Predicting Mechanical Properties of Clear Wood from *Acacia mangium* Provenances Using Ultrasound

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Ultrasound was considered as a means for determining mechanical properties of clear wood in six different *Acacia mangium* provenances from a trial forest planted in Vietnam. A total of 30 trees (5 trees from each provenance) with no major defects were selected, and a 50-cm-long log was obtained at 1.3 m above the ground from each tree for the assessment of mechanical properties. The measured average ultrasound velocities for provenances tested in the longitudinal direction ranged from 4094 m/s to 4271 m/s. The predicted average dynamic modulus of elasticity (E_d) values varied from 7.42 GPa to 8.70 GPa among provenances. The E_d indicated significant positive correlation coefficients with modulus of elasticity (0.64 to 0.96), modulus of rupture (0.44 to 0.87), and compression strength (0.54 to 0.92) for provenances examined in this study. The results indicated that the use of ultrasound was feasible to determine the mechanical properties of *A. mangium* provenances planted in Vietnam.

Keywords: Acacia mangium; Non-destructive evaluation; Ultrasound; Modulus of elasticity; Dynamic MOE; Mechanical properties

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INTRODUCTION

Acacia mangium, one of the most important plantation forest tree species in Vietnam, is mainly planted in the Northeast and the North Central regions (Vietnam Ministry of Agriculture and Rural Development 2017). In Vietnam, plantations of *A. mangium* were originally established for the production of pulp, paper, and particleboard. In recent decades, *A. mangium* tree breeding programs in Vietnam focused on increasing the quantity and quality of wood products through the appropriate selection of seed provenances within species. However, growth and tree-form properties have been the focus of selection due to the cost of measuring wood properties. One of the main limitations in the breeding programs is the lack of genetic parameters based on wood properties, although wood is the final desired product. Thus, it is necessary to include the characteristics and properties of wood into breeding programs for establishing timber from *A. mangium* plantations in Vietnam. In addition, to gain the maximum benefits from commercial forestry, it is necessary to improve the capacity for early selection (Schimleck *et al*. 2019). Therefore, the use of advanced technologies is an efficient way to improve the quality of timber resulting from tree breeding programs.

Non-destructive evaluation (NDE) of wood properties has received much attention during the past few decades because it has contributed considerably toward reducing the limitations of the destructive tests such as expense, time consumption, and damage to experimental material (Wang *et al*. 2001). Pellerin and Ross (2002) defined NDE as "the science of identifying the physical and mechanical properties of a piece of material without altering its end-use capabilities and then using this information to make decisions regarding appropriate applications".

There are widespread non-destructive techniques, equipment, and evaluation procedures available today that are used to assess properties of trees (Hasegawa and Sasaki 2000; Schimleck *et al*. 2006; Guntenkin and Aydin 2016; Duong and Matsumura 2018; Duong and Ridley-Ellis 2021). Among various NDE methods, the acoustic technique using the ultrasonic wave propagation in wood is considered as a good option for the prediction of wood stiffness without modifying its end-use (Karlinasari *et al*. 2008; Vazquez *et al*. 2015; Posta *et al*. 2016). In addition, the benefit of the ultrasonic techniques is the capability to test small specimens and the possibility of testing the same specimens several times due to the nondestructive nature of these measurements (Bucur 2006; Vazquez *et al*. 2015). For example, Vazquez *et al*. (2015) reported that the ultrasound technique is a powerful method for determining the elastic constants of small specimens (20 × 20 × 40 mm^3) from *Castanea sativa* wood. The significant relationships between the static and the ultrasound dynamic moduli of elasticity for small clear specimens were also stated in other hardwood species (Baar *et al*. 2015; De Melo *et al*. 2020). However, published information on using ultrasonic techniques for assessing mechanical properties of *A. mangium* – one of the most important woody species in tropical and sub-tropical countries – is currently limited with a few studies (Nugroho *et al*. 2012; Sharma and Shukla 2012).

