Correlation among Physico-Acoustic Properties of *Boscia angustifolia* and *Albizia adianthifolia* Wood

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Abstract

Underutilization of some wood species can be largely attributed to a dearth of scientific information. Therefore, identifying the acoustic characteristics of lesser used wood species such as *Boscia angustifolia* and *Albizia adianthifolia* wood is expected to encourage their use in acoustic applications. Thus, studying their acoustic properties and the relationship among these properties will help reveal their use potential for acoustic purposes and also highlight possible predictor variable(s) for other acoustic parameters in wood acoustics. This study aimed at measuring the acoustic properties of *B. angustifolia* and *A. adianthifolia* wood and investigating the correlation among these properties. Three trees of each species were felled, and a total of 270 wood samples of 20 by 20 by 300 mm^3 were collected. The samples were conditioned before acoustic measurement. The longitudinal free vibration method was adopted to measure the acoustic properties. Some of the mean acoustic results obtained for *B. angustifolia* and *A. adianthifolia* wood were 835.89 Hz, 3,657.51 m/s, 0.008, 13.59 GPa, 935.39 $m^4\ kg^{-1}\ s^{-1}$, and 807.78 Hz, 3,542.66 m/s, 0.009, 12.65 GPa, 731.75 $m^4\ kg^{-1}\ s^{-1}$, respectively, for fundamental sound frequency (FF), velocity of sound (V), damping factor ($\tan \delta$), specific dynamic modulus of elasticity (Es), and acoustic conversion efficiency (ACE). The correlation of FF with $\tan \delta$ was negatively significant (–0.59), while it was positively significant with Es and ACE (0.99 and 0.74). This study found the two wood species suitable for making frame boards only and highlights sound frequency and velocity of sound as the major predicting acoustic variables for measuring good acoustic wood.

Acoustics can be simply defined as the science of sound (Pulsar 2020), and all material is expected to produce sound when set into vibration by an external body, including wood. Wood's ability to produce sound effects when excited has made it a unique material for musical instruments and other acoustic applications. Thus, it has been used to produce several musical instruments, such as guitars, violins, pianos, xylophones, and other string, percussion, and woodwind instruments (Tsoumis 1991).

Measurement of acoustic properties of wood is not only essential when selecting wood species suitable for musical purposes, but researchers have also found it helpful in successfully estimating some other wood properties, such as the modulus of elasticity (Sedik et al. 2010, Leite et al. 2012, Olaoye 2019).

Some of these acoustic properties are sound frequency, dynamic modulus of elasticity, specific dynamic modulus of elasticity, acoustic radiation coefficient, and damping factor. Meanwhile, one of the acoustic properties of wood that receives less research coverage is the sound frequency. Similarly, Leite et al. (2012) stated that the correlation between damping factor and specific dynamic modulus of elasticity in tropical wood is rarely reported.

Furthermore, different methods have been adopted by researchers to determine the acoustic properties of wood. For instance, Sedik et al. (2010), Traoré et al. (2010), Leite et al. (2012), Baar et al. (2016), and Hamdan et al. (2016) used a flexural free vibration test; Halachan et al. (2017)

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used an ultrasonic tester; while Jalili et al. (2010) and Olaoye et al. (2019) used a longitudinal vibration test in the course of determining wood acoustic properties. Meanwhile, Chauhan and Sethy (2016) investigated the difference between these methods and found a higher value of acoustic parameters with the ultrasonic method. Their findings corroborate Haines et al. (1996), Ilic (2001), and Hassan et al. (2013).

In Nigeria, use of wood species for acoustic purposes has been driven by indigenous knowledge through trial and error only. Wood such as *Tectona grandis, Cordia millenii,* and *Gmelina arborea* had gained prominent use in acoustic and other wood applications, such as for structural purposes. Overdependence on these species has put pressure on them; *G. arborea* and *T. grandis* are no longer readily available, and *C. millenii* is now extinct. To avoid further extinction of preferred wood species, afforestation should be encouraged, and more scientific findings should be done to test for potential suitability of lesser used wood species for acoustic application.

Although many studies have been carried out on the acoustic properties of wood species, only a few have reported the acoustic potential of Nigerian wood species, especially lesser used and lesser known wood species. Also, in a bid to determine the suitability and potentiality of wood for acoustic purposes, researchers engage in measuring all acoustic properties considered essential. These measurements can be clumsy and difficult to execute, especially for practitioners or end users.

