Radial and Among-clonal Variations of the Stress-wave Velocity, Wood Density, and Mechanical Properties in 5-year-old *Acacia auriculiformis* Clones

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Radial and between-clone variations in stress-wave velocity, air-dry density (AD), and mechanical properties in six clones of 5-year-old *Acacia auriculiformis* trees planted in Vietnam were investigated. The potential to predict modulus of elasticity (MOE) and modulus of rupture (MOR) using stress-wave velocity of standing trees (SWV_T) or small specimens (SWV_S) was also examined. The examined SWV_T, SWV_S, and wood properties differed significantly among clones, particularly with two (clones 1 and 6) well suited for *A. auriculiformis* tree breeding programs focusing on lumber production, as they had the highest static bending values and no significant difference in AD between positions near pith and bark. At the specimen level, the best prediction of static bending properties could be achieved when both SWV_S and AD were used in a model for calculation of dynamic modulus of elasticity (MOE_d) in air-dry conditions. Significant correlations between SWV_T and average MOE (r = 0.83) and MOR (r = 0.61) of test specimens indicated that the use of stress-wave technique for assessing MOE and MOR for selecting the best *A. auriculiformis* clones in terms of lumber performance was possible.

DOI: 10.15376/biores.17.2.2084-2096

Keywords: Acacia auriculiformis; Wood density; MOE; MOR; Stress wave velocity

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INTRODUCTION

Acacia auriculiformis A. Cunn. Ex Benth. occurs naturally in Australia, Papua New Guinea, and Indonesia, and it was introduced into Vietnam in the 1960s (Pinyopusarek *et al*. 1991; Hai 2009). In Vietnam, *A. auriculiformis* has become an important species especially in central and southern regions because it grows fast, fixes nitrogen, and displays adaptability to a wide range of environmental conditions. It produces acceptable pulp wood (pulp yield = 43-44%, fiber length approximately 1 mm (Jahan *et al*. 2008)) and small sawlogs in rotations as short as 7 to 10 years (Hai *et al*. 2008). The wood is recognized as being very attractive for furniture, wood turning and carving, as well as being suitable for construction work, *e.g.* framing and flooring (Hai 2009). Provenance trials of *A. auriculiformis* were established in the 1980s, and the best performing provenances (Coen River (Queensland, Australia), Mibini (PNG), and Morehead (PNG)) were selected to plant in several parts of Vietnam (Le 2001; Nguyen 2003). However, tree breeding programs for *A. auriculiformis* generally emphasize improvements in tree growth, stem form, and pest and disease resistance. There is little information available to *A. auriculiformis* breeding programs in Vietnam regarding wood properties, such as wood density and mechanical properties, which determine suitability for lumber production.

Modulus of rupture (MOR) and modulus of elasticity (MOE) are important properties in terms of understanding the performance of lumber when used in construction (Zobel and van Buijtenen 1989). Commonly, static bending properties are measured destructively by some methods that are expensive, time consuming, and damage experimental samples to varying degrees. Therefore, non-destructive evaluation techniques have emerged as alternative approaches for the estimation of mechanical properties of lumber. Tree breeders prefer non-destructive methods because it makes the rapid assessment of wood properties of standing trees possible (Schimleck *et al*. 2019). One non-destructive technique that measures the speed of sound waves within standing trees has received considerable attention (Wang *et al*. 2001). Prior to cutting, trees can be evaluated by measuring the acoustic velocity to sort high-quality from low-quality trees (Apiolaza *et al*. 2011).

In studies based on small defect-free specimens, the potential of acoustics for predicting mechanical properties has been demonstrated (Wang *et al*. 2001; Duong *et al*. 2019; Duong and Hasegawa 2021). However, wood is a biological material and has many natural defects, such as knots, slope of grain, spiral grain, reaction wood, and decay, which may reduce wood mechanical properties. There has been little work on using acoustic method to estimate static bending properties of wood containing knots (Qin *et al*. 2018), which are frequently encountered when testing young trees. If non-destructive techniques are to be used operationally on small *A. auriculiformis* trees, it is very likely that readings will be influenced by knots as this species retains many small branches when young. Thus, for *A. auriculiformis* breeding programs the potential of acoustic measurement as a rapid and non-destructive method for stiffness and strength prediction should be based on both small clear specimens and also specimens with small knots.

