japan Meteorological Agency (https://www.jma.go.jp/jma/menu/menureport.html).

updated since around the 1960s in Japan (Kitamura and Imata 1955, Takashima et al. 1959). The wood properties of *P. tomentosa* should be re-examined as an 'old but new' fast-growing tree species in Japan.

This study aims to evaluate the possibility of re-establishing the *P. tomentosa* forestry and wood industry as sustainable wood production from new forestry. This will be done with the use of fast-growing trees and succession of the traditional wooden culture of *P. tomentosa* in Japan. The authors began planting *P. tomentosa* trees for wood production in Tochigi, Japan, in 2020. Therefore, plantation-grown *Paulownia* trees of a suitable size could not yet be obtained for evaluating lumber properties. In the present study, an approximately 50-year-old *P. tomentosa* tree, which was initially planted for traditional wood use, was used as an alternative. Only one tree was purchased because of the high cost of *P. tomentosa* wood for traditional use. Although the number of samples is limited, preliminary evaluation of the bending properties of the dimension lumber (2 by 4, 38 by 89 mm in transverse section) and small-clear specimens was completed. Based on the results, the possibility of producing dimension lumber from this species is discussed.

Materials and Methods

A 50-year-old tree of *Paulownia tomentosa* growing in Mashiko, Tochigi, Japan (36°24′N and 140°5′E), was used for the experiments. The climatic conditions of the sampling site are shown in Figure 1. Stem diameter at 1.3 m above the ground and tree height were 88.5 cm and 19.2 m, respectively. After harvesting the tree, a log with a length of 2 m was collected from 1.3 to 3.3 m above the ground. A total of 15 items of lumber with dimensions of 50 by 100 mm in the transverse section were obtained from the log. The lumber was air-dried outside (with a roof) of the laboratory at Utsunomiya University, Japan, from October 2022 to January 2023. The temperature and relative humidity during air-drying are also shown in Figure 1. During air-drying, moisture content and weight were measured by a moisture meter (HM-520, Kett, Tokyo, Japan) and an electric balance (SL-20K, A&D, Tokyo, Japan). After reaching the constant weight, the lumber was planed into 38 by 89 mm in the transverse section. Dynamic Young's modulus [DMOE] and static bending properties (modulus of elasticity [MOE] and modulus of rupture [MOR]) of lumber were determined by the method described in a previous report (Tumenjargal et al. 2020a). After the bending test, small specimens (3 cm in the longitudinal direction) without any visual defects were collected from the lumber for measuring air-dry density and moisture content at testing. The moisture content of the small specimens was determined by the oven-drying method. As a result, the mean moisture content of lumber was 9.4 percent. Thus, the DMOE, MOE, and MOR values in lumber were adjusted to those at 15 percent moisture content by the method described in a previous report (Tumenjargal et al. 2020b). Although the number of pieces of lumber tested in the present study was limited, a 5 percent lower tolerance limit with a 75 percent confidence level ($TL_{75\%,95\%}$) in MOR was preliminarily calculated by the method described in Tumenjargal et al. (2020b).

Small-clear specimens (15 [R] by 15 [T] by 240 [L] mm) were prepared from remaining samples after producing the lumber. The exact size specimens were also prepared from different origins (a *P. tomentosa* tree [ca. 26 yr old, corrected from Fukushima, Japan] and *Paulownia* sp. [age unknown, purchased in the market, imported from China]). The sampling position within the stem of the tree was unknown. Static bending tests were conducted by a universal testing machine (MSC-/5/500-2, Tokyo Testing Machine, Tokyo). The span was 210 mm. The load was applied to the radial surface of the center of the specimen with a load speed of 4 mm/min. The MOE_{SC} and MOR_{SC} of small-clear specimens were calculated.

