Prediction of Mechanical Properties of Hardwood Species Using the Longitudinal Vibration Acoustic Method

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Abstract

Acoustic test methods such as longitudinal vibration have been developed to predict the elastic properties of wood. However, attention has not been shifted to using this method to predict other mechanical properties, especially on Nigeria's preferred, and lesser-used wood species. Thus, we further investigate relationships among mechanical and acoustic properties of selected hardwood species with a view of predicting the mechanical properties of wood from acoustic parameters. Clear wood samples (324) of 20 by 20 by 20 mm^3 were collected axially from *Albizia adianthifolia*, *Gmelina arborea*, *Delonix regia,* and *Boscia anguistifolia* trees, and conditioned before testing. The longitudinal vibration method was adopted to test for the dynamic (acoustic) parameters and properties (fundamental frequency, damping factor, dynamic modulus of elasticity, sound velocity, specific elastic modulus, radiation coefficient, acoustic conversion efficiency, acoustic impedance) while the universal testing machine was used to test for the mechanical properties (static modulus of elasticity, modulus of rupture, maximum compression strength parallel to grain). The damping factor, dynamic modulus of elasticity, and acoustic impedance were the best acoustic parameters that significantly correlated with the static modulus of elasticity (–0.57, 0.81, 0.76), modulus of rupture –0.64, 0.82, 0.85) and maximum compression strength parallel to grain (–0.52, 0.78, 0.84), respectively. There was a significant difference in the mechanical properties with respect to species, thus *A. adianthifolia* and *G. arborea* were mechanically better than *D. regia* and *B. anguistifolia* for construction or structural purposes. This study revealed that additional new acoustic measures are suitable for inferring mechanical wood properties.

Acoustic properties of wood are associated with the wood structure's response to vibration generally induced by surface impact or excitation (Shirmohammadi et al. 2020). The general acoustic properties of interest are dynamic modulus of elasticity (dMOE), sound velocity (V), damping ratio (tan δ), specific dynamic elastic modulus (Es), and acoustic coefficient (K) (Spycheret al. 2008, Sproßmann et al. 2017). Authors such as Obataya et al. (2000) and Olaoye et al. (2019) have found the longitudinal vibration acoustic method suitable for predicting static elastic modulus of wood.

Wood is one of the oldest, most versatile, and most lightweight renewable resources that has been accepted and conditioned for structural and construction applications on its stiffness properties (Green 2001, Smith and Snow 2008, Ramage et al. 2017). The strength properties of wood considered for construction purposes may be generally assessed through visual grading; however, it is scientifically determined through assessing the mechanical properties. Mechanical properties are characterized by the response of a material to externally applied forces (Murugan 2020). Furthermore, it was highlighted that static modulus of elasticity (sMOE), bending strength, and parallel compression strength are the most sought-after mechanical properties for assessing the strength of wood. (Vernay 2000, Messaoudene et al. 2008).

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Mechanical methods such as resistance drilling, screw withdrawal, hardness test (Nowak et al. 2021), and the use of a universal testing machine (UTM) have been adopted for measuring the strength properties of wood. Notwithstanding, the common method of determining the mechanical properties of wood is through the use of the UTM. This method is considered expensive, demanding high maintenance cost; it is time-consuming—about 10 minutes per sample—and also damages the wood samples, thus rendering an undesirable effect. Consequently, there has been a continuous and concerted effort to search for cheaper, faster, safer, and non-destructive means of determining the mechanical properties of wood.

In light of the above, scholars have endeavored to engage acoustic techniques such as the longitudinal vibration method to evaluate some mechanical properties of wood. Leite et al. (2012), Olaoye (2019), and Olaoye and Okon-Akan (2020) estimated the sMOE of selected wood species from the dMOE, while Chauhan and Sethy (2016) estimated the modulus of elasticity (MOE) and modulus of rupture (MOR) from dMOE using three different vibration acoustic methods. They all found a suitable relationship among properties measured. However, the suitability of the longitudinal vibration acoustic method where two or more species are combined has yet to be adequately demonstrated.

Although the relationship between sMOE and dMOE of wood has been established, there is little or no investigation into the suitability of other acoustic parameters such as V, tan δ, and Es as predictors for other static mechanical properties. It is thus appropriate to suspect additional significant relationships. Additionally, the application of the longitudinal vibration acoustic method on Nigeria's preferred and lesser-used wood species has not gained prominence. Therefore, investigation into the relationship among these properties is needed to reveal and broaden knowledge of other acoustic parameters useful for predicting more mechanical properties, especially on selected wood species in Nigeria. Hence, this study aimed at determining the relationship among the mechanical and acoustic properties of selected hardwood species with the view of predicting the mechanical properties using the longitudinal vibration acoustic method.

The selected wood species considered in this study were *Albizia adianthifolia*, *Gmelina arborea*, *Delonix regia*, and *Boscia anguistifolia*. *Albizia adianthifolia* is a tall tree (about 36 m) with a few large, widely spreading branches. It is widespread in tropical Africa and southern Africa, and is commonly called ''ayinre bona bona'' in Yoruba, southwestern Nigeria (Lock and Keay 1991). Also, *G. arborea* is a widely cultivated and distributed exotic wood species in Nigeria. It has found prominence in uses for acoustic application and musical instruments such as the talking drum (Aiyeloja et al. 2015). It produces high-quality wood, which is harvested for the manufacture of furniture, musical instruments, plywood, and matches (Beentje et al. 2003, Orwa et al. 2009). *Delonix regia* belongs to the family Fabaceae, and is a medium-sized tree found in tropical countries (Shewale et al. 2012). Its wood has been explored for making cutlery, industrial and domestic woodware, musical instruments, tool handles, and toys (Patro 2016). *Boscia angustifolia* is a shrub or small tree about 6 m high that belongs to the family Capparaceae and it is commonly found across Africa (Burkill 1985).

Materials and Methods

Sample collection and preparation

Three trees (diameter at breast height of 25 $\pm$ 2 cm) of each species, *A. adianthifolia*, *G. arborea*, *D. regia,* and *B. anguistifolia* (making a total of 12 trees), were felled. *Gmelina arborea* and *B. anguistifolia* were felled from Gambari Forest Reserve, Oyo State, Nigeria, while *A. adianthifolia* and *D. regia* were felled from farmland. The trees were partitioned axially (top, middle, and base) using a chainsaw, and further converted to wood samples of 20 by 20 by 20 mm^3 (radial by tangential by longitudinal; British standards [BS] 373 1957) using the circular machine. Twenty-seven clear wood samples were collected from each tree for the acoustic and mechanical properties test, thus making a total of 324 wood samples (i.e., 27 wood samples with 3 replicates of each tree species and 4 tree species) considered for this study. All wood samples were oven-dried at 103°C $\pm$ 2°C for 24 hours and conditioned at 80% relative humidity and 30°C for 1 month before testing, to reach equilibrium moisture content.

Gambari Forest Reserve, formally known as Ibadan District Native Authority Forest Reserve, lies between latitudes 7°25′N and 7°55′N and longitudes 3°53′E and 3°9′E. It is situated between River Ona on the west and the main motor road from Ibadan to Ijebu-Ode on the east. The site map is shown in Figure 1. The forest reserve has a typical humid climate with two distinct seasons a year. The two seasons are the rainy season, which runs from April until October, and the dry season, which falls between November and March. The annual rainfall is 1,257 mm. The relative humidity ranges between 84.5% (June till September) and 78.8% (December till January). The mean annual temperature ranges from 21.0°C to 31.3°C (Shomade 2000).

Wood density

The green volume of the wood samples was measured and the mass after conditioning was weighed. Hence, Equation 1 was adopted for the calculation of the wood density (ρ).

$$\rho = \frac{m}{v}(\mathrm{g\ cm^{-3}}) \qquad (1)$$

where m is the mass of the wood sample at 11% moisture content and v is the green volume of the wood sample.