In this study, the authors assessed acoustic and mechanical properties of six *A. auriculiformis* clones from a trial in north central Vietnam. The specific objectives were to: a) Clarify radial and among-clonal variation in stress-wave velocity, wood density, MOR, and MOE of small wood specimens including samples containing natural knots, and b) Examine the prediction of *A. auriculiformis* mechanical properties using stress wave velocity measured both on standing trees and small wood specimens. This information will be used to develop appropriate selection strategies for *A. auriculiformis* breeding programs for lumber production in Vietnam.

EXPERIMENTAL

Materials

Sample trees were harvested from an *A. auriculiformis* clonal trial established by the Vietnamese Academy of Forest Sciences to assess the growth rate and stem quality of different clones. The site is located in Cam Hieu commune, Cam Lo district, Quang Tri province, north central Vietnam (16°45'60"N and 107°01'12"E). The plantlets were propagated by tissue culture technology and planted at the site in December 2015 using a randomized complete block design with four replicates. Each plot comprised 36 ramets from a clone (6 lines × 6 ramets/line). The initial spacing between ramet was 3.0 x 3.0 m^2 (1100 tree ha^{-1}). Fertilizer application at planting was 100 g nitrogen (N), phosphate (P_2O_5), and potassium oxide (K_2O) (VADFCO, Hanoi, Vietnam) (elemental ratio 16 : 16 : 8) per ramet and 100 g NPK one year later.

Sampling

A total of 30 ramets (5 per clone) were chosen based on straightness, branching, and absence of disease or pest symptoms in December 2020. Stress-wave velocity of standing tree (SWV_T) was measured using a Fakopp Microsecond Timer for each tree (Serial No.: FN-12/2020, Fakopp Enterprise Bt., Fenyo u.26, Hungary) with start and stop sensors at heights of 1.5 m and 0.5 m, respectively. The stress-wave propagation time was measured six times at the same position of the stem by hitting the start sensor with a small hammer. The SWV_T was calculated by dividing the distance between two sensors (1.0 m) by the averaged stress-wave propagation time. Before felling, stem diameter at a height of 1.3 m was measured and the north and south sides were marked for all sampled ramets, and once felled, total height was measured. Mean values for stem diameter and height for each clone are presented in Table 1.

Table 1. Mean Values and Standard Deviations of Stem Diameter and Tree Height for Each Clone

Clone	Code	*n*	DBH (cm)	Tree Height (m)
Clt7	1	5	11.28 ± 0.53	13.20 ± 0.39
Clt18	2	5	12.23 ± 0.74	12.91 ± 0.29
Clt19	3	5	10.83 ± 0.84	12.40 ± 1.80
Clt25	4	5	11.68 ± 0.85	13.20 ± 0.68
Clt26	5	5	13.72 ± 0.61	13.49 ± 1.67
Clt57	6	5	11.01 ± 0.48	12.70 ± 1.63

Note: DBH is diameter at breast height (1.3 m above the ground); *n* is number of sampled ramets

A 1.0-m log was collected between 0.5 to 1.5 m from each sampled stem. These logs were dried in a room at ambient conditions for approximately 2 months without humidity control. After drying, eight 20 (radial) × 20 (tangential) × 300 (longitudinal) mm^3 small wood specimens were cut from each log for additional stress wave measurements and destructive evaluation of wood strength (MOR) and stiffness (MOE). Because the average radius at breast height of the 30 ramets was small (approximately 60 mm), these specimens were carefully cut from locations near pith and bark with the aim of obtaining a representative sample for the examination of radial variation in wood properties. A total of 240 small wood specimens (120 specimens near pith and bark, respectively, and representing the north and south directions) were obtained from the 30 harvested stems. Small specimens in this study included both clear specimens and specimens with small knots (the knots were located near the ends; Fig. 1). Specimens were conditioned at 20 °C and 60% relative humidity for 4 weeks to constant weight. The average moisture content (MC) of the tested specimens at time of measurement was approximately 12%. Once equilibrium was reached, air-dry density (AD) of the specimens was determined as the ratio of weight and volume. Then, stress-wave propagation time (in the longitudinal direction) was measured for each specimen using a Fakopp Microsecond Timer and used to calculate stress wave velocity (SWV_S) by dividing specimen length by propagation time (end to end). Dynamic modulus of elasticity of each specimen (MOE_d) was estimated using Eq. 1,

$$MOE_d = AD \times SWV_s^2 \times 10^{-9} \tag{1}$$

where MOE_d is the dynamic modulus of elasticity of specimen (GPa), AD is the air-dry density (kg/m^3), and SWV_S is the stress-wave velocity measured in small wood specimen (m/s).