All statistical analyses were conducted by Program R software (version 4.2.2, R Core Team 2022). Relationships between measured properties were evaluated as Pearson's correlation coefficients. In the bending properties of small-clear specimens, the effects of sample origins (*P. tomentosa* from Tochigi and Fukushima, and *Paulownia* sp. from China) on relationships among air-dry density and bending properties were evaluated by the following mixed-effects models with random effect of sample origins (Models I to

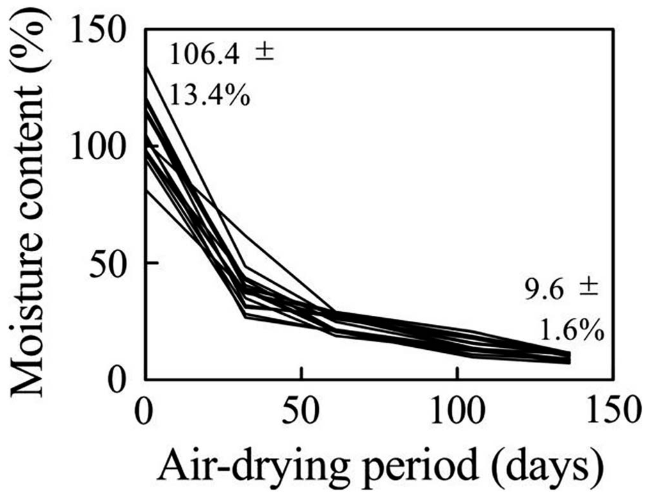

Figure 2.—Changes in moisture content of lumber during air-drying.

III) using lme4 and lmerTest packages or only fixed-effects model (Model IV):

$$\text{Model I: } y_{ij} = (\alpha + \text{Origin}_j)x_{ij} + \beta + \text{Origin}_j + e_{ij}$$

$$\text{Model II: } y_{ij} = \alpha x_{ij} + \beta + \text{Origin}_j + e_{ij}$$

$$\text{Model III: } y_{ij} = (\alpha + \text{Origin}_j)x_{ij} + \beta + e_{ij}$$

$$\text{Model IV: } y_i = \alpha x_i + \beta + e_i$$

where y_{ij} or y_i is the response variable (wood property of ith specimen of jth sample origin or wood property of ith specimen), x_{ij} or x_i is the explanatory variable (the other wood property of ith specimen of jth sample origin or the other wood property of ith specimen), $Origin_j$ is the random-effect parameter of the jth sample origin (Tochigi, Fukushima, and China), α and β are the fixed-effect parameters, and e_{ij} or e_i is the residual. Root mean square error (RMSE) was calculated in each model, and then the model with minimum RMSE was regarded as the best model.

Results

Figure 2 shows changes in lumber moisture content during air-drying. Moisture content dramatically decreased from green condition (106.4% in mean value) to about 40 percent in the first month and then gradually decreased to 9.6 percent up to 136 days after air-drying.

The mean values of air-dry density, $DMOE_{15}$, MOE_{15}, and MOR_{15} of lumber were 0.28 g cm^{-3}, 4.87 GPa, 4.58 GPa, and 24.2 MPa, respectively (Fig. 3). Preliminary obtained $TL_{75\%,95\%}$ in MOR_{15} was 12.1 MPa. Air-dry density was significantly correlated with MOE_{15} (r = 0.542, P = 0.037) but not with MOR_{15} (r = 0.448, P = 0.094; Fig. 4). Significant correlation coefficients were found between $DMOE_{15}$ and MOE_{15} (r = 0.550, P = 0.034) or MOR_{15} (r = 0.619, P = 0.014; Fig. 4). A very low correlation coefficient was obtained between MOE_{15} and MOR_{15} (Fig. 4).

Table 1 shows statistical values of bending properties of small-clear specimens from three different origins of *Paulownia* wood. Wood from Tochigi showed significantly higher mean values of air-dry density (0.30 g cm^{-3}) than samples from China, MOE_{SC} (5.52 GPa) than samples from Fukushima, and MOR_{SC} (55.4 MPa) than samples from either China or Fukushima. Among the developed models for explaining the relationship between measured properties in small-clear specimens, the minimum RMSE value was found in Model IV (only fixed-effect model) for all relations (Table 2). Figure 5 shows relationships between measured properties in small-clear specimens. Significant correlations were found in air-dry density (r = 0.337, P = 0.036) or MOE_{SC} (r = 0.855, P < 0.001) with MOR_{SC} (Fig. 5).