The longitudinal vibration test

The wood acoustic parameters measured and calculated were: fundamental frequency (FF), dMOE, damping factor (tanδ), Es, velocity (V), acoustic coefficient (K), and acoustic conversion efficiency (ACE). The set-up and experiment were done according to Olaoye (2019; Fig. 2). Each sample (20 by 20 by 20 mm^3) was tied with a thread on both sides and suspended from a top with the threads; this is done to ensure no external sound was produced during testing and to simulate a free bar. A wooden hammer was used to hit the wood sample from one end and the response vibrating sound was picked by a microphone and recorded in a wave format file using a recording software (Audacity) on the computer, at the other end. The first bending natural frequency (FF) was then obtained from the recorded sound signal using the fast Fourier transform spectrum analyzer. Thereafter, the dMOE was calculated according to Görlacher (1984) with the following equation:

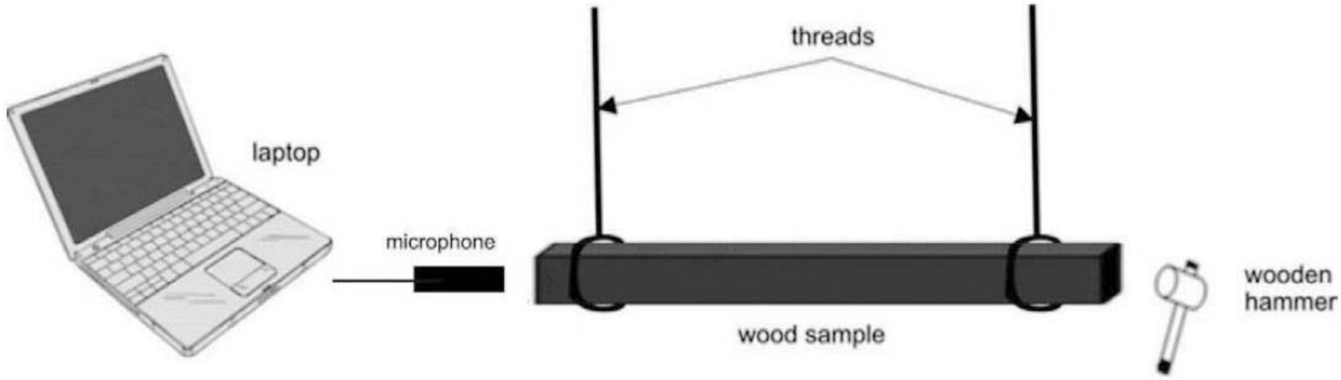

Figure 1.—The set-up of the flexural free vibration test.

$$\text{dMOE} = \left(\frac{2f_n}{\gamma_n \pi}\right)^2 \frac{mL^3}{I}\,(\text{GPa}) \qquad (2a)$$

where m is the specimen weight, f_n is the first bending natural (fundamental) frequency, n is the mode number, L is the length of the sample, γ_n is a constant for the first mode (2.267), and I is inertia moment.

$$I = \frac{(bh^3)}{12} \qquad (2b)$$

where b is the width and h is the thickness of the specimen.

Equations 3 through 9 were used to calculate other selected acoustic parameters.

Equation 3 measures damping factor due to internal friction,

$$(\tan\delta) = \frac{\lambda^1}{\pi} \qquad (3)$$

where λ^1 is the logarithmic vibrating decrement factor, as defined in Equation 4,

$$\lambda^1 = \left(\frac{1}{n}\right) \ln\left(\frac{X_1}{X_{n+1}}\right) \qquad (4)$$

where n is the number of successive peaks, and X_1 and X_{n+1} are the first and (n + 1)th amplitude of vibration respectively, as shown in Figure 3.

The specific dynamic elastic modulus (Es) is calculated as

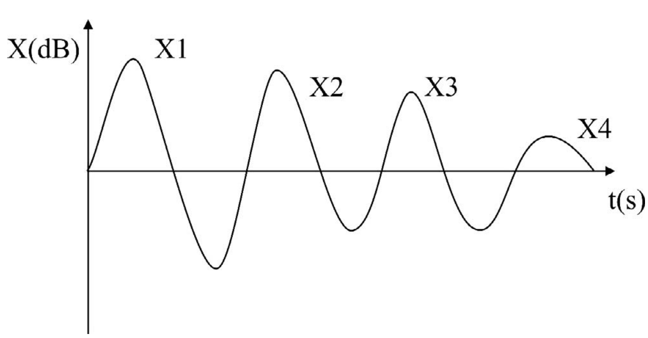

Figure 2.—The amplitude decrement of the first mode of vibration through time.

$$\text{Es} = \frac{\text{dMOE}}{\rho}\,(\text{GPa}) \qquad (5)$$

where ρ is the wood density.

Equation 6 calculates the velocity of sound (V) (Ono and Norimoto 1983, Akitsu et al. 1993):

$$V = \sqrt{\frac{\text{dMOE}}{\rho}}\,(\text{m/s}) \qquad (6)$$

Figure 3.—Wood sample under static bending test of UTM.

where dMOE is the dynamic modulus of elasticity, and ρ is the wood density.

The acoustic coefficient of the vibrating body (K) is shown in Equation 7,

$$K = \left(\frac{\text{dMOE}}{\rho^3}\right)^{0.5} \quad (7)$$

and acoustic conversion efficiency (ACE; Ross and Pellerin 1994) is calculated as

$$\text{ACE} = \frac{K}{\tan\delta}(\text{m}^4\ \text{kg}^{-1}\ \text{s}^{-1}) \quad (8)$$

Equation 9 is used to calculate impedance (Z):

$$Z = V\rho(\text{kg m}^{-2}\text{s}^{-1}) \quad (9)$$

where V is sound velocity.

Static bending test

Subsequently, the wood samples used for the longitudinal vibration test were used for the static bending test. Eighty-one samples per species were used, and the test was carried out under standard procedure (British standards [BS] 373 1957), in three-point bending stress, using the Instron 3369 model UTM. The load was applied at the rate of 0.1 mm/s with the grain perpendicular to the direction of loading, while the maximum load that caused failure in each sample was recorded. Equations 10, 11, and 12 were used to calculate MOE, MOR, and maximum compression strength parallel to grain (MCS//) respectively.

$$\text{MOE} = \frac{pl^3}{4b\Delta d^3}(\text{N mm}^{-2}) \quad (10)$$

$$\text{MOR} = \frac{3pl}{2bd^2}(\text{N mm}^{-2}) \quad (11)$$

$$\text{MCS//} = \frac{p}{A}(\text{N mm}^{-2}) \quad (12)$$

where p is maximum load at failure (N), l is the span of the material between the supports (mm), b is width of the material (mm), d is thickness of the material (mm), Δ is deflection, and A is the sectional area of the test sample.

Statistical analysis

The experiment was set up in a completely randomized design and data obtained were subjected to analysis of variance, Pearson correlation (r), and regression analysis at $\alpha_{0.05}$.

$Yij = \mu + Ti + Eij$

Yij = individual observation

μ = mean

Ti = treatment effect (tree species)

Eij = error term

Results

The mean mechanical and acoustic properties of the hardwood species are reported in Table 1. The sMOE was highest (9.58 GPa) for *G. arborea* wood while *A. adianthifolia* wood had the highest MOR (106.31 N mm^{-2}) and MCS// (52.61 N mm^{-2}). For the acoustic properties measured, *G. arborea* wood had the highest values for FF (1073 Hz), dMOE (11.30 GPa), V (4528.54 m s^{-1}), Es (20.55 GPa), K (8.27), ACE (4013.83 m^4 kg^{-1} s^{-1}), Z (2,492.05 × 10^3 kg m^{-2} s^{-1}), but lowest value for tanδ (0.002).