The aim of this study was to evaluate the potential of an ultrasonic technique by testing the feasibility of using small clear wood specimens from previous static bending properties of six different *A. mangium* provenances planted in Vietnam (Duong *et al*. 2021). The properties of small clear specimens are expected to be usefully representative of these properties for full-sized sawn timber, except for strength. However, in this context, it was hypothesized that ultrasonic measurements will not be better on sawn timber than on small clear wood specimens. The main objective of this study was to determine the strength of relationship between dynamic modulus of elasticity (E_d) using longitudinal ultrasound propagation and mechanical properties (modulus of elasticity – MOE, modulus of rupture – MOR; and compression strength – CS) obtained by destructive methods.

EXPERIMENTAL

Sampling

A total of 30 trees (5 trees from each provenance) were collected from six *A. mangium* provenances (listed in Table 1) that were established as a trial of testing the growth rate and stem quality of different provenances by the Vietnamese Academy of Forest Science since 2014 (Table 1). The trial site was located in Cam Hieu commune, Cam Lo district, Quang Tri province in center Vietnam (16°46'14"N and 107°01'28"E). A detailed description about the trial forest is described in the authors' previous paper (Duong *et al*. 2021).

Table 1. Mean Values and Standard Deviations of Growth and Static Bending Properties in Each Provenance (Duong *et al*. 2021)

Original Provenance of Seeds	Code	*n*	DBH (cm)	Tree Height (m)	MOR (MPa)	MOE (GPa)
Bau Bang (Vietnam)	BB	5	17.36 ± 0.79	16.86 ± 0.54	66.63 ± 16.31	7.03 ± 1.39
Ba Vi (Vietnam)	BV	5	18.29 ± 1.46	16.32 ± 0.79	76.70 ± 14.89	7.92 ± 1.28
Balimo (Australia)	BLM	5	18.05 ± 2.06	16.36 ± 0.63	73.64 ± 17.79	7.65 ± 1.54
Ham Yen (Vietnam)	HY	5	17.67 ± 0.69	16.18 ± 0.56	75.83 ± 8.37	7.58 ± 0.83
Long Thanh (Vietnam)	LT	5	16.12 ± 0.85	16.68 ± 0.41	84.19 ± 14.50	8.23 ± 1.23
Dai tra san xuat (Vietnam)	DTSX	5	16.83 ± 1.17	16.48 ± 0.69	78.39 ± 11.13	7.78 ± 0.98
Note: DBH is diameter at breast height (at 1.3 m above the ground); *n* is number of sample tree						

From each tree, four samples [20 (radial) × 20 (tangential) × 300 (longitudinal) mm^3] were carefully cut from parts near the pith and near the bark (two samples from each radial position) at 1.3 m height above the ground and dried under laboratory conditions at a constant temperature (20 °C) and relative humidity (60 %) to constant weight, as presented in the authors' previous study (Duong *et al*. 2021). Three-point static bending test was conducted using a universal testing machine (Autograph AG-G, Shimazu, Kyoto, Japan) with a bending span of 260 mm. The load was applied at the radial face of center of the specimens at a speed of 5 mm per minute. After static bending tests (MOR and MOE), specimens (20 × 20 × 40 mm^3) for ultrasound measurement and compression test were sampled from the ends of the bending samples, if no mechanical damage was observed. Some specimens containing knots, irregular grain, and cracks were rejected. The total number of small clear specimens cut from six provenances was 117. The specimens were continuously conditioned to constant mass at a temperature of 20 °C and a relative humidity of 60% and maintained in this condition until required for testing. The overall mean value of MC in all observed provenances was 9.33%.

Ultrasonic Measurement

Before ultrasonic measurement, the air-dry density (AD) of the specimens was determined by the ratio between mass and volume of the samples. The ultrasonic wave velocities were measured with a setup comprising of a pulser-receiver (JPR-10CK; Japan Probe Co., Ltd., Yokohama, Japan), preamplifier, and monolithic composite transducers (14 mm × 20 mm-type) with a resonant frequency of 200 kHz according to the method described by Duong *et al*. (2019). Figure 1 illustrates the test and the equipment utilized for the ultrasonic measurement. The propagation time measurement was repeated three times for each specimen, and an average value was used as the experimental value. The longitudinal velocity (V_u) was obtained as a ratio of the length of wood specimen in longitudinal direction to the wave propagation time. The dynamic modulus of elasticity (E_d) was calculated using Eq. 1,

$$E_\mathrm{d} = AD \times V_\mathrm{u}^2 \tag{1}$$

where E_d is dynamic modulus of elasticity (Pa), *AD* is air-dry density (kg/m^3), and V_u is propagation speed (m/s) of ultrasonic waves.