Discussion

Olson et al. (1989) reported that the moisture content of *Paulownia* lumber reached 20 percent by air-drying for 39 days (from May 20 to July 22 in Kentucky, United States; drying rate = 3.5% moisture content loss per day). As shown in Figure 2, drying rate of the present study showed slower value compared with that reported by Olson et al. (1989), as a result of differences of environmental conditions during air-drying. Further needed for the drying

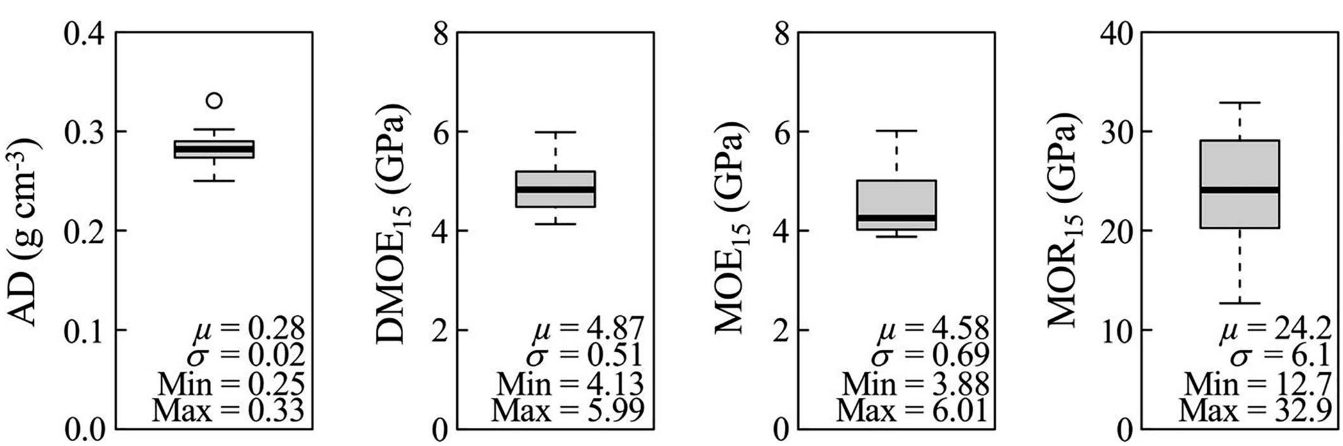

Figure 3.—Boxplot and statistical values in air-dry density, dynamic Young's modulus, MOE, and MOR of lumber. Note: AD is air-dry density; $DMOE_{15}$, MOE_{15}, and MOR_{15} are dynamic Young's modulus, modulus of elasticity, and modulus of rupture adjusted at 15 percent moisture content; μ is mean; σ is standard deviation; Min is minimum; Max is maximum.

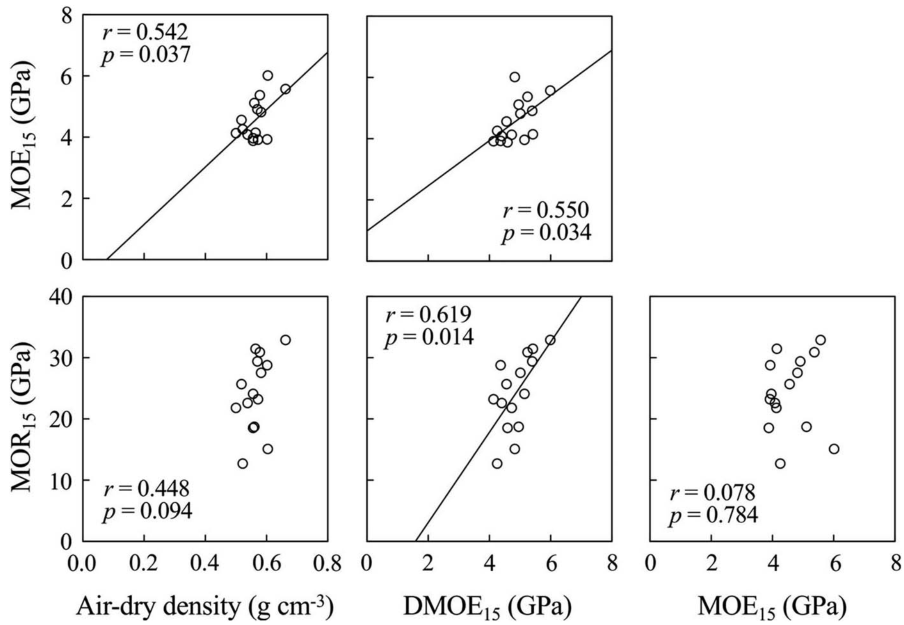

Figure 4.—Relationships between measured properties in lumber. Note: $DMOE_{15}$, MOE_{15}, and MOR_{15} are dynamic Young's modulus, modulus of elasticity, and modulus of rupture adjusted at 15 percent moisture content; r is correlation coefficient; p is P-value.

process including kiln-drying of dimension lumber of this species.