Table 2 shows the correlation analysis among the mechanical and acoustic properties. The least coefficient of correlation ($r = 0.15$) was obtained with MCS// and ACE while r was highest (0.85) with MOR and Z. All the correlations among these properties were significant, except for sMOE with ACE (0.18), and MCS// with ACE (0.15). Also, Figures 4 through 14 revealed the best selected significant relationship among the mechanical and acoustic properties measured. Each figure shows the exponential and linear relationships of selected properties, for effective comparison. The gray and black trend lines represent the exponential and linear relationships respectively. The highest coefficient of correlation of determination (R^2) obtained was with MOR and Z (0.73; linear relationship) while the least R^2 was with MCS// and tanδ (0.27; exponential and linear relationship). Meanwhile, Figures 15 through 25 show the graphical relationships among these properties for the different wood species.

Discussion

Wood species intended for construction purposes must possess good mechanical traits, this thus implies that a good evaluation of mechanical properties is essential. Therefore, *A. adianthifolia* and *G. arborea*, which have the highest significant values of the mechanical properties sMOE, MOR, and MCS//, is the most suitable for construction purposes among the four species examined. Meanwhile, classification of the strength property of wood based on sMOE values according to Upton and Attah (2003) is thus; ''very high'' (19 GPa and more), ''high'' (14 to 19 GPa), ''medium'' (11 to 14 GPa), ''low/medium'' (9 to 11 GPa) and ''low'' (below 9 GPa). Consequently, *A. adianthifolia* and *G. arborea* wood had low/medium strength while *D. regia* and *B. anguistifolia* had low strength traits.

The mean sMOE value obtained in this study for *G. arborea* wood was slightly higher than those reported by Ataguba et al. (2015), who found sMOE values ranging between 7,900 and 8,000 N mm^{-2} for similar species. Meanwhile, the mean sMOE for *B. anguistifolia* obtained by Adebawo et al. (2019; 6,250 N mm^{-2}) was a little higher than the mean sMOE obtained in this study while the MOR (46.44 N mm^{-2}) and MCS// (24.20 N mm^{-2}) were lower.

Interestingly, the sMOE values of the studied hardwood species were within the range of the following selected hardwood species in Nigeria: 7,090 N mm^{-2} for *Celtis mildbraedii*, 6,310 N mm^{-2} for *Afzelia africana*, 8,190 N mm^{-2} for *Khaya ivorensis*, 5,770 N mm^{-2} for *Meliceae excelsa,* and 3,930 N mm^{-2} for *Triplochiton scleroxylon* (Jamala 2013).

MCS// values are classified as very low (under 20 N mm^{-2}), low (20 to 35 N mm^{-2}), medium (35 to 55 N mm^{-2}), high (55 to 85 N mm^{-2}), and very high (over 85 N mm^{-2}; Ojo 2020). Therefore, *A. adianthifolia* and *G.arborea* possess a medium MCS// while *D. regia* and *B. anguistifolia* is within the range of low MCS//.

The mechanical properties of wood can be influenced by its anatomical makeup (Kasal 2004). Therefore, with different anatomical makeup of wood species, properties

Table 1.—Mechanical and acoustic properties of tested species.

Properties[a]	*Albizia adianthifolia*, mean (SE)	*Gmelina arborea*, mean (SE)	*Delonix regia*, mean (SE)	*Boscia anguistifolia,* mean (SE)
sMOE (N mm^{-2})	9,319.98 (280.41) B[b]	9,581.53 (341.20) B	5,910.61 (651.32) A	5,633.27 (407.15) A
MOR (N mm^{-2})	106.31 (4.74) C	99.13 (2.77) C	45.35 (2.80) A	64.80 (3.96) B
MCS// (N mm^{-2})	52.61 (1.21) C	49.70 (1.00) C	31.78 (1.40) B	35.57 (1.60) A
FF (Hz)	836 (16.83) A	1,073 (17.63) B	806 (21.86) B	829 (38.20) B
Tanδ	0.003 (0.000) AB	0.002 (0.000) A	0.006 (0.000) C	0.004 (0.000) B
dMOE (GPa)	10.45 (0.23) C	11.30 (0.24) D	6.14 (0.26) A	8.04 (0.34) B
V (m/s)	3,996.47 (40.01) A	4,528.54 (38.25) B	3,921.27 (52.47) A	3,961.48 (83.28) A
Es (GPa)	16.01 (0.32) A	20.55 (0.34) B	15.45 (0.42) A	8.04 (0.34) A
K	6.16 (0.13) A	8.27 (0.14) B	9.99 (0.17) C	7.86 (0.26) B
ACE (m^4 kg^{-1} s^{-1})	2,084.28 (131.75) AB	4,013.85 (325.05) C	1,952.08 (142.52) A	2,761.91 (327.50) B
$Z \times 10^3$(kg m^{-2} s^{-1})	2,611.36 (41.60) C	2,492.05 (4102.28) C	1,553.29 (4433.12) A	2,012.42 (4,819.94) B

[a] sMOE = static modulus of elasticity; MOR = modulus of rupture; MCS// = maximum compression strength parallel to grain; FF = fundamental frequency; tanδ = damping factor; dMOE = dynamic modulus of elasticity; V = sound velocity; Es = specific dynamic elastic modulus; K = acoustic coefficient; ACE = acoustic conversion efficiency; *Z* = impedance.

[b] Mean values across rows with different letters are significantly different from each other.

Table 2.—Correlation analysis among mechanical and acoustic properties of tested species.

	sMOE[a]	MOR	MCS//
FF	0.33*[b]	0.34*	0.26*
Tanδ	−0.57*	−0.64*	−0.52*
dMOE	0.81*	0.82*	0.78*
V	0.35*	0.36*	0.28*
Es	0.33*	0.34*	0.26*
K	−0.27*	−0.64*	−0.64*
ACE	0.18	0.26*	0.15
Z	0.76*	0.85*	0.84*

[a] sMOE = static modulus of elasticity; MOR = modulus of rupture; MCS// = maximum compression strength parallel to grain; FF = fundamental frequency; tanδ = damping factor; dMOE = dynamic modulus of elasticity; V = sound velocity; Es = specific dynamic elastic modulus; K = acoustic coefficient; ACE = acoustic conversion efficiency; *Z* = impedance.

[b] * Significant correlation at $P < 0.05$.

such as fiber length, wood density, the orientation of microfibrils, and chemical composition may be responsible for the strength performance of wood species.

Relationship between sMOE and acoustic properties

A higher value of dMOE compared with the sMOE obtained for all the tested hardwood species supports findings of other researchers (Ilic 2001, Burdzik and Nkwera 2002, Targa et al. 2005, Leite et al. 2012, Chauhan and Sethy 2016). However, lower values of dMOE have also been found in some studies (Hodoušek et al. 2017, Olaoye 2019, Olaoye and Okon-Akan 2020). Variation in trends like this can be attributed to the type of acoustic method used, or sample dimensions, as opined by Hodoušek et al. (2017), especially sample length (Bucur and Archer 1984).

All the acoustic properties measured in this study had significant correlations with sMOE, except ACE, an indication that acoustic properties are a good predictor of sMOE. Thus, tanδ, dMOE, and *Z* are the acoustic properties that had the best suitable relationship with sMOE. Also, the results revealed that tanδ had a negative correlation with sMOE while dMOE and *Z* had a positive correlation with sMOE. This implies that the lower the tanδ, the higher the sMOE, while the more the dMOE and *Z*, the more the sMOE.

