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ARTÍCULO

Relationship between acoustic wave velocity and mechanical properties in *Acacia mangium* wood

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Abstract:
There is a strong interest in developing and using acoustic technology to evaluate the mechanical properties of wood in situations where a static bending test is not feasible to undertake. In this study, the mechanical properties of *Acacia mangium* (black wattle) wood were predicted by using stress wave and ultrasonic wave methods. The values of dynamic modulus of elasticity based on stress wave and ultrasonic wave were 9,29 % and 4,75 % higher than those obtained from static modulus of elasticity, respectively. There was no statistically significant correlation between acoustic velocity and mechanical properties measured by destructive tests. The strong experimental correlation coefficients were found between stress wave and modulus of elasticity (r = 0,94; P < 0,001), and ultrasonic wave and modulus of elasticity (r = 0,83; P < 0,001). This result indicates that stress wave and ultrasonic wave techniques are suitable for predicting the static modulus of elasticity of *Acacia mangium* (black wattle) wood if the density of the measured elements is known. There was no dependence of wood density and acoustic propagation velocity measured in this study, whereas statistically significant correlations were found between the fiber length with stress wave velocity (r = 0,44; P < 0,05) and ultrasonic velocity (r = 0,48; P < 0,05).

Keywords: *Acacia mangium*, dynamic MOE, fiber length, static bending, stress wave, ultrasound.

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Introduction

There is a strong interest in developing and using acoustic technology to evaluate the mechanical properties of wood in situations where a static bending test is not feasible to undertake. The emergence of many nondestructive evaluation methodologies offers the potential to greatly enhance our understanding of the performance of lumber when used in construction (Schimleck *et al*. 2019). One of the most widespread and accurate nondestructive techniques used to give a reasonably good indication of the characteristics that determine wood quality is based on acoustic waves (Van Duong 2018).

A number of studies have shown that acoustic methods can be used to nondestructively evaluate the engineering properties of solid wood and other wood products (Ross and Pellerin 1998, Wang *et al*. 2003, Ross 2015). The acoustic study commonly used in the area of wood and wood-based materials is solid acoustics in the audible (20 Hz to 20 kHz) and ultrasound (> 20 kHz) frequency ranges (Smith 2001).

The common audio frequency acoustic can be produced by the stress wave generated by an impact, whereas ultrasonic measurements can be taken from broadband pulses or narrowband bursts (Bucur 2006). The use of acoustic technologies not only leads to greater efficient wood processing and utilization but can also gain profitability for the forest industry (Schimleck *et al*. 2019).

Modulus of elasticity (MOE) is a property that describes the material stiffness, while the modulus of rupture (MOR) is an indication of strength. Wood stiffness and strength are often seen to be of paramount importance by the wood industry, as they play a large part in determining the end-use potential of logs. A large number of investigations reported that the static bending properties of wood can be predicted using acoustic techniques both in softwood and hardwood species.

Wang *et al*. (2001) reported good relationships between the dynamic MOE obtained from stress-wave technique and the static bending properties (MOE and MOR) for small, clear specimens of western hemlock (*Tsuga heterophylla*) (respective *r* values for MOE and MOR were 0,92 and 0,68) and sitka spruce (*Picea sitchensis*) (respective *r* values for MOE and MOR were 0,91 and 0,69). Guntekin *et al*. (2014) and Baar *et al*. (2015) showed the accuracy of the ultrasonic technique for evaluating the static bending properties of oriental beech (*Fagus orientalis*) and some tropical hardwood species, respectively.

Van Duong and Ridley-Ellis (2021) also found a significant linear correlation between the static MOE and the dynamic MOE measured by stress wave method for chinaberry tree (*Melia azedarach* L.) wood. However, there is little information regarding to compare the stress wave and ultrasonic wave techniques for predicting the modulus of elasticity of timber. Comparison of different methodologies (acoustic methods) on the same set of samples is useful for identifying the suitability of these methods for a range of species. There are many factors that significantly influence the propagation of acoustic waves in wood, such as grain angle, wood density, anatomical structure, and moisture content (Van Duong *et al*. 2019).

The objective of this work was to compare the results of evaluation mechanical properties of black wattle (*Acacia mangium*) wood - one of the most extensively planted *Acacia* species in Vietnam - by stress wave and ultrasonic wave methods. In addition, the relationship between fiber length and acoustic propagation is discussed to determine whether fiber length can affect the sound propagation velocity along fibers in black wattle (*Acacia mangium*) wood.