Static bending tests were conducted using an Instron Tester (Autograph AG-G, Shimazu, Kyoto, Japan) in accordance with Japanese Industrial Standard, JIS Z2101:1994 (2000). The span length and cross head speed were 260 mm and 5 mm/min, respectively. The MOE and MOR were calculated with a data analyser attached with Instron Tester.

Fig. 1. Specimens with small knots

Data Analysis

Analysis of variance (ANOVA) was performed at a 5% significance level to determine the differences of SWV_T, SWV_S, AD, MOE_d, MOE, and MOR among the *A. auriculiformis* clones. Tukey tests were used to further analyze the differences among means. The difference in SWV_S and wood properties between the two radial positions was examined using a T-test. All analyses were conducted using R software version 4.0.0. (Version 4.0.0; RStudio, Boston, MA, USA).

RESULTS AND DISCUSSION

Among-clonal Variation of Stress Wave Velocity, Wood Density, and Mechanical Properties

Table 2 shows average SWV_S and wood properties for six *A. auriculiformis* clones planted in Vietnam. There were significant ($P < 0.001$) differences in SWV_S among clones. The overall mean of SWV_S among clones was 4242 m/s (at approximately 12% MC). The lowest and highest SWV_S values were observed in clone 2 (3972 m/s) and clone 1 (4393 m/s), respectively. In radial direction, the SWV_S values near the bark were significantly greater than those near the pith, except for clone 2. Hasegawa *et al.* (2015) reported that the longitudinal ultrasonic wave velocity of small clear wood specimens from 10-year-old *A. auriculiformis* is 4500 m/s. In 5-year-old *Acacia mangium*, Duong and Hasegawa (2021) found the average (200 kHz ultrasonic) velocity of small defect-free specimens as 4170 m/s.

There was a significant difference found in AD between positions near the pith and bark in clones 2 and 5. In contrast, no significant difference was found between inner and outer wood from pith for the other clones. The mean AD across the six *A. auriculiformis* clones was 0.54 g/cm^3, varying from 0.53 g/cm^3 (near pith) to 0.56 g/cm^3 (near bark). These results were comparable with those reported for 5½-year-old *A. auriculiformis* clones planted in southern Vietnam (0.52 g/cm^3 for heartwood and 0.56 g/cm^3 for sapwood) (Hai *et al*. 2010). However, the authors' results were lower than densities reported in older trees, for example in 8-year-old (0.66 g/cm^3) and 11-year-old (0.69 g/cm^3) *A. auriculiformis* (Shukla *et al*. 2007; Chowdhury *et al*. 2012).

The ANOVA showed significant differences in AD among clones (Table 2). The highest AD values were detected in clones 6 (0.59 g/cm^3) and 1 (0.57 g/cm^3), whereas clones 5 and 3 had the lowest (0.50 and 0.51 g/cm^3, respectively). Wood density is considered as one of the most important wood properties because it is related to sawn timber quality and pulp yield (Zobel and van Buijtenen 1989), and is also an integrator of strength properties, making it an important selection criterion for *Acacia* breeding programs that incorporate wood properties (Chowdhury *et al*. 2013). Clones 1 and 6, which had little radial variation in wood density, may help improve juvenile (core wood) wood properties. When coupled with their higher wood density the authors' data suggests that both have promise for breeding programs that focus on improving wood quality of *A. auriculiformis* grown in Vietnam.

The MOE and MOR are important wood properties for species mainly used for construction lumber. Overall, average MOE and MOR of the six *A. auriculiformis* clones was 8.07 and 92.12 MPa, respectively. The MOE values in this study were higher than MOE found by Sahri *et al*. (1998) in *A. auriculiformis*, but in the range of other studies of the same species (Chowdhury *et al*. 2012; Jusoh *et al*. 2014). Mean MOR was close to MOR of 8-year-old *A. auriculiformis* planted in India (99.7 MPa) (Shukla *et al*. 2007), but lower than values reported in 5½-year-old *A. auriculiformis* by Hai *et al*. (2010) (141.8 MPa) and 11-year-old *A. auriculiformis* (103.5 MPa) (Chowdhury *et al*. 2012).