Similarly, a negative correlation (–0.59) was found between sMOE and tanδ, as well as a positive relationship (0.94) between sMOE and dMOE (Leite et al. 2012), thus supporting the findings in this study. The higher values of coefficient of determination (R^2) imply that the exponential relationship for predicting sMOE from tanδ, dMOE, and *Z* was more suitable than its linear relationship (Figs. 3 through 5).

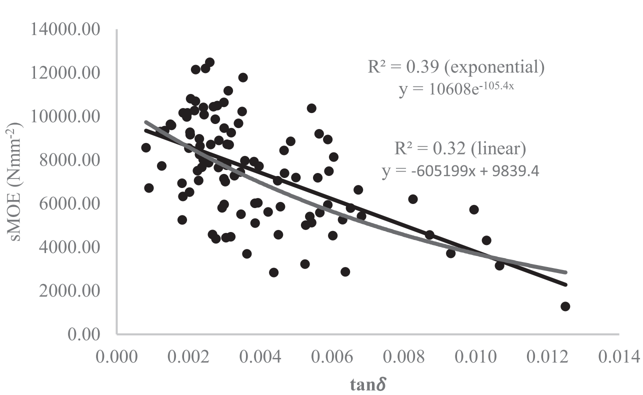

Figure 4.—Scatter plot showing the relationship between static modulus of elasticity (sMOE) and damping factor (tanδ).

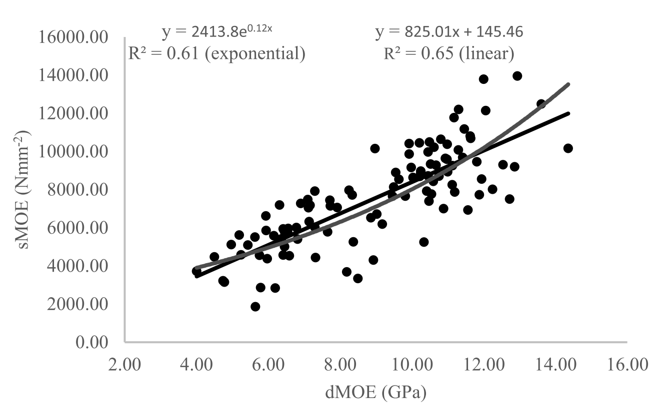

Figure 5.—Scatter plot showing the relationship between static modulus of elasticity (sMOE) and dynamic modulus of elasticity (dMOE).

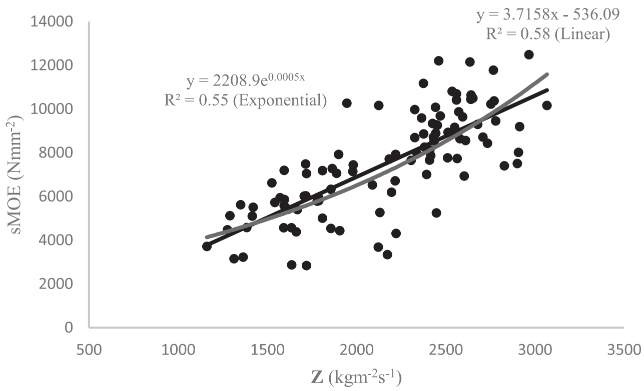

Figure 6.—Scatter plot showing the relationship between static modulus of elasticity (sMOE) and impedance (Z).

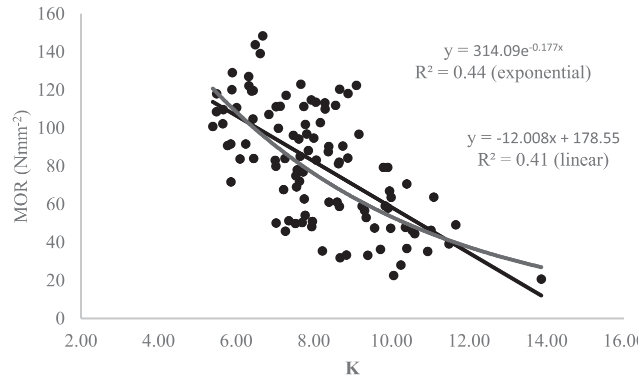

Figure 9.—Scatter plot showing the relationship between modulus of rupture (MOR) and acoustic coefficient (K).

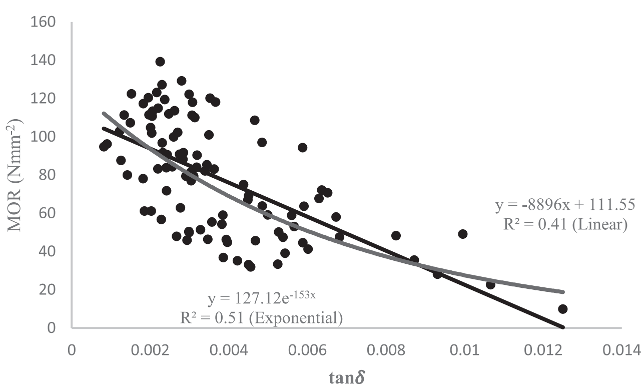

Figure 7.—Scatter plot showing the relationship between modulus of rupture (MOR) and damping factor (tanδ).

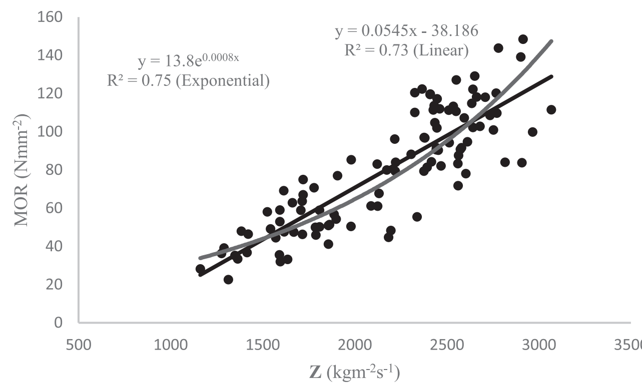

Figure 10.—Scatter plot showing the relationship between modulus of rupture (MOR) and impedance (Z).

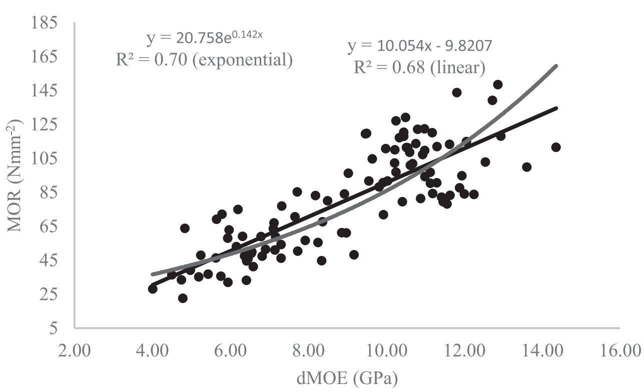

Figure 8.—Scatter plot showing the relationship between modulus of rupture (MOR) and dynamic modulus of elasticity (dMOE).

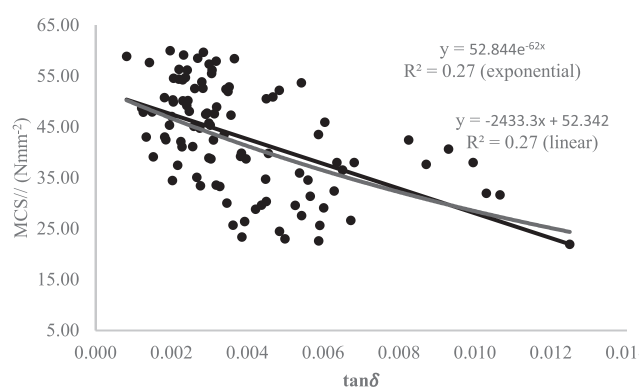

Figure 11.—Scatter plot showing the relationship between maximum compression strength parallel to grain (MCS//) and damping factor (tanδ).