Materials and methods

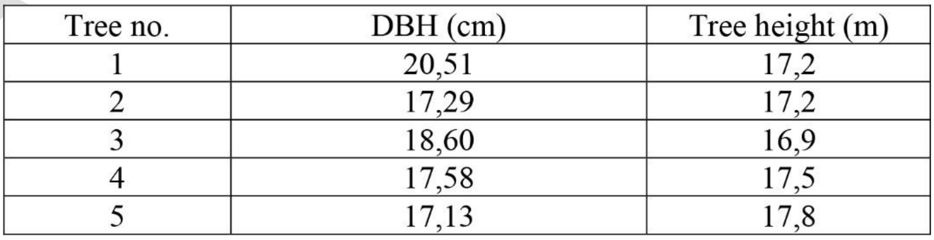
Sample trees were harvested from an black wattle (*Acacia mangium* Willd.) provenance trial established by the Vietnamese Academy of Forest Sciences to assess the growth rate and stem quality of Oriomo provenance (Papua New Guinea). The trial site was located in Quang Tri province (16°46'14"N and 107°01'28"E) in the north central region of Vietnam. Seedlings were planted in the rainy season (December 2014) with a spacing of 3 × 3 m, with a core area for growth measurements of 25 trees/plot.

The soil is highly degraded, the mean annual rainfall is 2325 mm, the mean annual temperature is 25 ^{o}C. Weeding was undertaken regularly during the first two years; no pruning and thinning was applied. A total of five trees were chosen based on straightness, branching, and absence of disease or pest symptoms in December 2019 at an age of 5 years. The north and south sides of each tree were marked before felling.

Details of the sampled trees are provided in Table 1. A log of 50 cm was cut from 1,0 m to 1,5 m height above the ground per tree. After air-drying, wood specimens with dimension of 20 (radial) × 20 (tangential) × 300 (longitudinal) mm^3 were carefully cut from parts near the pith and near the bark to both sides (north and south).

Because the radius at breast height of the sample trees was small, these specimens were cut carefully with the aim of obtaining a representative sample of the radial nature variation in wood properties. The specimens were conditioned in a room at a constant temperature (20 °C) and relative humidity (60 %) to constant weight.

Table 1: Diameter and height of five selected black wattle (*Acacia mangium* Willd.) trees.



Tree no.	DBH (cm)	Tree height (m)
1	20,51	17,2
2	17,29	17,2
3	18,60	16,9
4	17,58	17,5
5	17,13	17,8

DBH - diameter at breast height (at 1,3 m above the ground)

The air-dry density (*AD*) of the specimens was calculated from their dimensions and masses. The time of stress wave propagation in the longitudinal direction of the wood was measured on each specimen by using a Fakopp device (Serial No.: FN-12/2020, Fakopp Enterprise Bt., Fenyo u.26, Hungary). We averaged six readings per specimen and then the dynamic modulus of elasticity (E_s) was estimated using Equation 1:

$$E_s = ADV_s^2 \qquad (1)$$

Where E_s is the dynamic modulus of elasticity based on stress wave (GPa); *AD* is the air-dry density (kg/m^3); and V_s is the stress-wave velocity (m/s).

Static bending tests were carried out according to the procedure outlined by Van Duong and Ridley-Ellis (2021). MOE and MOR were assessed for each specimen using an Instron Tester (Autograph AG-G, Shimazu, Kyoto, Japan) in accordance with Japanese Industrial Standards, JIS Z2101 (1994). After the static bending test, a 40 mm long specimen for ultrasound and compression strength (*CS*) tests and a 10 mm long specimen for fiber length (*FL*) measurements were cut from the two ends of each sample.

The time of ultrasonic wave propagation in each specimen was measured using JPR-10CK device (JAPAN PROBE Co., LTD., Yokohama, Japan) as described by Van Duong *et al.* (2019). The longitudinal wave frequency was 200 kHz. Two transducers (14 by 20 mm type) were used to carry out the measurement. To ensure coupling between the wood specimen and the transducers during the measurements, a rubber band was used (Figure 1). 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 the wood specimen in the longitudinal direction to the wave propagation time. The dynamic modulus of elasticity (E_u) was calculated using the following Equation 2:

$$E_u = ADV_u^2 \qquad (2)$$

Where E_u is the dynamic modulus of elasticity based on ultrasound (GPa); AD is the air-dry density (kg/m^3); and V_u is the propagation speed of ultrasonic waves (m/s).