The T-test results showed that the mean values of MOE and MOR in the outer wood were higher than those near the pith in all tested clones, except for MOR in clones 3 and 5. This radial variation pattern of static bending properties was like that in *A. auriculiformis* clones reported by Hai *et al*. (2010). The results of ANOVA revealed that there were significant differences among clones for MOE and MOR. Similar to AD, the highest average MOE and MOR were also detected in clones 6 (8.90 GPa and 99.51 MPa, respectively) and 1 (9.14 GPa and 101.43 MPa, respectively), indicating the importance of both for tree improvement for lumber production. Wood properties are generally more heritable than growth properties (Cornelius 1994). However, wood properties are controlled not only by genetic factors but also by environmental factors (Zobel and van Buijitenen 1989). Further research must be done to examine the effects of environmental variation on clonal variation in *A. auriculiformis* wood properties.

A number of studies have reported that values of dynamic modulus of elasticity based on stress wave velocity are higher than those obtained by destructive tests (Wang *et al*. 2001; Duong and Matsumura 2018; Duong and Ridley-Ellis 2021). In this study, the overall mean value of MOE$_d$ was 17.82% higher than that of MOE (Table 2). The results of ANOVA showed that MOE$_d$ values had similar patterns in radial and among-clone variation comparing with MOE.

Table 2. Average Stress Wave Velocity and Wood Properties for Six *Acacia auriculiformis* Clones Planted in Vietnam