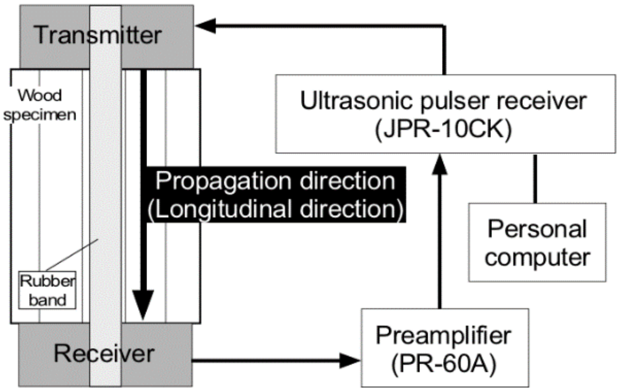

Fig. 1. Illustration of ultrasonic measurement

Compression Strength

After ultrasonic measurement, CS was assessed for each specimen using an Instron Tester (Autograph AG-G, Shimazu, Kyoto, Japan) in accordance with Japanese industrial standards JIS Z2101:1994 (2000). Compression parallel to the grain was performed using a 100 kN load in the universal testing machine, with 1% load accuracy, and the displacement was measured using the machine cross-head displacement, with a 1% deformation accuracy. After compression test, moisture content (MC) was determined by the oven-drying method for each wood specimen.

Data Analysis

All statistical analyses were performed using R software version 4.0.0. (Version 4.0.0; RStudio, Boston, MA, USA). Mean values for each provenance were obtained using mean values calculated from five sample trees for evaluating the variation in V_u and wood properties among provenances. The data of each measured parameter were analysed using one-way analysis of variance (ANOVA) followed by Tukey's *post hoc* test with the level of significant differences at $P < 0.05$.

RESULTS AND DISCUSSION

Table 2 presents the variations in V_u and wood properties among six different *A. mangium* provenances planted in Vietnam. The ANOVA showed significant differences in V_u among provenances. In all examined provenances, the overall mean of V_u was 4170 m/s. The minimum velocity (4094 m/s) was measured in the provenance BV, and the maximum velocity (4271 m/s) was measured in the provenance BLM (Table 2). These results are in accordance with those obtained by Shamar and Shukla (2012) and Duong *et al*. (2019) for small clear specimens in the longitudinal direction of *A. mangium* and *Melia azedarach*, respectively (Table 3). Using ultrasonic wave velocity, Hasegawa *et al*. (2015) and Ribeiro *et al*. (2013) reported a mean V_u of 4500 m/s in *A. auriculiformis* and 5057 m/s in *Eucalyptus grandis*, both being hardwoods of higher air-dry density than *A. mangium* provenances examined in this study (Table 3). It is likely that the ultrasonic velocity is observed to be higher in higher-density wood than in lower-density wood (de Oliveira and Sales 2006; Duong *et al*. 2019). In contrast, several studies confirmed that the sound propagation velocity is not dependent on wood density (Mishiro 1996; Ilic 2003). The propagation of sound in wood is influenced by factors, such as density, angle of cellulose microfibrils (S_2 layer), moisture content, decay, temperature, and geometry, of the specimen (Bucur and Böhnke 1994; Kabir *et al*. 1997; Baar *et al*. 2012). Therefore, it is difficult to establish a direct influence of wood density on sound propagation velocity, which explains the varying conclusions of the above reports.

Table 2. Acoustic and Wood Properties of *Acacia mangium* Trees from Six Provenances (Five Trees for Each Provenance)