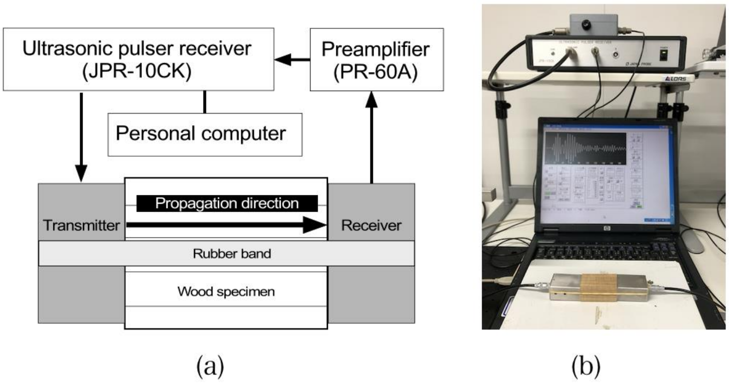


Figure 1: Schematic for ultrasonic measurement.
(a) Diagram and (b) Setup of ultrasonic velocity measurement.

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

From small specimens (20 (R) × 20 (T) × 10 (L) mm^3), *FL*s were measured as described by Van Duong *et al*. (2019). In each specimen, a tangential section of 40 µm thickness was cut and macerated with Schulze's solution (1:1 solution of 65 % nitric acid (HNO_3) and distilled water (H_2O) plus potassium chlorate ($KClO_3$) (3 g/100 ml solution)) for 5 days. These sections were rinsed three times with distilled water, stained with safranin, and then mounted on a glass slide. The *FL* of thirty fibers per small block was measured by Microscope (Olympus IX53P1F, Japan) and Image J software.

All statistical analysis of the measurement data was performed using R software version 4.0.0. (R Core Team 2020). Correlation coefficients among properties measured in black wattle (*Acacia mangium* Willd.) wood at the specimen's level were evaluated by linear regression analysis using the least squares method.

Results and discussion

The mean values of acoustic wave velocity, dynamic modulus of elasticity based on stress wave (E_s) and ultrasonic wave (E_u), and their descriptive statistics are shown in Table 2. It was observed that the propagation speed obtained from stress-wave method was slightly higher than that obtained from ultrasonic measurement. The average values of V_s and V_u were 4257 m/s and 4183 m/s (with an average *MC* of 9,71 %) with coefficients of variation of 3,30 % and 3,48 %, respectively. The comparison with acoustic velocity values found in the literature for black wattle (*Acacia mangium*) showed similar mean values.

Using ultrasonic technique, Sharma and Shukla (2012) found a mean V_u of 4100 m/s. Part of the reason for the difference between V_s and V_u may be attributed to the mechanism of measuring methods. Bucur and Feeney (1992) reported that an ultrasonic wave velocity is influenced by frequency from 100 kHz to 250 kHz. In this study, ultrasonic testing uses high frequency (200 kHz) sound energy driven by the pulser to make measurements, whereas stress-wave technique is based on the measurement of the velocity of propagation of a stress generated by an impact.

Table 2: Descriptive statistics for acoustic and wood properties of black wattle (*Acacia mangium*).

Properties	Values				
	Mean	Minimum	Maximum	SD	CV (%)
V_s (m/s)	4257	4003	4477	141	3,30
V_u (m/s)	4183	3901	4436	145	3,48
AD (kg/m^3)	450	330	520	50	10,44
E_s (GPa)	8,18	6,46	9,41	0,86	10,49
E_u (GPa)	7,79	6,05	9,23	0,95	12,19
MOE (GPa)	7,42	5,24	8,90	0,96	12,90
MOR (MPa)	73,88	39,25	91,04	13,26	17,94
CS (MPa)	30,58	43,21	50,16	5,42	12,53
FL (mm)	0,60	0,48	0,72	0,08	13,60
MC (%)	9,71	9,52	9,90	0,13	1,30

SD is standard deviation; CV is the coefficient of variation

The average value of E_s was 8,18 GPa, ranging from 6,46 GPa to 9,41 GPa, while average value of E_u was 7,79 GPa, ranging from 6,05 GPa to 9,23 GPa. The E_u values obtained from ultrasonic measurements were found to be near to the static MOE values rather than those obtained by the stress-wave method. The average values of E_s and E_u were 9,29 % and 4,75 % higher than those obtained from static MOE, respectively. These findings are similar to the results of other authors indicating that the dynamic MOE values obtained by the nondestructive methods were higher than those from the static tests.