The R^2 obtained in this study for sMOE and dMOE was lower than that of Leite et al. (2012; 0.85), Chauhan and Sethy (2016; 0.97), Baar et al. (2015; 0.83), Hodoušek et al. (2017; 0.81 to 0.87), but within range of Olaoye and Okon-Akan (2020; 0.65), Casado et al. (2010; 0.28 to 0.59), and Baar et al. (2015; 0.52). Figures 15 through 25 in this study confirms the opinion of Karlinasari et al. (2008) Ravenshorst et al. (2008), and Teles et al. (2011) that the strength of correlation between these properties can be dependent on species, or type of acoustic methods used, while Casado et al. (2010) also emphasized sample dimension as a cause of variation in strength correlation. Hence, the medium correlation obtained between sMOE and dMOE in this study may be due to different species used for this study or types of acoustic methods used in other studies.

Nevertheless, a significantly higher exponential relationship between sMOE and dMOE suggests that sMOE had a suitable exponential increment with an increasing dMOE, as against the linear relationship opined by several researchers

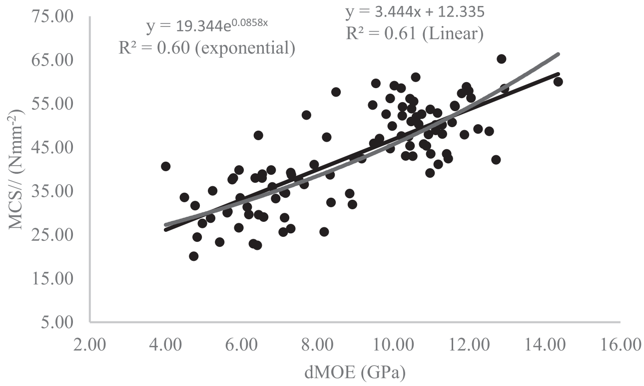

Figure 12.—Scatter plot showing the relationship between maximum compression strength parallel to grain (MCS//) and dynamic modulus of elasticity (dMOE).

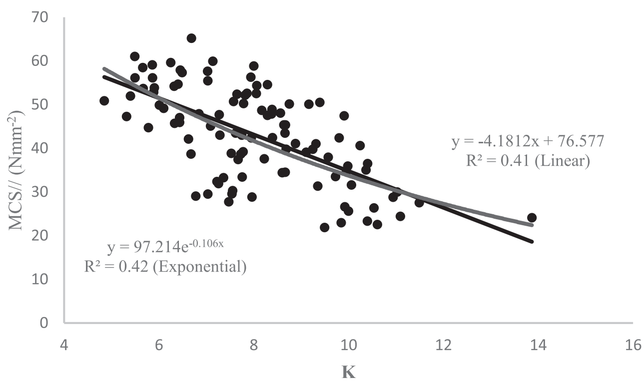

Figure 13.—Scatter plot showing the relationship between maximum compression strength parallel to grain (MCS//) and acoustic coefficient (K).

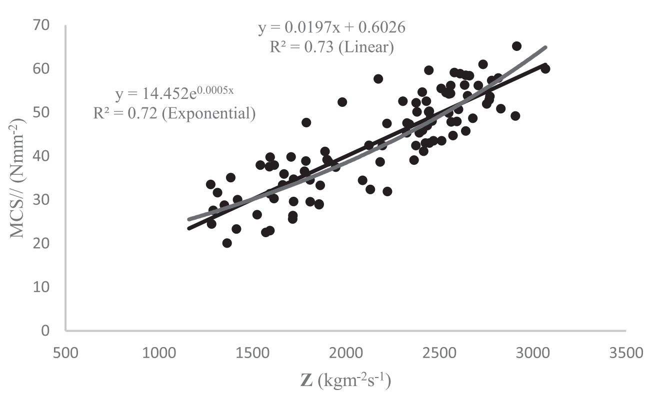

Figure 14.—Scatter plot showing the relationship between maximum compression strength parallel to grain (MCS//) and impedance (Z).

(Leite et al. 2012; Baar et al. 2015; Chauhan and Sethy 2016; Olaoye and Okon-Akan 2020).

The significant exponential positive relationship between sMOE and *Z* also implies that sMOE will increase exponentially with increasing *Z*. As such, the information provided by this study confirms that tanδ, dMOE, and *Z* had a better exponential relationship that is useful for predicting sMOE.

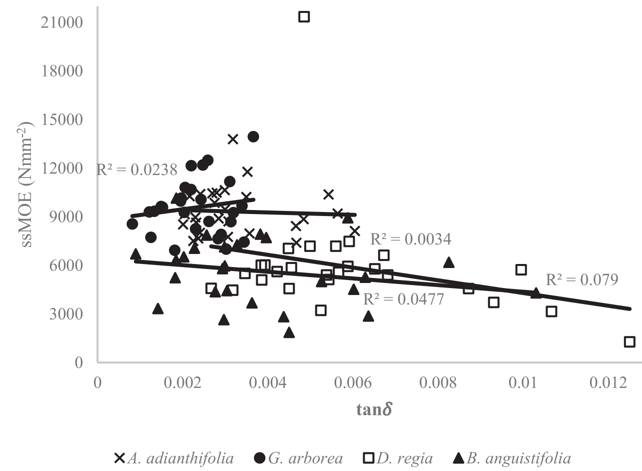

Figure 15.—Scatter plot showing the relationship between static modulus of elasticity (sMOE) and damping factor (tanδ) in the independent species.

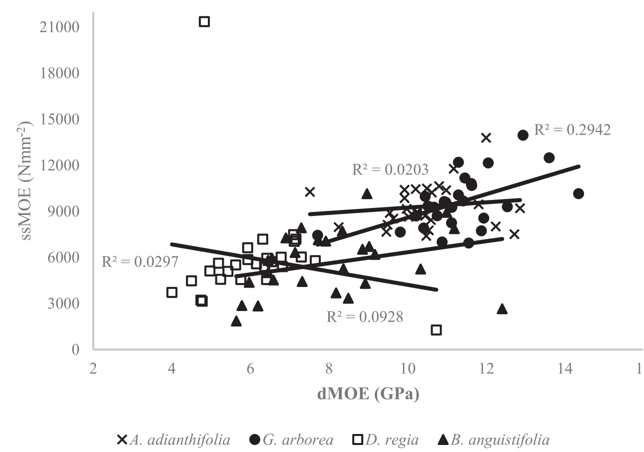

Figure 16.—Scatter plot showing the relationship between static modulus of elasticity (sMOE) and dynamic modulus of elasticity (dMOE) in the independent species.

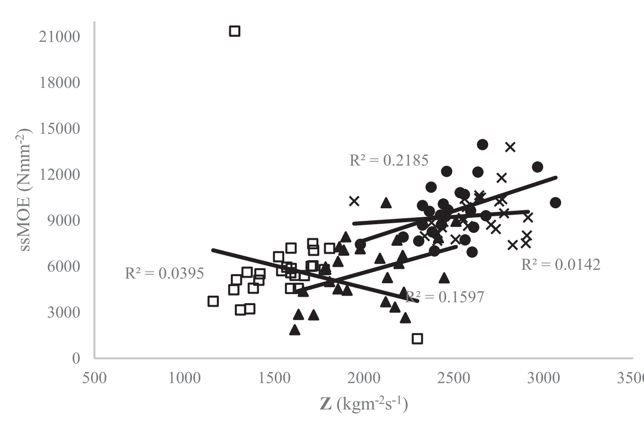

Figure 17.—Scatter plot showing the relationship between static modulus of elasticity (sMOE) and impedance (Z) in the independent species.