Thus, a faster and simple means of anticipating or measuring acoustic suitability of a wood would be useful. Getting adequate information about the relationships among these acoustic properties will help to identify a means to quickly anticipate the acoustic potentiality of a wood species, without measuring or calculating its other acoustic parameters.

Meanwhile, scholars have provided information on the correlation among selected wood acoustic properties; however, information available is not complete at all times. Therefore, finding the correlation among acoustic properties of wood species will help to reveal the complete existing relationships among these properties and provide necessary information on the prominent and most important predictor variable(s) that can be used to measure the viability of other acoustic properties of a wood species.

Boscia angustifolia belongs to the family Capparaceae. It is a shrub or small tree about 6 m high with a contorted fluted bole, commonly found in the dry savanna of the northern region, often on termite mounds from Senegal to Niger and northern Nigeria, and across Africa to Sudan, Ethiopia, east and south tropical Africa, and Arabia. Its common name in Nigeria is fula-fulfulde (Hausa) and Ilaoro (Yoruba; Burkill 1985). Maydel (1986) opined that *B. angustifolia* wood can be used in carpentry, for making water storage vessels, and for gunpowder in charcoal processing.

Albizia adianthifolia is a tall tree with a few large widely spreading branches and more or less horizontal branchlets producing a flat crown. The wood is widespread in tropical Africa and South Africa. It is commonly called 'ayinre bona bona in Yoruba, southwestern Nigeria. The tree grows to about 36 m high (Lock 1991). Albizia species have been useful in folk medicine for the treatment of cough, diarrhea, insomnia, irritability, rheumatism, stomachache, tuberculosis, and wounds (Singab et al. 2015). Its wood is occasionally used for timber purposes.

This study aimed at measuring the acoustic properties of *B. angustifolia* and *A. adianthifolia* wood and finding general correlation among the properties with the view of providing acoustic information on the selected species and highlighting any parameter(s) contributing to the measurement of other acoustic properties.

Materials and Method

Three trees of 18-year-old *B. angustifolia* and 16-year-old *A. adianthifolia*, each were obtained from Gambari Forest Reserve, Oluyole Local Government Area of Oyo State, Nigeria. Hence, bolts of 60 cm in length were collected axially (top, middle, and base). Forty-five wood samples of 20 by 20 by 300 mm^3 (R by T by L) were obtained from each tree at the radial positions (core, middle, and outer) of the bolts using a circular machine and planning machine as shown in Figure 1, thus making a total of 270 samples. The samples were oven-dried at 103°C ± 2°C for 24 hours, after which they were stored at an ambient temperature of 25°C and 60 percent relative humidity for 1 month prior to testing. The percentage equilibrium moisture contents for *B. angustifolia* and *A. adianthifolia* wood were 10 and 8 percent, respectively. Only samples devoid of defects were used.

Acoustic Property Test

Selected wood acoustic properties were measured using the longitudinal free vibration acoustic test method. The experiment was set up according to Jalili et al. (2014) in an enclosed soundproofed laboratory in order to ensure that external sound was suppressed. The basic acoustic parameters measured were sound frequency (fundamental and resonance frequency) and damping factor (tan δ), while the calculated acoustic properties were dynamic modulus of

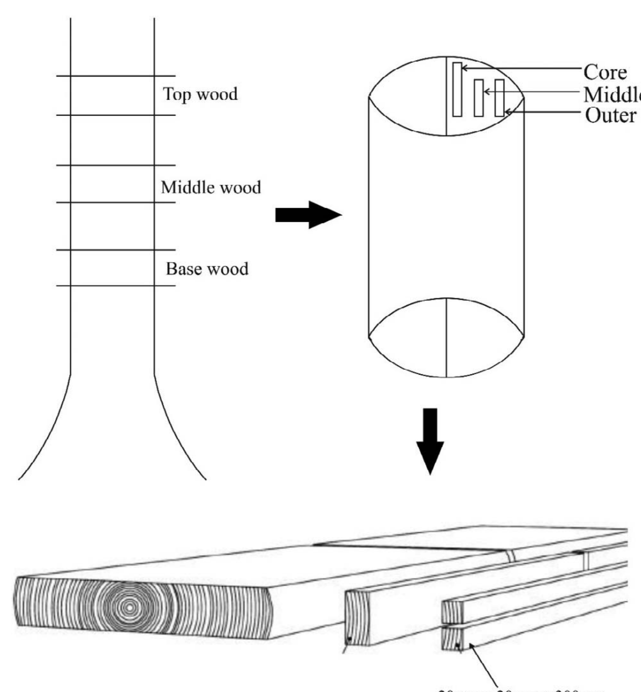

Figure 1.—Sample collection positions.

elasticity (E), specific dynamic modulus of elasticity (Es), velocity of sound (V), acoustic coefficient (K), sound quality (Q), acoustic conversion efficiency (ACE), and impedance (Z).