Van Duong and Ridley-Ellis (2021) showed that the value of MOE obtained by the bending test was about 15 % lower than the value of E_s measured by the stress-wave method for small clear specimens of chinaberry tree (*Melia azedarach*). Vazquez *et al*. (2015) reported that the average MOE from the bending tests was 2,90 % less than the average E_u obtained by ultrasound for chestnut (*Castanea sativa*) wood. The difference between the dynamic modulus of elasticity determined by acoustic methods and the modulus of elasticity measured by destructive tests are usually attributed to the component of shear deflection and embedment in static measurement whereas the acoustic results are shear-free dynamic modulus of elasticity values (Barrett *et al*. 2008).

In this study, the mean values of *AD*, MOE, MOR, and *CS* in the five trees were 450 kg/m^3, 7,42 GPa, 73,88 MPa, and 30,58 MPa with 10,44 %, 12,90 %, 17,94 %, and 12,53 % coefficients of variation, respectively. These results agree well with the values obtained by other authors. Makino *et al*. (2012) observed the mean values of basic density and *CS* for 5-year-old black wattle (*Acacia mangium*) planted in Indonesia were 420 kg/m^3 and 30 MPa. Moya and Muñoz (2010) reported the mean MOR and *CS* of black wattle (*Acacia mangium*) planted in Costa Rica were 78,40 MPa and 34 MPa, respectively.

Table 3 shows the relationships between stress wave and ultrasonic wave velocity and *AD*. The regression analysis showed that there is no dependence of wood density and sound propagation velocity measured in this study. Both measuring methods - stress wave and ultrasound - gave the same results for the effect of density. These results were compatible with those normally found in experiments carried out on eight tropical timbers for the relationship between acoustic velocity from longitudinal vibration and wood density (*r* = -0,21, no significance), and ultrasonic velocity and wood density (*r* = -0,04, no significance) (Chauhan and Sethy 2016). Baar *et al*. (2012) reported that the velocity of wave propagation in wood is probably much more affected by the microstructure of a particular species and it is not recommendable to try to predict it based on density only.

Table 3: Pearson correlation coefficients (*r*) between variables.

Properties	AD	MOE	MOR	CS	FL	MC
AD	-	$0,84^{***}$	$0,81^{***}$	$0,90^{***}$	$0,47^{*}$	$0,43^{ns}$
V_s	$-0,37^{ns}$	$0,02^{ns}$	$-0,30^{ns}$	$-0,25^{ns}$	$0,44^{*}$	$-0,36^{ns}$
V_u	$-0,12^{ns}$	$0,13^{ns}$	$-0,23^{ns}$	$-0,02^{ns}$	$0,48^{*}$	$-0,14^{ns}$
E_s	$0,74^{***}$	$0,94^{***}$	$0,69^{***}$	$0,77^{***}$	$0,68^{***}$	$0,17^{ns}$
E_u	$0,80^{***}$	$0,83^{***}$	$0,58^{**}$	$0,78^{***}$	$0,68^{***}$	$0,31^{ns}$

AD = air-dry density; V_s = stress-wave velocity; V_u = ultrasonic velocity; E_s = dynamic modulus of elasticity based on stress wave; E_u = dynamic modulus of elasticity based on ultrasound; MOE = modulus of elasticity; MOR = modulus of rupture; CS = compression strength; FL = fiber length; MC = moisture content; $^{***}P < 0{,}001$; $^{**}P < 0{,}01$; $^{*}P < 0{,}05$; *ns* no significant

The relations between acoustic velocity and mechanical properties (MOE, MOR, and *CS*) were studied. There was no significant correlation between acoustic velocity (both by stress wave and ultrasound) and the mechanical properties examined by destructive tests in this study (Table 3). Overall, our results suggest that it would not be possible to effectively assess the static bending properties of black wattle (*Acacia mangium*) wood by using only the stress wave or ultrasonic wave velocity.