The characteristic value of MOR of 2 by 4 lumber for construction, standard, and utility grades in "Matters to determine the standard strength of wood *Fc*, *Ft*, *Fb*, and *Fs*" in Notification of Ministry of Land, Infrastructure, Transport and Tourism No. 910 were 14.8, 8.2, and 3.9 MPa in JS-II (Japanese cedar [*Cryptomeria japonica*]) (Japan 2 × 4 Lumber JAS Council 2020). This is the most common plantation forestry species, and it is extensively used as structural lumber in Japan. The characteristic values in W cedar (including Western redcedar [*Thuja plicata*] and other species) were 12.0, 6.6, and 3.6 MPa, respectively (Japan 2 × 4 Lumber JAS Council 2023). Although lumber was not visually graded in the present study, $TL_{75\%,95\%}$ in MOR_{15} was 12.1 MPa, indicating that the characteristic value of MOR of 2 by 4 lumber of standard and utility grades in JS-II and construction grade in W cedar was exceeded, but not exceeded in construction grade in JS-II. As shown in Figure 4, no correlation was found between MOE_{15} and MOR_{15} in lumber. This phenomenon might be related to the slope of grain: lumber with the

Table 1.—Statistical values of bending properties in small-clear specimens.

Origin of sample[a]	Statistical value[b]	MC[c] (%)	AD[d] (g cm^{-3})	MOE_{SC}[e] (GPa)	MOR_{SC}[f] (MPa)
Tochigi ($n = 11$)	Mean	6.1AB	0.30A	5.52A	55.4A
	SD	0.2	0.02	0.33	3.4
	Minimum	5.9	0.28	4.99	48.8
	Maximum	6.3	0.33	6.06	59.6
Fukushima ($n = 15$)	Mean	6.3A	0.29A	4.03B	43.1C
	SD	0.2	0.01	0.36	3.9
	Minimum	6.0	0.26	3.40	35.6
	Maximum	6.5	0.32	4.59	47.8
China ($n = 13$)	Mean	6.0B	0.27B	5.16A	47.7B
	SD	0.1	0.01	0.42	3.1
	Minimum	5.8	0.25	4.32	43.1
	Maximum	6.3	0.28	5.73	54.6
Total ($n = 39$)	Mean	6.2	0.28	4.82	48.1
	SD	0.2	0.02	0.75	6.06
	Minimum	5.8	0.25	3.40	35.6
	Maximum	6.5	0.33	6.06	59.6

[a] n, number of small-clear specimens.
[b] SD, standard deviation. Different alphabet letters after mean values indicate significant differences ($P < 0.05$) among the origin of samples by Tukey honestly significant difference (HSD) test.
[c] MC, moisture content at static bending test.
[d] AD, air-dry density at static bending test.
[e] MOE_{SC}, modulus of elasticity in the small-clear specimen.
[f] MOR_{SC}, modulus of rupture in the small-clear specimen.

Table 2.—Comparison of root mean square error (RMSE) in the developed models for explaining the relationship between measured properties in small-clear specimens.

Variable[a]		RMSE[b]			
Explanatory	Response	Model I	Model II	Model III	Model IV
AD	MOE_{SC}	0.755	0.756	0.757	**0.741**
	MOR_{SC}	5.652	5.652	5.651	**5.624**
MOE_{SC}	MOR_{SC}	3.147	3.096	3.097	**3.095**

[a] AD, air-dry density at bending test; MOE_{SC}, modulus of elasticity in the small-clear specimen; MOR_{SC}, modulus of rupture in the small-clear specimen.

[b] Bold values indicate the minimum RMSE value among the developed models.

severe slope of grain was easily ruptured during the bending test. On the other hand, a significant correlation was found between MOE_{SC} and MOR_{SC} in small-clear specimens without severe slope of grain (Fig. 5). Based on the results, it is considered that when the visual grading eliminates lumber with a severe slope of grain, the $TL_{75\%,95\%}$ value may reach or exceed the characteristic value of MOR of 2 by 4 lumber for construction grade in JS-II. Thus, further research is needed to determine the effect of the visual grading on the bending properties of lumber with many samples from fast-growing *Paulownia* plantations.