The longitudinal free vibrations test.—Each wood sample was tied with a thread on both sides and suspended from a ceiling with the threads (Fig. 2)—this was done to ensure no external sound was produced when the sample was excited during testing. The microphone served as the receiving device. A wooden hammer was used to hit the wood from one end, and sound generated was recorded in wave format and analyzed using Audacity software from the other end. The fundamental frequency and resonance frequency were measured in the frequency domain, through the fast Fourier transform (FFT) spectrum (Fig. 3). Meanwhile, logarithmic vibrating decrement factor (λ') was measured from the sound signal in the time domain (Fig. 4). Hence, other acoustic properties were calculated with relevant equations. The experiment was repeated for all samples.

Dynamic modulus of elasticity (E) was calculated using Equation 1 (Görlacher 1984):

$$E = \left(\frac{2f_n}{\gamma_n \pi}\right)^2 \frac{mL^3}{I} \qquad (1a)$$

where f is the fundamental frequency, n is the mode number, γ_n is the first mode 2.267, m is the specimen weight, L is the length of the sample, and I is inertia.

$$I = \frac{(bh^3)}{12} \qquad (1b)$$

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

Damping factor of the wood was calculated using Equation 2:

$$\text{Damping factor due to internal friction}(\tan\delta) = \frac{\lambda'}{\pi} \qquad (2)$$

where λ^1 = logarithmic vibrating decrement factor.

$$\lambda^1 = \left(\frac{1}{n}\right)\ln\left(\frac{X_1}{X_{n+1}}\right) \qquad (3)$$

where n = number of successive peaks and X_1 and X_{n+1} are the first and (n+1)th amplitude of vibration, respectively.

Meanwhile, Equations 4 through 10 were used to calculate specific dynamic modulus of elasticity, velocity of sound, acoustic coefficient, sound quality factor, acoustic conversion efficiency, and impedance.

Specific dynamic modulus of elasticity (Es):

$$Es = \frac{E}{\text{SG}} \qquad (4)$$

where SG = specific gravity.

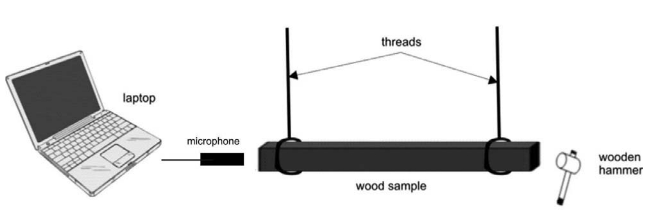

Figure 2.—The setup of the longitudinal free vibration test.

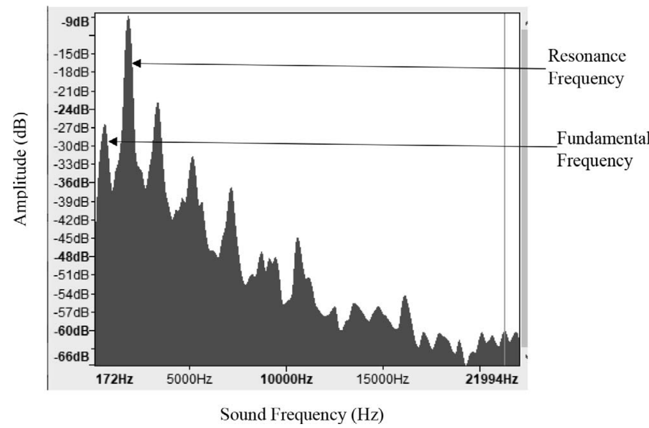

Figure 3.—Fundamental frequency measured in frequency domain.

$$\text{SG} = \frac{m/v}{\rho} \qquad (5)$$

where m = ovendried mass of wood sample, v = green volume, and ρ = density of water.