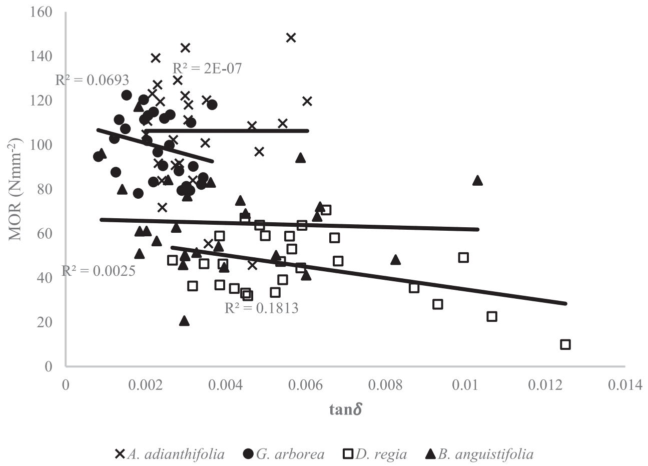

Figure 18.—Scatter plot showing the relationship between modulus of rupture (MOR) and damping factor (tanδ) in the individual species.

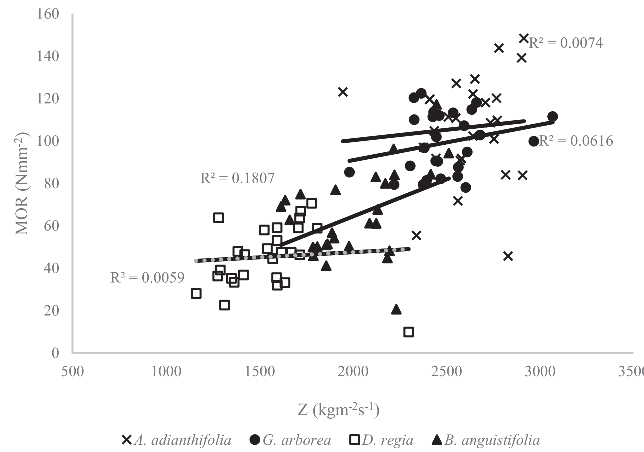

Figure 21.—Scatter plot showing the relationship between modulus of rupture (MOR) and impedance (Z) in the independent species.

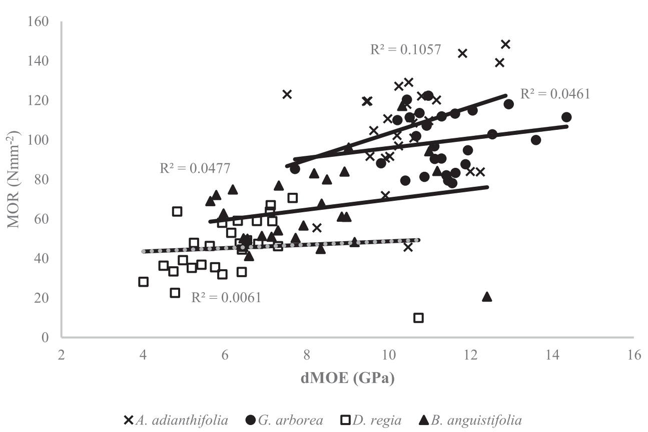

Figure 19.—Scatter plot showing the relationship between modulus of rupture (MOR) and dynamic modulus of elasticity (dMOE) in the independent species.

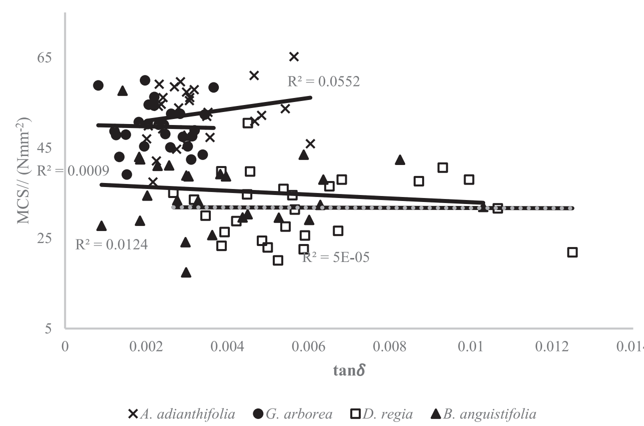

Figure 22.—Scatter plot showing the relationship between maximum compression strength parallel to grain (MCS//) and damping factor (tanδ) in the independent species.

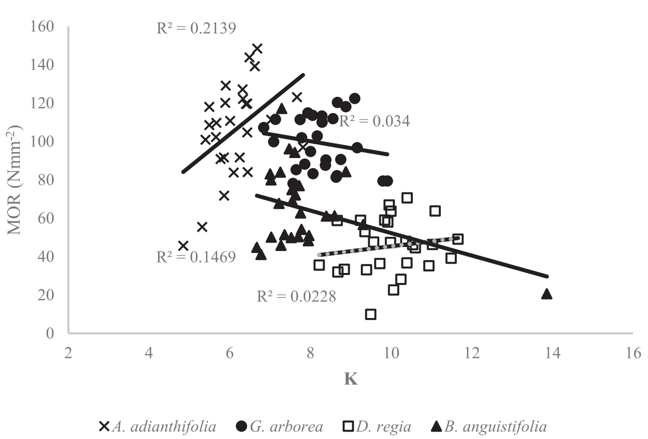

Figure 20.—Scatter plot showing the relationship between modulus of rupture (MOR) and acoustic coefficient (K) in the independent species.

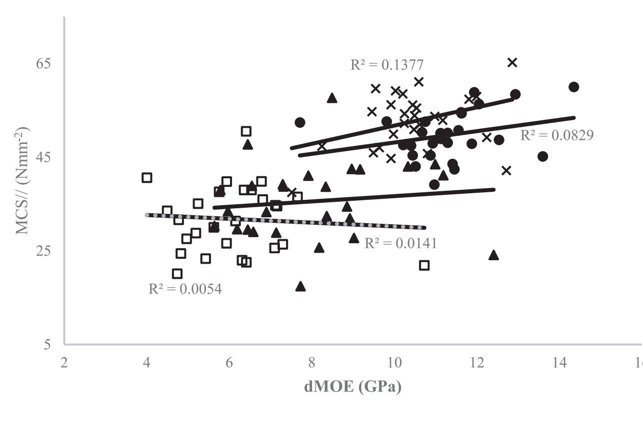

Figure 23.—Scatter plot showing the relationship between maximum compression strength parallel to grain (MCS//) and dynamic modulus of elasticity (dMOE) in the independent species.

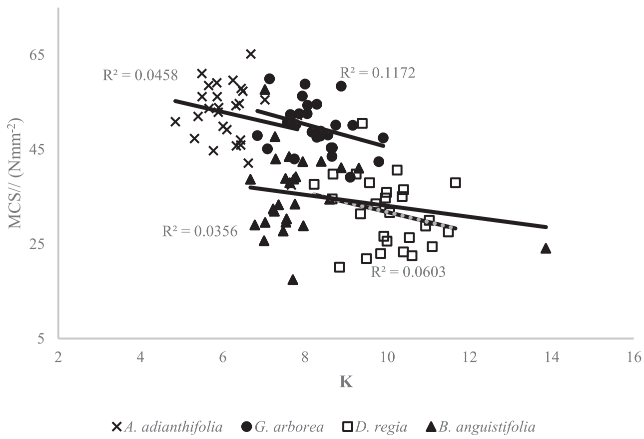

Figure 24.—Scatter plot showing the relationship between maximum compression strength parallel to grain (MCS//) and acoustic coefficient (K) in the independent species.