Provenances	*n*	V_u (m/s)	*AD* (g/cm^3)	E_d (GPa)	*CS* (MPa)
BB	19	$4103^{b} \pm 171$	$0.44^{b} \pm 0.06$	$7.42^{b} \pm 1.27$	$41.91^{a} \pm 6.08$
BV	20	$4094^{b} \pm 113$	$0.48^{ab} \pm 0.04$	$7.97^{ab} \pm 0.87$	$44.57^{a} \pm 5.97$
BLM	18	$4271^{a} \pm 173$	$0.45^{b} \pm 0.07$	$8.27^{ab} \pm 1.76$	$43.79^{a} \pm 8.45$
HY	20	$4126^{ab} \pm 157$	$0.48^{ab} \pm 0.03$	$8.22^{ab} \pm 0.87$	$44.39^{a} \pm 4.18$
LT	20	$4177^{ab} \pm 166$	$0.50^{a} \pm 0.04$	$8.70^{a} \pm 1.12$	$47.30^{a} \pm 5.28$
DTSX	20	$4256^{a} \pm 163$	$0.47^{ab} \pm 0.03$	$8.46^{ab} \pm 0.85$	$45.44^{a} \pm 3.75$
Average	117	4170 ± 170	0.47 ± 0.05	8.18 ± 1.20	44.60 ± 5.87

Mean values are followed by standard deviation;
n Number of small clear wood specimens;
^{a,b,c} Means with different superscript within a column significantly differ ($P < 0.05$) among provenances

Table 2 also shows the among-provenance variation in AD of six *A. mangium* provenances examined in this study. The overall mean value of AD was 0.47 g/cm^3, ranging from 0.44 g/cm^3 for provenance BB to 0.50 g/cm^3 for provenance LT. The result of ANOVA analysis shows the significant differences in AD among provenances (Table 2). Makino *et al*. (2012) and Jusoh *et al*. (2014) reported that the mean values of wood density of *A. mangium* planted in Indonesia and Malaysia were 0.45 g/cm^3 and 0.46 g/cm^3, respectively.

Table 3. Ultrasonic Velocity in the Longitudinal Direction in this Study and Previous Studies

Species	V_u (m/s)	*AD* (g/cm^3)
Acacia mangium (this study)	4094 to 4271	0.44 to 0.50
Acacia mangium [a]	4100	0.47
Melia azedarach [b]	4033	0.50
Acacia auriculiformis [c]	4500	0.68
Eucalyptus grandis [d]	5057	0.56

Note: [a] Shamar and Shukla (2012); [b] Duong *et al*. (2019); [c] Hasegawa *et al*. (2015); [d] Ribeiro *et al*. (2013)

In this study, the overall mean values of E_d and CS in six provenances were 8.18 GPa and 44.60 MPa, respectively. Makino *et al*. (2012) reported that the lower mean CS for 5- and 7-year-old *A. mangium* trees planted in Indonesia was 30.00 MPa and 32.80 MPa, respectively. There was a significant difference among provenances in E_d, while the variation of CS among provenances was small and without statistical significance (Table 2). It is noteworthy that the lowest values of both E_d and CS were sawn in the provenance BB (respective values for E_d and CS were 7.42 GPa and 41.91 MPa) and the highest values of E_d and CS were sawn in the provenance LT (respective values for E_d and CS were 8.70 GPa and 47.30 MPa) (Table 2). The findings of the present study are in agreement with the authors’ previous study, wherein the highest average value of MOE and MOR measured by destructive method were observed in the provenance LT (Duong *et al*. 2021). Therefore, this result once again indicates that LT might be more appropriate provenance than the others examined for breeding programs focused on timber or saw log of *A. mangium* in the north central region of Vietnam.

Table 4 summarizes the results of the relations of V_u and E_d with mechanical properties (MOE, MOR, and CS) for six different *A. mangium* provenances examined in this study. Correlation coefficients for V_u and mechanical properties were different among the six provenances. In provenances BLM, HY, and combined provenances, significant positive correlation coefficients were found between V_u and mechanical properties (Table 4 and Figs. 2A, C, and E). However, in the other four provenances, there were no statistically significant correlations between V_u and mechanical properties, except for the relationship between V_u and MOE in provenance BB ($r = 0.49$; $P < 0.05$) (Table 4).

There is a contradiction in the literature on whether V_u is correlated with mechanical properties or not. Sharma and Shukla (2012) obtained good relationships ($r^2 = 0.95$ to 0.98) for small clear specimens between ultrasonic velocity along the longitudinal direction and MOE in air-dry condition of *Acacia mangium*, *Grevillea robusta*, and *Mangifera indica*. Duong *et al*. (2019) also reported a strong positive correlation existed between V_u and CS ($r = 0.70$) of *Melia azedarach*. In contrast, Mascarenhas *et al*. (2021) showed that there was a significant ($P < 0.001$) but weak correlation ($r^2 = 0.29$) between ultrasonic propagation speed and bending strength of tropical wood species. In addition, Duong and Ridley-Ellis (2021) reported a poor relationship between stress wave velocity and MOE ($r^2 = 0.23$) and no significant relationship between stress wave velocity and MOR for *Melia azedarach*. Based on the present results and previous reports, the relationship between acoustic velocity and static bending properties depends on tree species.