Properties	*n*	*F*	Clone						
			1	2	3	4	5	6	Mean
AD (g/cm^3)									
Near pith	120	48.10	0.56$^{(a)}$ ± 0.02^{b}	0.53$^{(b)}$ ± 0.03^{c}	0.50$^{(a)}$ ± 0.03^{d}	0.55$^{(a)}$ ± 0.03^{b}	0.48$^{(b)}$ ± 0.02^{e}	0.58$^{(a)}$ ± 0.02^{a}	0.53$^{(b)}$ ± 0.04
Near bark	120	27.43	0.57$^{(a)}$ ± 0.02^{a}	0.57$^{(a)}$ ± 0.02^{a}	0.51$^{(a)}$ ± 0.02^{b}	0.57$^{(a)}$ ± 0.04^{a}	0.52$^{(a)}$ ± 0.02^{b}	0.59$^{(a)}$ ± 0.03^{a}	0.56$^{(a)}$ ± 0.04
Total average	240	54.80	0.57 ± 0.02^{ab}	0.55 ± 0.03^{b}	0.51 ± 0.03^{c}	0.56 ± 0.04^{b}	0.50 ± 0.03^{c}	0.59 ± 0.03^{a}	0.54 ± 0.04
SWV$_S$ (m/s)									
Near pith	120	18.51	4295$^{(b)}$ ± 106^{ab}	3954$^{(a)}$ ± 142^{d}	4098$^{(b)}$ ± 149^{c}	4150$^{(b)}$ ± 137^{c}	4314$^{(b)}$ ± 143	4176$^{(b)}$ ± 147^{bc}	4164$^{(b)}$ ± 182
Near bark	120	29.54	4491$^{(a)}$ ± 95^{a}	3991$^{(a)}$ ± 104^{d}	4340$^{(a)}$ ± 187^{bc}	4291$^{(a)}$ ± 84^{c}	4426$^{(\acute{a})}$ ± 185^{ab}	4376$^{(a)}$ ± 167^{abc}	4319$^{(a)}$ ± 213
Total average	240	34.16	4393 ± 140^{a}	3972 ± 124^{d}	4219 ± 207^{c}	4221 ± 133^{c}	4370 ± 173^{ab}	4276 ± 186^{bc}	4242 ± 213
MOE$_d$ (GPa)									
Near pith	120	45.44	10.35$^{(b)}$ ± 0.64^{a}	8.24$^{(b)}$ ± 0.58^{d}	8.40$^{(b)}$ ± 0.61^{cd}	9.50$^{(b)}$ ± 0.61^{b}	8.85$^{(b)}$ ± 0.59^{c}	10.14$^{(b)}$ ± 0.50^{ab}	9.25$^{(b)}$ ± 1.00
Near bark	120	35.29	11.55$^{(a)}$ ± 0.54^{a}	9.15$^{(a)}$ ± 0.45^{d}	9.68$^{(a)}$ ± 0.88^{cd}	10.43$^{(a)}$ ± 0.82^{b}	10.23$^{(a)}$ ± 0.72^{bc}	11.33$^{(a)}$ ± 0.69^{a}	10.40$^{(a)}$ ± 1.09
Total average	240	43.30	10.95 ± 0.84^{a}	8.70 ± 0.69^{d}	9.04 ± 0.99^{cd}	9.96 ± 0.86^{b}	9.54 ± 0.96^{bc}	10.74 ± 0.85^{a}	9.82 ± 1.19
MOE (GPa)									
Near pith	120	30.43	8.75$^{(b)}$ ± 0.72^{a}	7.28$^{(b)}$ ± 0.57^{bc}	6.89$^{(b)}$ ± 0.74^{c}	7.66$^{(b)}$ ± 0.65^{b}	7.10$^{(b)}$ ± 0.44^{bc}	8.55$^{(b)}$ ± 0.61^{a}	7.70$^{(b)}$ ± 0.94
Near bark	120	28.62	9.54$^{(a)}$ ± 0.55^{a}	7.76$^{(a)}$ ± 0.60^{b}	7.86$^{(a)}$ ± 0.69^{b}	8.22$^{(a)}$ ± 0.77^{b}	8.00$^{(a)}$ ± 0.54^{b}	9.24$^{(a)}$ ± 0.64^{a}	8.44$^{(a)}$ ± 0.94
Total average	240	43.53	9.14 ± 0.75^{a}	7.52 ± 0.63^{bc}	7.37 ± 0.86^{c}	7.94 ± 0.76^{b}	7.55 ± 0.67^{bc}	8.90 ± 0.71^{a}	8.07 ± 1.01
MOR (MPa)									
Near pith	120	8.83	98.17$^{(b)}$ ± 10.95^{a}	86.90$^{(b)}$ ± 12.08^{bcd}	82.81$^{(a)}$ ± 11.13^{cd}	89.53$^{(a)}$ ± 11.38^{abc}	77.68$^{(b)}$ ± 9.07^{d}	94.44$^{(b)}$ ± 12.80^{ab}	88.26$^{(b)}$ ± 13.02
Near bark	120	19.31	104.68$^{(a)}$ ± 6.18^{a}	99.03$^{(a)}$ ± 8.49^{a}	86.64$^{(a)}$ ± 7.99^{b}	91.01$^{(a)}$ ± 7.02^{b}	89.95$^{(a)}$ ± 6.56^{b}	104.57$^{(a)}$ ± 10.74^{a}	95.98$^{(a)}$ ± 10.61
Total average	240	19.08	101.43 ± 9.38^{a}	92.96 ± 12.00^{b}	84.72 ± 9.76^{c}	90.27 ± 9.37^{bc}	83.81 ± 9.99^{c}	99.51 ± 12.74^{a}	92.12 ± 12.47

Note: Mean values are followed by standard deviation; *n* = number of wood specimens; SWV$_S$ = stress wave velocity of specimen; AD = air-dry density; MOE$_d$ = dynamic modulus of elasticity; MOR = modulus of rupture; MOE = modulus of elasticity. The same letter after the standard deviation indicates no significant difference among clones based on Tukey's HSD test at 5%. The same letter in parenthesis indicates no significant difference between positions near the pith and bark based on T-test at 5%; *F* values were obtained by ANOVA.

Relationships among Measured Properties

Relationships among wood properties and SWV$_S$ are shown in Table 3. The correlations between SWV$_S$ and MOE were positive, ranging from 0.29 (clone 4) to 0.73 (clone 6). There was a significant, but weak correlation between SWV$_S$ and MOR in clones 1 ($r = 0.48$) and 6 ($r = 0.32$), although the properties have no relationship in the remaining clones (Table 3). There was a moderate ($r = 0.56$; $P < 0.001$) correlation between SWV$_S$ and MOE and a weak correlation ($r = 0.14$, $P < 0.05$) between the SWV$_S$ and MOR for combined clones (Table 3).