Velocity of sound (V; Ono and Norimoto 1983, Akitsu et al. 1993):

$$V = \sqrt{\frac{E}{\text{SG}}} \qquad (6)$$

Acoustic coefficient of the vibrating body (K):

$$K = \left(\frac{E}{\text{SG}^3}\right)^{0.5} \qquad (7)$$

where E = dynamic modulus of elasticity and SG = specific gravity.

Sound quality factor (Q) and acoustic conversion efficiency (ACE; Ross and Pellerin 1994):

$$Q = \frac{1}{\tan\delta} \qquad (8)$$

$$\text{ACE} = \frac{K}{\tan\delta} \qquad (9)$$

where K is the acoustic coefficient of the vibrating body.

Impedance (Z):

$$Z = V\rho \qquad (10)$$

where V = sound velocity and ρ = wood density.

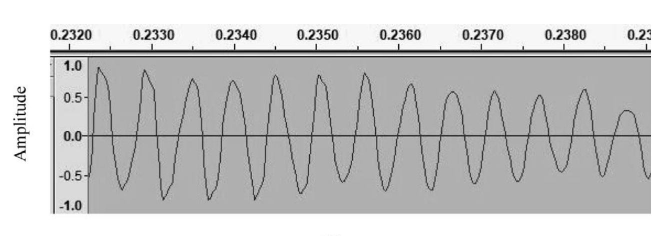

Figure 4.—View of amplitude decrement of the vibration through time in time domain.

Statistical Analysis

SSPS software was used to analyze data obtained. Descriptive statistics, Pearson correlation, and scatter plot were statistical tools used.

Results

Tables 1 and 2 represent the acoustic properties measured for *B. angustifolia* and *A. adianthifolia* wood, respectively. The mean FF, tan δ, *Es*, and ACE for *B. angustifolia* are 835.61 Hz, 0.008, 13.67 GPa, and 956.54 $m^4\ kg^{-1}\ s^{-1}$, while *A. adianthifolia* wood had 807.94 Hz, 0.009, 12.65 GPa, and 731.75 $m^4\ kg^{-1}\ s^{-1}$, respectively. Figures 3 and 4 show the sound frequency measured in frequency and time domain, respectively.

The correlation among the acoustic properties is presented in Table 3, while the scatter plots and histograms of the measured properties are shown in Figure 5. Of the correlation values presented, correlations of FF with *V* and *Es* as well as *V* with *Es* were highest, having 0.99 correlation of coefficient. Meanwhile, the correlation between *K* and tan δ was the lowest, having 0.10 correlation of coefficient.

Discussion

Acoustic properties

Sound frequency directly measures the pitch of the sound of a material. It can be defined as the number of a whole cycle of vibration per second (Plack et al. 2005). Fundamental frequency represents the first frequency, while resonance frequency is the frequency with the highest amplitude, as revealed in the frequency domain. Values obtained for sound frequency in this study mean that *B. angustifolia* had a higher sound pitch than *A. adianthifolia* wood, but lower than what was obtained for *G. arborea* wood (Olaoye et al. 2019). Similarly, the velocity of sound was higher for *B. angustifolia* wood yet lower than wood of *G. arborea* (Olaoye et al. 2019), *Aningeria robusta* (Olaoye et al. 2016), amboyna, bamboo (Yoshikawa and Waltham 2014), and walnut (Jalili et al. 2014). Age or anatomical traits may be a reason for differences in acoustic property results obtained for the species.

Table 1.—Physico-acoustic properties of B. angustifolia *wood.*[a]

Parameter	Mean	Minimum	Maximum	SD	CV (%)
FF (Hz)	835.61	704.00	1,008.50	111.61	13.36
RF (Hz)	2,229.17	1,829.50	2,548.00	272.84	12.24
V (m/s)	3,669.36	3,095.40	4,417.21	477.54	13.01
E (GPa)	6.87	4.02	10.54	2.33	33.90
Es (GPa)	13.67	9.58	19.51	3.63	26.53
Q	128.45	90.91	200.00	40.47	31.50
tan δ	0.008	0.005	0.011	0.002	28.46
K	7.43	6.51	8.56	0.69	9.31
ACE ($m^4\ kg^{-1}\ s^{-1}$)	956.54	650.18	1,427.50	320.84	33.54
Z (×106) ($kg\ m^{-2}\ s^{-1}$)	1.83	1.31	2.40	3.93	21.47
SG	0.49	0.42	0.58	0.05	10.80

[a] FF = fundamental frequency; RF = resonance frequency; *V* = velocity of sound; *E* = dynamic modulus of elasticity; *Es* = specific dynamic modulus of elasticity; *Q* = quality factor; tan δ = damping factor; *K* = radiation coefficient; ACE = acoustic conversion efficiency; *Z* = impedance; SG = specific gravity; CV = coefficient of variation.