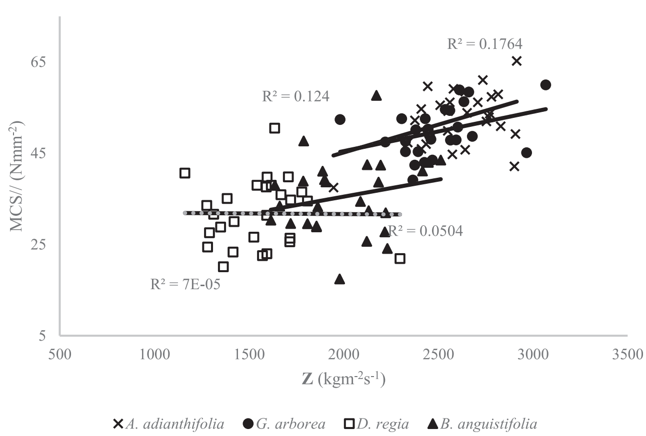

Figure 25.—Scatter plot showing the relationship between maximum compression strength parallel to grain (MCS//) and impedance (Z) in the independent species.

Relationship between MOR and acoustic properties

As is evident in Table 2, all the acoustic properties had either a positive or negative significant relationship with MOR. However, tanδ, dMOE, K, and *Z* had the best significant coefficient of correlation with MOR. The *r* values are indications that tanδ, dMOE, K, and *Z* had degrees of linear association of 64%, 82%, 64%, and 85% respectively.

The *r* (0.54) obtained by Baar et al. (2015) for MOR and dMOE was lower, while Chauhan and Sethy (2016) found a higher *r* (0.88). Nonetheless, different *r* values for correlation between MOR and dMOE have been recorded for different wood species ($r = 0.76$, 0.52, 0.58, 0.62, 0.17) and with different acoustic methods ($r = 0.54$, 0.49, 0.27, 0.12, 0.22;Baar et al. 2015). Therefore, it can be opined that acoustic methods, wood species, and combination of different wood species contributed differently to the degree of association between MOR and dMOE, thus, supporting Karlinasari et al. (2008), Ravenshorst et al. (2008), and Teles et al. (2011). It can then be argued that *r* values can be altered where more than one species is jointly studied, as evident in Figures 15 through 25.

Furthermore, the linear relationships of MOR with dMOE and *Z* were stronger than their exponential relationships whereas MOR with tanδ had a stronger exponential relationship. Meanwhile, the relationship (exponential and linear) between MOR and K was neutral. These assertions were reached based on the values of R^2 found for each relationship (Figs. 6 through 9). Inferentially, MOR can be best predicted by dMOE (linearly), *Z* (linearly), and tanδ (exponentially)

Relationship between MCS// and acoustic properties

Similarly, MCS// was significantly correlated with all acoustic properties measured except with ACE. Since tanδ, dMOE, K, and *Z* had the best degree of association with MCS//, then they can be considered as the most suitable acoustic predictors for MCS//.

It can be deduced from Figures 10 through 13 that a linear relationship is stronger than an exponential relationship where acoustic properties are utilized for predicting MCS// based on the proportion of variation explained. This study has therefore revealed dMOE and *Z* as the best acoustic properties having a good positive linear relationship needed to predict MCS// of wood.

The wood species performed differently in terms of their relationship with dynamic properties. Notwithstanding, the R^2 values obtained with species combinations were higher than R^2 for the independent species. This shows that species effect exists for longitudinal acoustic method on wood, as it does with acoustic testing on standing trees (Wang and Ross 2008), thus suggesting that the application of longitudinal vibration acoustic method for two or more wood species combination is better than for independent species. Due to the significant relationship found among the acoustic and mechanical properties, this study confirms the suitability of the longitudinal vibration acoustic method for predicting dMOE and other mechanical properties of wood, especially with Nigerian species.

Conclusion

This study successfully investigated the relationship between mechanical and acoustic properties of selected hardwood species useful for predicting mechanical properties of wood. Owing to some of the significant relationships recorded, it is concluded that the longitudinal vibration acoustic method is more suitable for use when considering species combinations, and suggests that it can be easily and cheaply used to predict the mechanical properties of wood species in Nigeria. It was found that *A. adianthifolia* and *G. arborea* were better because of their significantly higher values of MOE, MOR, and MCS//. As such, these species are more suitable for construction and mechanical purposes than *D. regia* or *B. anguistifolia*.

Literature Cited

Adebawo, F., O. Ajala, and T. Aderemi. 2019. Variation of physical and mechanical properties of *Boscia angustifolia* (A. RICH.) wood along radial and axial stem portion. *Proligno* 15(1):34–42.

Aiyeloja, A. A., G. A. Adedeji, and L. A. Adebisi. 2015. Suitability of *Gmelina arborea* (Roxb.) wood for making talking drum in Nigeria. *IOSR J. Agric. Vet. Sci. Ver. II*. 8(2):95–100. DOI:10.9790/2380-082295100

Akitsu, H., M. Norimoto, T. Morooka, and R. Rowell. 1993. Effect of humidity on vibrational properties of chemically modified wood. *Wood Fiber Sci*. 25(3):250–260.

Ataguba, C., C. Enwelu, W. Aderibigbe, and E. Okiwe. 2015. A comparative study of some mechanical properties of *Gmelina arborea*, *Parkia biglobosa* and *Prosopis africana* timbers for structural use. *Int. J. Tech. Res. Appl*. 3(3):320–324.

Baar, J., J. Tippner, and P. Rademacher. 2015. Prediction of mechanical properties—modulus of rupture and modulus of elasticity—of five tropical species by nondestructive methods. *Maderas: Cienc. Tecnol*. 17(2):239–252. DOI:10.4067/S0718-221X2015005000023

Beentje, H., L. P. A. Oyen, R. H. M. J. Lemmens, C. H. Bosch, J. S. Siemonsma, and L. P. A. Oyen. 2003. Plant resources of tropical Africa. *Kew Bull*. 58(2):510.

British Standards (BS) 373. 1957. Method of Testing Small Clear Specimens of Timber. British Standards Institution, London.

Bucur, V. and R. R. Archer. 1984. Elastic constants for wood by an ultrasonic method. *Wood Sci. Technol*. 18:255–265. DOI:10.1007/BF00353361

Burdzik, W. M. G. and P. D. Nkwera. 2002. Transverse vibration tests for prediction of stiffness and strength properties of full size *Eucalyptus grandis*. *Forest Prod. J*. 52(6):63–67.

Burkill, H. M. 1985. The Useful Plants of West Tropical Africa. 2nd ed. Vol. 1: Families AD. Kew, Royal Botanic Gardens, Richmond, UK.

Casado, M., L. Acuña, D. Vecilla, E. Relea, A. Basterra, G. Ramón, and G. López. 2010. The influence of size in predicting the elastic modulus of *Populus* × *euramericana* timber using vibration techniques. *In:* Structures and Architecture—Proceedings of the 1st International Conference on Structures and Architecture, ICSA 2010, July 21–23, 2010, Guimaraes, Portugal; CRC Press, Boca Raton, Florida. pp. 618.

Chauhan, S. and A. Sethy. 2016. Differences in dynamic modulus of elasticity determined by three vibration methods and their relationship with static modulus of elasticity. *Maderas: Cienc. Tecn*. 18(2):373–382. DOI:10.4067/S0718-221X2016005000034

Görlacher, R. 1984. Ein Neues Meßverfahren Zur Bestimmung Des Elastizitätsmoduls von Holz. *Holz Als Roh- Und Werkstoff: Eur. J. Wood Wood Ind*. 42:219–222. DOI:10.1007/BF02607231

Green, D. W. 2001. Wood: strength and stiffness. *Encycl. Mater. Sc. Technol*. 9732–9736. DOI:10.1016/b0-08-043152-6/01766-6

Hodoušek, M., A. M. P. G. Dias, C. Martins, A. F. S. Marques, and M. Böhm. 2017. Comparison of non-destructive methods based on natural frequency for determining the modulus of elasticity of *Cupressus lusitanica* and *Populus* × *canadensis*. *BioResources*. 12(1):270–282. DOI:10.15376/biores.12.1.270-282

Ilic, J. 2001. Relationship among the dynamic and static elastic properties of air-dry *Eucalyptus delegatens*is R. Baker. *Holz Als Roh - Und Werkstoff*. 59:169–175. DOI:10.1007/s001070100198

Jamala, G. Y. 2013. Physical and mechanical properties of selected wood species in tropical rainforest ecosystem, Ondo State, Nigeria. *IOSR J. Agric. Vet. Sci*. 5(3):29–33.