Correlation analyses were also performed between the mechanical properties and density for each clone and all clones combined (Table 3). For individual clones AD had significant positive correlations with both MOE and MOR, except for clone 6. At specimens level, all clones combined correlation coefficients of AD with MOE and MOR were 0.60 ($P < 0.001$) and 0.62 ($P < 0.001$), respectively. For *A. auriculiformis* grown in Bangladesh, Chowdhury *et al*. (2012) found a statistically significant coefficient of determination between AD and MOR ($r^2 = 0.63$) and no correlation between AD and MOE.

Table 3. Pearson Correlation Coefficients (r) for Relationships between Variables (SWV$_S$, AD, MOE$_d$, MOE, and MOR)

Clone	Properties	AD	SWV$_S$	MOE$_d$	MOE
1	SWV$_S$	0.19^{ns}	-	-	-
	MOE$_d$	0.58^{***}	0.90^{***}	-	-
	MOE	0.44^{**}	0.66^{***}	0.75^{***}	-
	MOR	0.40^{**}	0.48^{**}	0.57^{***}	0.46^{**}
2	SWV$_S$	-0.15^{ns}	-	-	-
	MOE$_d$	0.60^{***}	0.69^{***}	-	-
	MOE	0.32^{*}	0.69^{***}	0.79^{***}	-
	MOR	0.45^{**}	0.12^{ns}	0.44^{**}	0.39^{*}
3	SWV$_S$	-0.09^{ns}	-	-	-
	MOE$_d$	0.41^{**}	0.86^{***}	-	-
	MOE	0.47^{**}	0.70^{***}	0.87^{***}	-
	MOR	0.53^{***}	0.10^{ns}	0.33^{*}	0.54^{***}
4	SWV$_S$	-0.14^{ns}	-	-	-
	MOE$_d$	0.69^{***}	0.61^{***}	-	-
	MOE	0.74^{***}	0.29^{ns}	0.79^{***}	-
	MOR	0.68^{***}	-0.27^{ns}	0.33^{*}	0.54^{***}
5	SWV$_S$	-0.05^{ns}	-	-	-
	MOE$_d$	0.58^{***}	0.78^{***}	-	-
	MOE	0.62^{***}	0.55^{***}	0.83^{***}	-
	MOR	0.68^{***}	0.20^{ns}	0.58^{***}	0.69^{***}
6	SWV$_S$	-0.45^{**}	-	-	-
	MOE$_d$	0.10^{ns}	0.85^{***}	-	-
	MOE	-0.18^{ns}	0.73^{***}	0.72^{***}	
	MOR	0.07^{ns}	0.32^{*}	0.41^{**}	0.64^{***}
Combined Clones	SWV$_S$	-0.11^{ns}	-	-	-
	MOE$_d$	0.56^{***}	0.76^{***}	-	-
	MOE	0.60^{***}	0.56^{***}	0.87^{***}	-
	MOR	0.62^{***}	0.14^{*}	0.53^{***}	0.66^{***}

Note: *ns* Not significantly different; *Significantly different at $P < 0.05$; **Significantly different at $P < 0.01$; ***Significantly different at $P < 0.001$

There was no correlation between AD and SWV_S except for clone 6 ($r = -0.45$; $P < 0.01$, Table 3). A possible explanation for the negative relationship in clone 6 was that the increase in density was not accompanied by a corresponding increase in wood stiffness, and therefore the propagation speed decreased with increasing density. Baar *et al*. (2012, 2013) reported that the velocity of wave propagation in tropical hardwoods (*Afzelia bipindesis* Harms, *Astronium graveolens* Jacq, *Intsia bijuga* Kuntze, and *Millettia laurentii* De Wild) is probably much more affected by the microstructure of particular species such as grain angle, the proportion of fibers, and vessel elements; and it is not recommendable to try to predict it based solely on density. In contrast to relationships between AD and mechanical properties, little data are available relating the relationship between AD and SWV_S for *A. auriculiformis*. In other species, no significant correlation between acoustic velocity and wood density has been reported (Mishiro 1996; Ilic 2003; Yanez *et al*. 2021).