Table 2.—Physico-acoustic properties of A. adianthifolia *wood. See Table 1 for definitions.*

Parameter	Mean	Minimum	Maximum	SD	CV (%)
FF (Hz)	807.94	708.50	887.33	56.49	6.99
RF (Hz)	2,051.20	1,623.00	2,430.33	241.01	11.75
V (m/s)	3,542.66	3,106.62	3,890.76	247.69	6.99
E (GPa)	7.92	5.63	10.59	1.67	21.11
Es (GPa)	12.65	9.66	15.15	1.73	13.64
Q	126.01	75.09	155.95	26.85	21.31
tan δ	0.009	0.007	0.0113	0.002	24.59
K	5.76	4.28	7.07	0.65	11.31
ACE ($m^4\ kg^{-1}\ s^{-1}$)	731.75	456.51	1,090.33	209.38	28.61
Z (×106) ($kg\ m^{-2}\ s^{-1}$)	2.21	1.80	2.72	3.51	15.84
SG	0.62	0.52	0.73	0.07	11.70

Although the sound velocities of the wood species measured in this study were lower compared with the selected species reviewed, they still fall within the range of acceptable velocity of sound for wood (3,300 to 5,000 m/s; Engineering Toolbox 2018).

Ono and Norimoto (1983), Tanaka (1987), Matsunaga et al. (1996), and Hamdan et al. (2016) opined that internal friction, specific dynamic Young's modulus, and acoustic conversion efficiency are the three major acoustic properties of wood. Internal friction is related to sound damping factor (Akitsu et al. 1993), while ACE is related to the ratio of acoustic energy radiated from a musical instrument to the energy given by the string (Tanaka 1987).

A lower value of tan δ of wood is an indication of a better acoustic species because it represents the wood's property when subjected to cyclical stresses in which mechanical energy is converted into heat (Brancheriau et al. 2006). An average value of tan δ considered good for acoustic purposes is 0.006 (Brémaud 2012). This implies that wood species having tan δ $\leq$ 0.006 are good acoustic species. Therefore *B. angustifolia* and *A. adianthifolia* wood cannot be considered suitable for an acoustic purpose where lower damping due to internal friction is required.

Typically, wood suitable for making soundboards is required to have a higher *Es* and lower tan δ (Tanaka 1987; Yano et al. 1992, 1995; Matsunaga et al. 1996). Also, Hamdan et al. (2016) highlighted a high ACE value for excellent soundboards, while lower ACE and higher tan δ are identifiable with making frame boards. Although *Es*, tan δ, and ACE of *B. angustifolia* was better than *A. adianthifolia* wood, it still compared poorly with *G. arborea* wood (Olaoye et al. 2019), *Dialium* sp. (Hamdan et al. 2016), and *Endospermum diadenum* (Sedik et al. 2010). Thus, these species are not considered suitable for making soundboards.

Conclusively, the majority of the acoustic values obtained for *B. angustifolia* wood were better than *A. adianthifolia* wood. However, the two wood species cannot be considered suitable for making soundboards of musical instruments, but they can still be used for frame boards.

Correlation among acoustic properties

As observed through the data presented, sound frequency, velocity of sound, and modulus of elasticity had better numbers of significant correlations with other variables. Since tan δ, *Es*, and ACE have been established as