The relationships between static and dynamic MOE are given in Table 3 and Figure 2a. The strong experimental correlation coefficient was found between E_s and MOE ($r = 0{,}94$; $P < 0{,}001$). A lower coefficient was obtained between E_u and MOE ($r = 0{,}83$; $P < 0{,}001$). This result indicates that stress wave and ultrasonic wave techniques are suitable for predicting the static MOE of black wattle (*Acacia mangium*) wood if the density of the measured element is known. However, the method based on ultrasound propagation is less suitable for the prediction of the MOE in comparison with the stress wave method.

The observed relationships were similar to the findings of Van Duong and Matsumura (2018), who reported a strong correlation between E_s and MOE ($r = 0{,}92$; $P < 0{,}001$) for chinaberry tree (*Melia azedarach*). Ilic (2001) found that the dynamic longitudinal elastic modulus was highly related to MOE ($r = 0{,}95$) in alpine ash (*Eucalyptus delegatensis*). Yin *et al*. (2010) reported that significant relationships were observed between the E_s and E_u of the logs and the static MOE ($r = 0{,}57$ and $0{,}45$, respectively) of small clear specimens from those logs of china fir (*Cunninghamia lanceolata*) wood. The strength of correlation between static and dynamic MOE depends on the species and the method used.

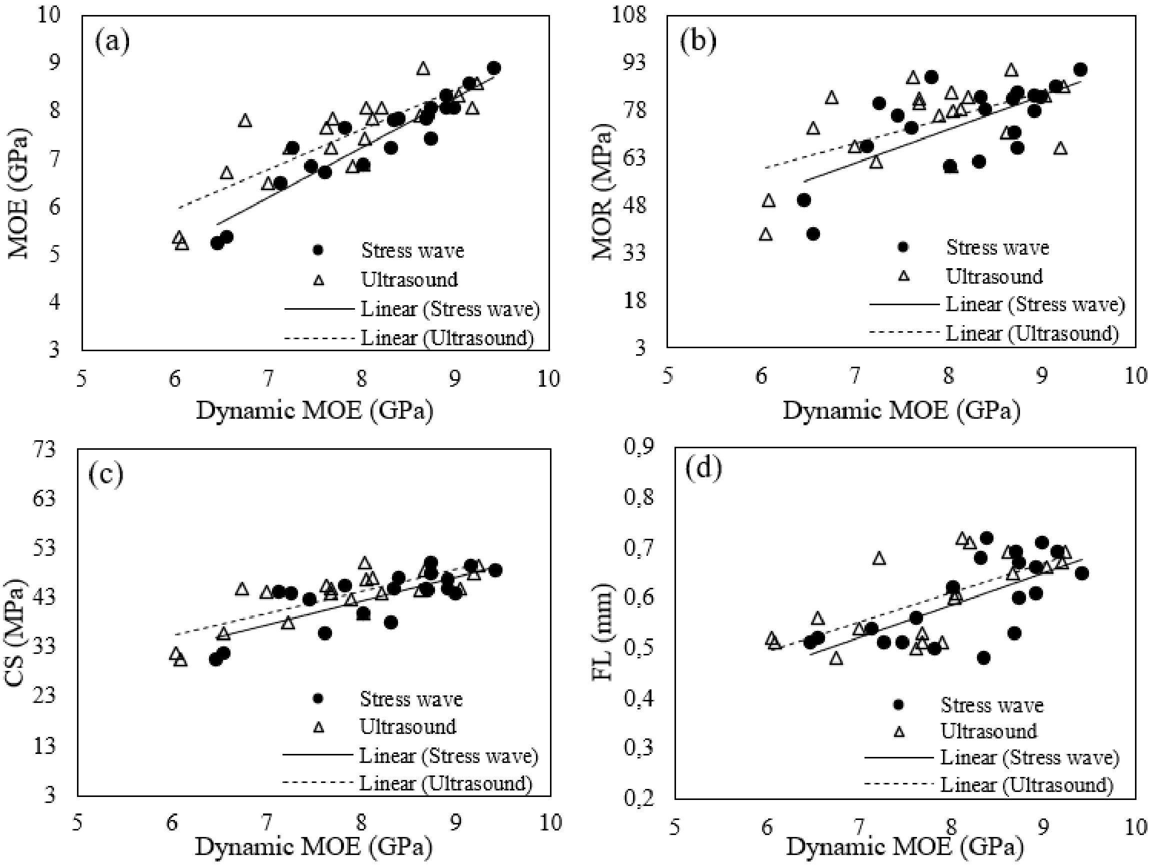
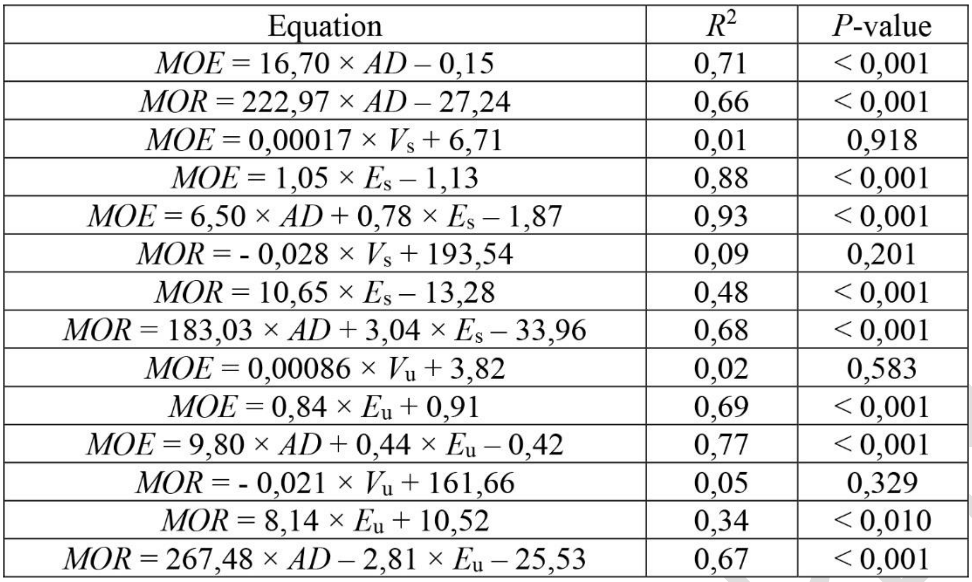