As stated by Wang *et al*. (2001), Posta *et al*. (2016), and Duong and Matsumura (2018), non-destructive methods based on the propagation of stress waves are suitable for predicting dynamic MOE and have a high correlation with the results of the destructive tests. For example, Duong and Matsumura (2018) obtained a good relationship ($r = 0.92$) between MOE and dynamic moduli determined from stress wave velocity in small clear samples of *Melia azedarach* L. However, the measurements of small clear samples may not reflect other wood characteristics such as the presence of knots, deviations from straight grain, and splits. In this study, MOE_d was well related to MOE. The overall correlation for all combined samples was 0.87 and ranged from 0.72 to 0.87 among clones (Table 3). The relationships between MOE and MOE_d for *A. auriculiformis* wood obtained in this study were weak compared with other species. This could be explained by effects of knots on stress wave propagation. Lin and Wu (2013) showed that knots have significant impact on longitudinal stress wave propagation in Korean pine (*Pinus koraiensis* Siebold & Zucc.). Stress wave propagation time in wood samples with knots is shorter than that in clear wood samples with similar moisture content and density. In future experiments, the effects of knots on stress wave propagation in *A. auriculiformis* wood requires clarification.

Table 3 shows the relationships between the MOR and MOE_d for each clone and specimens combined for all clones. The correlation coefficient between MOR and MOE_d in combined clones was 0.53 ($P < 0.001$) and ranged from 0.33 for clone 3 to 0.58 for clone 5 (Table 3). These correlations were weaker than the correlations between MOE and MOE_d. Relationships between MOE_d and MOR in this study were similar to those from other hardwood species using acoustic velocity. For example, De Olivera *et al*. (2002) reported the coefficients of determination between MOE_d (predicted by the ultrasound technique) and MOR for *Goupia glabra* Aubl. and *Hymenaea sp.* as 0.36 and 0.55, respectively.

Prediction of Static Bending Properties by Stress Wave Velocity of Standing Trees

Acoustic technologies have been well established as material evaluation tools for assessing wood properties on standing trees before harvesting and wood processing to maximize value extracted from the resource (Schimleck *et al*. 2019). Many studies have demonstrated moderate to good relationships between tree acoustic velocity and MOE of structural products or MOE of small wood specimens cut from trees (Ishiguri *et al*. 2008; Vazquez *et al*. 2015; de Melo *et al*. 2020). However, most of the studies were on softwood species. The published information on using tree acoustic technique for predicting mechanical properties in hardwood species is currently limited to a few studies (Dickson *et al*. 2003; Ngadianto *et al*. 2020; Yanez *et al*. 2021). Results obtained from measuring SWV_T for each clone and combined clones of *A. auriculiformis* planted in Vietnam are summarized in Table 4. The average SWV_T was 3417 m/s and ranged from 3291 m/s (clone 3) to 3609 m/s (clone 1), with a notably small 4.48% coefficient of variation. The results of ANOVA analysis showed significant differences in SWV_T among clones (Table 4). Clones 1 and 6 had significantly higher SWV_T values than other clones examined in this study. In previous studies, Makino *et al*. (2012) and Ngadianto *et al*. (2020) reported different mean SWV_T values for *A. mangium* which are 3590 and 3570 m/s. Prasetyo *et al*. (2017) reported the SWV_T values in three *Eucalyptus* species in Indonesia ranged from 2640 to 3890 m/s. The current authors observed that the average value of stress wave velocity in small specimens was approximately 20% greater than that in standing trees. Wang and Chuang (2000) showed that the acoustic velocity increases rapidly with decreasing moisture content below the fiber saturation point.

Table 4. Descriptive Statistics for Stress Wave Velocity of Trees (SWV_T) for *Acacia auriculiformis* Clones

Clone	*n*	SWV_T (m/s)				
		Mean	Minimum	Maximum	SD	CV (%)
1	5	3609^a	3468	3686	85	2.36
2	5	3339^b	3230	3465	101	3.02
3	5	3291^b	3193	3402	74	2.25
4	5	3347^b	3304	3412	45	1.34
5	5	3353^b	3206	3532	153	4.56
6	5	3561^a	3430	3706	106	2.98
Combined	30	3417	3193	3706	153	4.48
Note: SD is standard deviation; CV is coefficient of variation; *n* is number of sampled ramets						