Table 4. Correlation of V_u and E_d with Mechanical Properties at Provenance Level

Provenances	Properties	*n*	MOE	MOR	CS
BB	V_u	19	0.49^{*}	0.43^{ns}	0.38^{ns}
	E_d	19	0.87^{***}	0.85^{***}	0.89^{***}
BV	V_u	20	-0.02^{ns}	-0.18^{ns}	-0.07^{ns}
	E_d	20	0.79^{***}	0.59^{**}	0.79^{***}
BLM	V_u	18	0.69^{**}	0.53^{*}	0.62^{**}
	E_d	18	0.96^{***}	0.87^{***}	0.92^{***}
HY	V_u	20	0.66^{**}	0.52^{*}	0.48^{*}
	E_d	20	0.64^{**}	0.50^{*}	0.71^{***}
LT	V_u	20	0.43^{ns}	0.33^{ns}	0.43^{ns}
	E_d	20	0.82^{***}	0.76^{***}	0.86^{***}
DTSX	V_u	20	0.32^{ns}	0.06^{ns}	-0.16^{ns}
	E_d	20	0.73^{***}	0.44^{*}	0.54^{*}
Combined Provenances	V_u	117	0.42^{***}	0.30^{**}	0.32^{***}
	E_d	117	0.83^{***}	0.75^{***}	0.84^{***}