Figure 2: Relationship between the dynamic modulus of elasticity determined by using stress wave and ultrasonic wave methods and mechanical properties (MOE, MOR, and *CS*) measured by destructive tests and fiber length (FL).

As shown in Table 3 and Figure 2b and Figure 2c, the two nondestructive methods used in this study were moderate predictors of MOR and good predictors of *CS*. The correlation coefficients between MOR and dynamic moduli of elasticity determined by stress-wave and ultrasonic techniques were 0,69 and 0,58, respectively (Figure 2b). The better correlations were obtained between E_u and *CS* (r = 0,78), and E_s and *CS* (r = 0,77) (Figure 2c).

De Oliveira *et al*. (2002) obtained the coefficients of determination of 0,55 to 0,36 between the E_u and MOR for two tropical species, goupi (*Goupia glabra*) and *Hymenaea sp*, respectively. Using E_s, Van Duong and Matsumura (2018) reported a slightly better relationship (r = 0,84) for predicting the bending strength of chinaberry tree (*Melia azedarach* L.). The density is another suitable indicator of mechanical properties. Relationships between *AD* and mechanical properties of black wattle (*Acacia mangium*) are presented in Table 3. Analyses revealed *AD* had strong positive relationships at the 0,001 confidence level with MOE (r = 0,84), MOR (r = 0,81), and *CS* (r = 0,90). Table 3 shows that *AD* is the best predictor of MOR as well as *CS*. A measurement of *AD* allows a much better estimation of MOE through the calculation of E_s. The coefficient of determination (R^2) of E_s and MOE is usefully high (R^2 = 0,88), but for MOR the use of *AD* alone (R^2 = 0,66) is better than E_s (R^2 = 0,48) and E_u (R^2 = 0,34) (Table 4). For both MOE and MOR, the use of *AD* and E_s; *AD* and E_u together did not improve the correlation, except for MOE estimated by *AD* and E_s (R^2 = 0,93) (Table 4). This is due to acoustic velocity is not an intrinsic property of wood but a direct consequence of the density and stiffness in combination. In this case, the stiffness is directly proportional to *AD* at this moisture content, the acoustic velocity simply does not change much (the respective CV values for V_s and V_u were 3,30 and 3,48 %, Table 2), and therefore has no power for indicating the wood quality when used on its own. The results confirm the findings from the literature that the use of *AD* alone for predicting MOR could be a better indicator than the use of *AD* and stress wave velocity together for chinaberry tree (*Melia azedarach* L.) clear wood (Van Duong and Ridlly-Elis 2021).