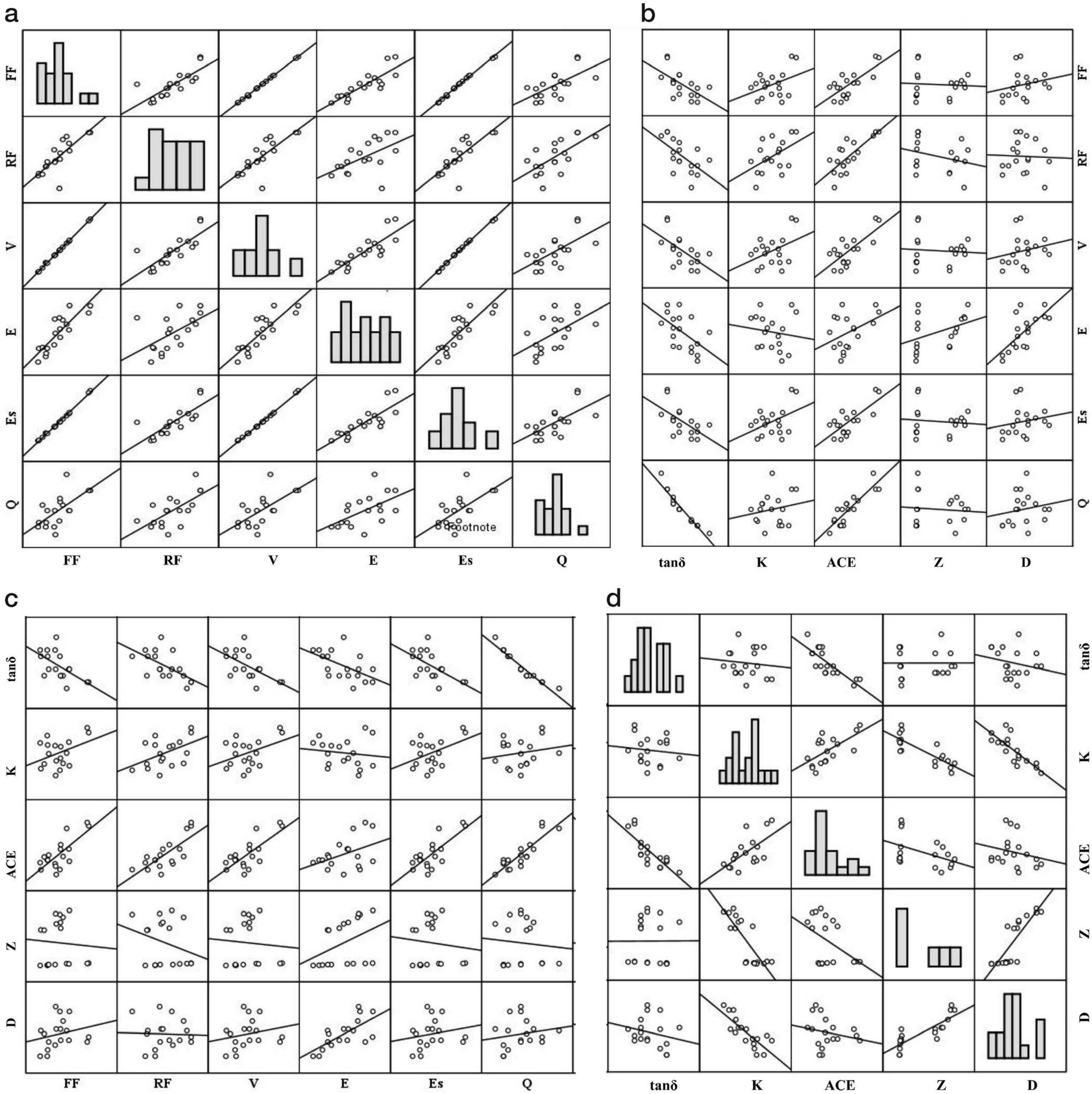

Figure 5.—(a) Scatter plot matrix among acoustic properties of B. angustifolia *and* A. adianthifolia *wood; (b) scatter plot matrix among physico-acoustic properties of* B. angustifolia *and* A. adianthifolia *wood; (c) scatter plot matrix among physico-acoustic properties of* B. angustifolia *and* A. adianthifolia *wood; (d) scatter plot matrix among physico-acoustic properties of* B. angustifolia *and* A. adianthifolia *wood. FF = fundamental frequency; RF = resonance frequency;* V *=velocity of sound;* E *= dynamic modulus of elasticity;* Es *= specific dynamic modulus of elasticity;* Q *= quality factor; tan δ = damping factor;* K *= radiation coefficient; ACE = acoustic conversion efficiency;* Z *= impedance.*

measuring the major acoustic properties of wood, it is thus appropriate to highlight other acoustic parameters that can measure them.