Note: $^{***}P < 0.001$, $^{**}P < 0.01$, $^{*}P < 0.05$, *ns* no significant

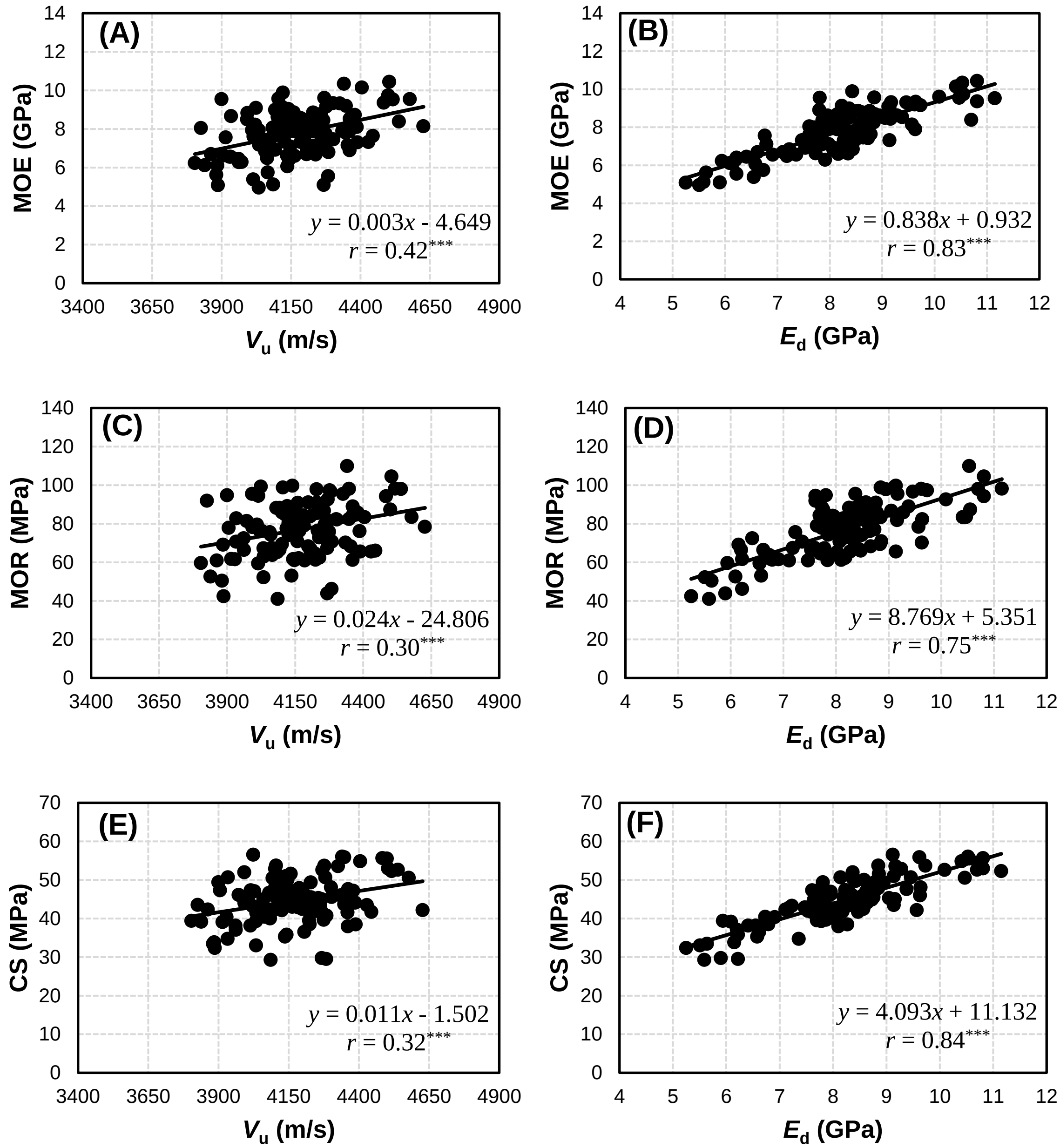

Fig. 2. Relationships between longitudinal ultrasonic velocity (V_u), dynamic modulus of elasticity (E_d), and mechanical properties (MOE, MOR, and CS)

Significant relationships were found between E_d and mechanical properties measured by destructive method in each provenance as well as in combined provenances (Table 4). The correlation coefficient between E_d and MOE in combined provenances was 0.83 ($P < 0.001$) that ranged from 0.64 for provenance HY to 0.96 for provenance BLM (Table 3 and Fig. 2B). In general, the results from other studies pointed out that NDE methods based on propagation speed of ultrasonic waves are suitable for measurement of the E_d and have a good relationship with the destructive static bending test (de Oliveira *et al*. 2002; Karlinasari *et al*. 2008; Baar *et al*. 2015). In this study, the relationships between E_d and CS were observed to be moderately good to very good correlations (r = 0.54 to 0.92)

(Table 4). When all provenances were considered together, the correlation coefficient between E_d and CS was 0.84 (P < 0.001) (Fig. 2F).

The correlation coefficient between E_d determined using ultrasound and bending strength from destructive test was 0.75 (P < 0.001) when all samples of the observed provenances were combined (Fig. 2D). The correlation coefficients ranged between 0.44 and 0.87 for individual provenances (Table 4). Considering the relationship between E_d and MOR in this study, the results were similar to those from tropical wood species (Baar *et al*. 2015; Mascarenhas *et al*. 2021). Using ultrasound, de Oliveira *et al*. (2002) reported coefficients of determination between E_d and MOR for *Goupia glabra* and *Hymenaea* sp. were 0.36 and 0.55, respectively. The lower accuracy of the ultrasound method for prediction of MOR than MOE and CS is probably caused by its property in the measurement path. The acoustic velocity is directly related to elasticity (stiffness) not the failure point of the material; therefore, E_d only reflects the properties in the measurement path of the sample (Daniels and Clark 2006).

CONCLUSIONS

1. Coupled with the higher modulus and elasticity (MOE) and modulus of rupture (MOR), provenance LT also had higher dynamic modulus of elasticity (E_d) and compression strength (CS) than the other provenances examined in this study. Therefore, LT might be selected for *A. mangium* tree breeding programs focused on improving wood quality specifically for lumber productions. However, as the present study was based on a single site, further research must be done to examine its properties across a range of locations.
2. There were significant positive correlations between E_d and mechanical properties for small clear specimens at MC approximately 9.33%. Therefore, it is highly promising that the non-destructive ultrasonic method can be used to evaluate mechanical properties of *A. mangium* wood in situations where a static bending test is not feasible to undertake. In the future, the authors will measure the properties of standing trees with ultrasound method and report the prediction of stiffness in lumber production.

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