Karlinasari, L., M. E. Wahyuna, and N. Nugroho. 2008. Non-destructive ultrasonic testing method for determining bending strength properties of Gmelina wood (*Gmelina arborea*). *J. Trop. Forest Sci*. 20(2):99–104.

Kasal, B. 2004. Wood formation and properties | mechanical properties of wood. *In:* Encyclopedia of Forest Sciences. J. Burley, J. Evans, and J. Younquist (Eds). Elsevier, Amsterdam. pp. 1815–1828.

Leite, E., R. da Silva, P. R. G. Hein, T. M. de Souza, and G. F. Rabelo. 2012. Estimation of the dynamic elastic properties of wood from *Copaifera langsdorffii* Desf using resonance analysis. *CERNE*. 18(1):41–47. DOI:10.1590/s0104-77602012000100006

Lock, J. M. and R. W. J. Keay. 1991. Trees of Nigeria. *Kew Bull*. DOI:10.2307/4110619

Messaoudene, M., M. Tafer, A. Loukkas, and R. Marchal. 2008. Propriétés physiques du bois de chêne zéen de la forêt des Aït Ghobri (Algérie). *BoisForets Trop*. 298(4):37–48. DOI:10.19182/bft2008.298.a20364

Murugan, S. S. 2020. Mechanical properties of materials: definition, testing and application. Int. *J. Mod. Stud. Mech. Eng*. 6(2):28–38. doi:10.20431/2454-9711.0602003.

Nowak, T., F. Patalas, and A. Karolak. 2021. Estimating mechanical properties of wood in existing structures—selected aspects. *Materials*. 14(8):1–26. DOI:10.3390/ma14081941

Obataya, E., T. Ono, and M. Norimoto. 2000. Vibrational properties of wood along the grain. *J. Mater. Sci*. 35(12):2993–3001. DOI:10.1023/A:1004782827844

Ojo, A. R. 2020. Determination of the utilization potentials of the wood of *Borassus aethiopum* Mart. through its strength properties. *J. Indian Acad. Wood Sci.* DOI:10.1007/s13196-020-00263-z

Olaoye, K. O. 2019. Investigation into the determination of modulus of elasticity of *Gmelina arborea* (Roxb.) wood using a non-destructive acoustic method. *Pro Ligno* 15(1):11–16.

Olaoye, K. O., A. O. Oluwadare, E. A. Adelusi, and J. K. Abiola. 2019. Acoustic properties of *Gmelina arborea* (Roxb.). *J. Mater. Sci. Res. Rev*. 4(1):1–9.

Olaoye, K., and O. A. Okon-Akan. 2020. Estimation of modulus of elasticity of *Boscia angustifolia* wood using longitudinal vibration acoustic method. *Int. Wood Prod. J*. DOI:10.1080/20426445.2020.1738118

Ono, T. and M. Norimoto. 1983. Study on Young's modulus and internal friction of wood in relation to the evaluation of wood for musical instruments. *Japn. J. Appl. Phys*. DOI:10.1143/JJAP.22.611

Orwa, C., A. Mutua, R. Kindt, R. Jamnadass, and A.C. Simons A. 2009. A tree reference and selection guide version 4.0. *Agroforestree Database* 4:1–5. http://www.worldagroforestry.org/sites/treedbs/treedatabases.asp. Accessed July 31, 2021.

Patro, R. 2016. Flamboyant (*Delonix regia*). *Invasive Species Compendium*. https://www.jardineiro.net/plantas/flamboyant-delonix-regia.html. Accessed June 30, 2021.

Ramage, M. H., H. Burridge, M. Busse-Wicher, G. Fereday, T. Reynolds, D. U. Shah, G. Wu, L. Yu, P. Fleming, D. Densley-Tingley, J. Allwood, P. Dupree, P. F. Linden, and O. Scherman. 2017. The wood from the trees: the use of timber in construction. *Renewable and Sustainable Energy Reviews* 68(September 2016):333–359. DOI:10.1016/j.rser.2016.09.107

Ravenshorst, G. J. P., J. W. G. Van De Kuilen, M. Brunetti, and A. Crivellaro. 2008. Species independent machine stress grading of hardwoods. *In:* 10th World Conference on Timber Engineering 2008, Vol. 2, June 2–5 2008, Miyazaki, Japan; Engineered Wood Products Association, Madison, Wisconsin. pp. 834–841.

Ross, R. J. and R. F. Pellerin. 1994. Pitch: Neural coding and perception. *US General Tech. Rep*. 70(1).

Shewale, V. D., T. A. Deshmukh, L. S. Patil, and V. R. Patil. 2012. Anti-inflammatory activity of *Delonix regia* (Boj. ex. Hook). *Adv. Pharmacol. Sci.* DOI:10.1155/2012/789713

Shirmohammadi, M., A. Faircloth, and A. Redman. 2020. Determining acoustic and mechanical properties of Australian native hardwood species for guitar fretboard production. *Eur. J. Wood Wood Prod*. 78(6):1161–1171. DOI:10.1007/s00107-020-01599-6

Shomade, A. F. 2000. Effects of period of seed harvest on germination, storage, biochemical composition and early seedling growth of *Mansonia altissima*. PhD Thesis. University of Ibadan, Nigeria.

Smith, I., and M. A. Snow. 2008. Timber: an ancient construction material with a bright future. *Forestry Chron*. 84(4):504–510. DOI:10.5558/tfc84504-4

Sproßmann, R., M. Zauer, and A. Wagenführ. 2017. Characterization of acoustic and mechanical properties of common tropical woods used in classical guitars. *Results Phys*. 7:1737–1742. DOI:10.1016/j.rinp.2017.05.006

Spycher, M., F. W. M. R. Schwarze, and R. Steiger. 2008. Assessment of resonance wood quality by comparing its physical and histological properties. *Wood Sci. Technol*. 42(4):325–342. DOI:10.1007/s00226-007-0170-5

Targa, L. A., A. W. Ballarin, and M. A. M. Biaggioni. 2005. Avaliação do módulo de elasticidade da madeira com uso de método não-destrutivo de vibração transversal. *Engenharia Agrícola*. DOI:10.1590/s0100-69162005000200001

Teles, R. F., C. S. Del Menezzi, F. Souza, and M. R. Souza. 2011. Nondestructive evaluation of a tropical hardwood: interrelationship between methods and physical-acoustical variables. *Rev. Ciênc. Madeira*. DOI:10.12953/2177-6830.v02n01a01

Upton, D. A. J. and A. Attah. 2003. Commercial timbers of Ghana: the Potential for Lesser Used Species. Commonwealth Secretariat, London.

Vernay, M. 2000. Le teck en France, pour quoi faire? *Bois et Forêts Trop*. 263(263):31–37.

Wang, X. and R. J. Ross. 2008. Acoustic evaluation of Alaskan young-growth wood. *In:* Proceedings of the 15th International Symposium on Nondestructive Testing of Wood: September 10–12, 2007. Madison, Wisconsin; Forest Products Society. pp. 97–105.