Wood density is generally significantly correlated with MOE and MOR (Tumenjargal et al. 2020b). Some results obtained in the present study were inconsistent with the general trends between wood density and bending properties (Figs. 4 and 5). The lack of correlation between air-dry density and bending properties might be due to almost stable or slight increase in wood density from pith to bark in this species (Kitamura and Imata 1955). On the other hand, significant correlations were found between dynamic Young's modulus and bending properties in lumber (Fig. 4). This trend was consistent with the previous research for the structural lumber of softwood (Tumenjargal et al. 2020a). Thus, the bending properties of lumber in this species can be nondestructively predicted by dynamic Young's modulus even in the lumber containing grain slope.

As shown in Table 2, the minimum RMSE was obtained in the model without the random effect of sample origin for explaining the relationships between air-dry density and bending properties. In *Paulownia* spp., the result indicates that the relationships between air-dry density and bending properties or between MOE and MOR are not always affected by the difference in sample origins and species. However, further research is needed to clarify the effects of sample origins and species among genus *Paulownia* on the relationships, using many specimens and more species.

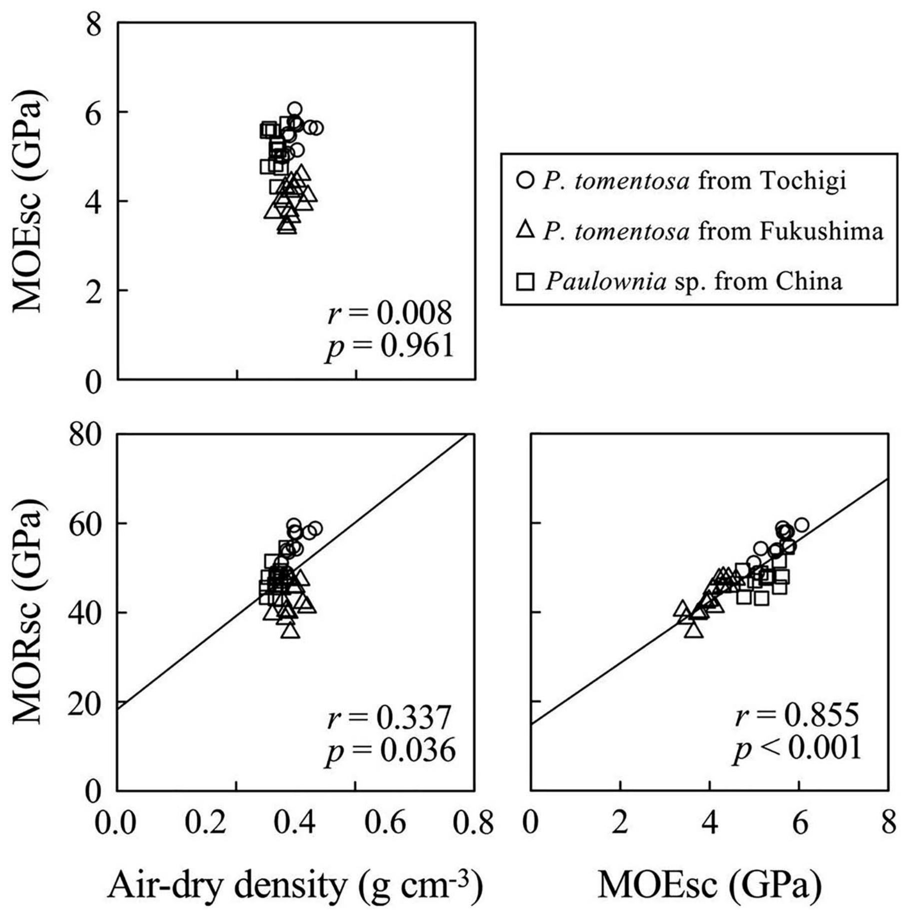

Figure 5.—Relationships between measured properties in small-clear specimens. Note: MOE_{SC} is modulus of elasticity in the small-clear specimen; MOR_{SC} is modulus of rupture in the small-clear specimen; r is correlation coefficient; p is P-value.

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