Figure 2 shows the relationships between the SWV_T and the average MOE or MOR in static bending of small specimens for all *A. auriculiformis* clones combined (where the average values of MOE and MOR were calculated by averaging all values for each property for specimens obtained from a ramet within a clone). There was a relatively high correlation ($r = 0.83$, $P < 0.001$) between SWV_T and MOE of specimens. A statistically significant ($r = 0.61$, $P < 0.001$) correlation was also found between SWV_T and MOR of specimens. This suggested that selection for increased SWV_T may result in significant increases in MOE and MOR and that tree breeders could identify the best clones in terms of lumber quality based on stress wave velocity for crossing and/or propagation. Correlation coefficients between SWV_T and static properties (MOE and MOR) of specimens were higher than those between SWV_S and static properties of specimens when clone data were combined (Table 3). One probable explanation is the effects of knots on stress wave propagation. SWV_T was measured in the outerwood of a tree to a depth of 20 to 30 mm over a distance between two sensors (1.0 m), while SWV_S was measured for specimens both in outerwood and corewood of the stem. The corewood of *A. auriculiformis* presented more knots than the outerwood because this species retains many small branches when young.

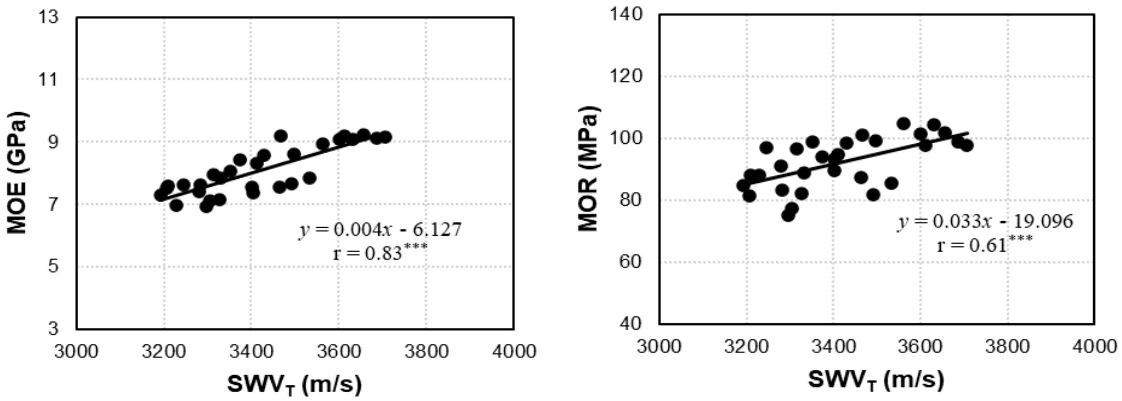

Fig. 2. Relationship between the SWV$_T$ and the average MOE or MOR in static bending of small specimens

CONCLUSIONS

In this study, the SWV$_T$, SWV$_S$, AD, MOE$_d$, MOE, and MOR properties were evaluated for six clones of *A. auriculiformis* planted in a trial site at Quang Tri, Vietnam.

1. The stress-wave velocity and other wood properties examined in this study significantly differed from those obtained among the six clones. Coupled with no significant difference in AD between inner and outer woods from pith, clones 1 and 6 had greater AD, MOE, and MOR than the other clones examined. Therefore, clones 1 and 6 might be appropriate for *A. auriculiformis* tree breeding programs focused on improving wood quality specifically for lumber production in the north central region of Vietnam.
2. A good coefficient of correlation was found between MOE$_d$ measured by stress wave method and MOE measured by destructive test. This could allow for the prediction of static bending properties of *A. auriculiformis* wood with knots using the stress wave technique.
3. Regarding the relationships of SWV$_T$ and static bending properties, the increase of SWV$_T$ may result in significant increase in MOE and MOR. Therefore, tree breeders could identify the best trees in term of the performance of lumber based on the stress wave velocity for crossing and/or propagation.

ACKNOWLEDGMENTS

This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED), Grant No. 106.06-2019.319.

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Article submitted: December 4, 2021; Peer review completed: February 5, 2022; Revised version received and accepted: February 8, 2022; Published: February 10, 2022.
DOI: 10.15376/biores.17.2.2084-2096