Consequently, FF, V, E, and Q had negatively significant correlations with tan δ. This implies that the damping factor of wood decreases with increasing sound frequency, velocity of sound, dynamic modulus of elasticity, and sound quality factor. Meanwhile, FF, V, E, Q, and Z were positively and significantly correlated with Es, an indication that specific dynamic modulus of elasticity increases with a correlating increase in acoustic variables. Also, ACE significantly increases with an increase in FF, V, Q, and K.

Sound frequency, velocity of sound, dynamic modulus of elasticity, sound quality factor, acoustic coefficient, and impedance were the only variables having significant correlations with the major acoustic properties previously mentioned.

Table 3.—Pearson correlation analysis among physico-acoustic properties of *B. angustifolia* and *A. adianthifolia* wood. See Table 1 for definitions.[a]

	FF	RF	*V*	*E*	*Es*	*Q*	tan δ	*K*	ACE	*Z*	SG
FF	1.00										
RF	0.79*	1.00									
V	0.99*	0.79*	1.00								
E	0.85*	0.55*	0.84*	1.00							
Es	0.99*	0.79*	0.99*	0.83*	1.00						
Q	0.62*	0.62*	0.61*	0.56*	0.61*	1.00					
tan δ	−0.60*	−0.58*	−0.59*	−0.55*	−0.59*	−0.97*	1.00				
K	0.39	0.48*	0.41	−0.13	0.43	0.13	−0.10	1.00			
ACE	0.73*	0.74*	0.73*	0.42	0.75*	0.87*	−0.83*	0.60*	1.00		
Z	0.65*	0.36	0.65*	0.95*	0.63*	0.46	−0.46	−0.42	0.20	1.00	
SG	0.22	−0.03	0.21	0.70*	0.19	0.22	−0.23	0.80*	0.20	0.88*	1.00

[a] * = Significantly different at $P < 0.05$.

On the other hand, similar correlations, as with *Es* and tan δ, *D* shown in this study, were found by Traoré et al. (2010) at 0.84 and 0.77 coefficient of correlation. Conversely, the nonsignificant correlation of SG with *V* was found by Halachan et al. (2017), who discovered an increase in the velocity of sound propagation with increasing density, which supports Chauhan and Sethy (2016) and Hassan et al. (2013). Owing to this variation, this study cannot validate the relationship between density and velocity of sound for *B. angustifolia* and *A. adianthifolia* wood.

Nonetheless, the relationship between SG and *E* was in congruence with Brémaud (2012), Chauhan and Sethy (2016), and Halachan et al. (2017). As such, SG can be used to measure the dynamic modulus of elasticity. However, a nonsignificant relationship found between SG and *Es* was similar to that found by Brémaud (2012) and Leite et al. (2012) but was different from that found by Traoré et al. (2010).

Another important relationship that needs to be identified is the correlation among the specified major acoustic properties. For this study, *Es* and ACE had a significant negative correlation with tan δ, while *Es* and ACE had a significant positive correlation with each other. These relationships were typical of wood, as was observed with some of the species in works of literature reviewed (Traoré et al. 2010, Brémaud 2012, Leite et al. 2012).

Furthermore, the scatter plot diagrams revealed that the correlation between velocity of sound and sound frequency is one of the strongest correlations between variables. This relationship disagrees with the USDA Forest Service Forest Products Laboratory (2010), who stated that velocity of sound decreases slightly with increasing frequency of vibration, though it was noted that such a slight relationship can be insignificant.

It was evident that sound frequency and velocity of sound had the highest number and strongest significant correlations with other variables. This implies that the higher these variables, the better the other acoustic variables. This existing number of correlations is not surprising, since some of the other calculated acoustic properties were derived from them. Nevertheless, sound frequency is the first acoustic parameter to be determined when measuring the acoustic properties of wood, and all the significant correlations obtained for FF and RF with other variables were favorable. Hence, a higher value of sound frequency is an indication that a wood can be anticipated or measured as good acoustic wood, even without measuring other acoustic parameters. However, more study is required to set a sound frequency benchmark with which wood will be measured for good acoustics.

Conclusion

Acoustic properties of *B. angustifolia* and *A. adianthifolia* were successfully measured, and findings revealed they are suitable for making frame boards only. Also, sound frequency and velocity of sound were identified as the best predicting acoustic variables that can measure the viability of wood species for acoustic purposes. Further, since the sound frequency is the first acoustic property to be obtained, it is thus appropriate to recommend it as the simple, fast, better, and reliable variable for measuring other acoustic properties of wood.

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