Table 4: Prediction models for static properties (MOE and MOR) based on air-dry density (*AD*), stress wave velocity (V_s), ultrasonic velocity (V_u), and dynamic modulus of elasticity based on stress wave (E_s) and ultrasound (E_u) for black wattle (*Acacia mangium*) clear wood.



Equation	R^2	P-value
$MOE = 16,70 \times AD - 0,15$	0,71	$< 0,001$
$MOR = 222,97 \times AD - 27,24$	0,66	$< 0,001$
$MOE = 0,00017 \times V_s + 6,71$	0,01	0,918
$MOE = 1,05 \times E_s - 1,13$	0,88	$< 0,001$
$MOE = 6,50 \times AD + 0,78 \times E_s - 1,87$	0,93	$< 0,001$
$MOR = - 0,028 \times V_s + 193,54$	0,09	0,201
$MOR = 10,65 \times E_s - 13,28$	0,48	$< 0,001$
$MOR = 183,03 \times AD + 3,04 \times E_s - 33,96$	0,68	$< 0,001$
$MOE = 0,00086 \times V_u + 3,82$	0,02	0,583
$MOE = 0,84 \times E_u + 0,91$	0,69	$< 0,001$
$MOE = 9,80 \times AD + 0,44 \times E_u - 0,42$	0,77	$< 0,001$
$MOR = - 0,021 \times V_u + 161,66$	0,05	0,329
$MOR = 8,14 \times E_u + 10,52$	0,34	$< 0,010$
$MOR = 267,48 \times AD - 2,81 \times E_u - 25,53$	0,67	$< 0,001$

Wave propagation is controlled by the material characteristics such as anatomical structure, grain orientation, microfibril alignment, etc. One of the anatomical wood properties that has a significant effect on sound velocity along the grain is usually assigned to the *FL*. The velocity of the acoustic wave in the longitudinal direction increases with an increasing length of fibers (Bucur 2006). Table 3 shows the relationship of stress wave and ultrasonic wave velocity to the *FL* in black wattle (*Acacia mangium*) trees planted in Vietnam.

There were statistically significant (0,1% level) but weak correlations between V_s and *FL* (r = 0,44); and V_u and *FL* (r = 0,48). There are different reports about the relationship between *FL* and acoustic velocity in hardwood species. Similar to the results presented in this study, Baar *et al*. (2013) reported a low correlation (r = 0,45) between *FL* of wenge (*Millettia laurentii*) De Wild and ultrasound velocity. In contrast, Van Duong *et al*. (2019) obtained a moderate relationship (r = 0,69) for chinaberry tree (*Melia azedarach* L.) wood, while Polge (1984) reported a higher relationship (r = 0,90) for cherry wood. However, the effect of the *FL* on sound velocity can be indirect and caused rather by a change of microfibril angle (*MFA*) in the S_2 layer of cell walls. *MFA* plays an important role in guiding the propagation of acoustic waves (Hasegawa *et al*. 2011).

Multivariate analysis regarding wood properties is useful for solving the effect of MFA on acoustic velocity in black wattle (*Acacia mangium*). The better results for the prediction of *FL* of black wattle (*Acacia mangium*) were obtained when the acoustic wave velocity and *AD* were used together, which were expressed by a correlation coefficient of 0,68 for both nondestructive methods (Figure 2d).

Conclusions

Dynamic moduli of elasticity for small, clear specimens of *A. mangium* in Vietnam were measured by using stress wave and ultrasonic wave methods, and compared with *MOE* examined by destructive tests. The mean values of E_s and E_u were 9,29 % and 4,75 % higher than those obtained from static MOE, respectively. The correlation coefficients between static bending properties (MOE and MOR) and dynamic modulus of elasticity using stress-wave method were stronger than those using the ultrasonic method. There was no dependence of wood density and sound propagation velocity measured in this study. In contrast, *FL* had a significant effect both on stress wave ($r = 0,44$; $P < 0,05$) and ultrasonic wave ($r = 0,48$; $P < 0,05$) speed along fibers in *A. mangium* wood.

Authorship contributions

D. V-D.: Conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, writing - original draft. M. H.: Data curation, investigation, validation, writing - review & editing.

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