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Physical, mechanical and acoustic properties of *Terminalia superba*, *Cleistopholis patens* and *Holarrhena floribunda* woods used in sculpture and instrument making in Benin

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Wood is important in several fields including sculpture and instrument making. In the last two fields, *Terminalia superba*, *Cleistopholis patens*, and *Holarrhena floribunda* are three of Benin's most used wood species. In this work, we have, on prismatic samples (500 mm × 20 mm × 20 mm) of the wood of these species, used the acoustic method *Beam Identification by Non-destructive Grading* (BING) of CIRAD-Forêt to determine the density ρ , Young's modulus E , shear modulus G and internal friction $\tan \delta$ that allowed the evaluation of the specific stiffness modulus E/ρ and the other acoustic parameters. These tests showed that *T. superba*, *C. patens* and *H. floribunda* wood species have specific moduli of elasticity of 18 ± 3 , 17 ± 2 and 15 ± 1 GPa, respectively; internal friction of the order of 10^{-2} and sound velocities of the order of 4000 m s^{-1} . All these three species have an average acoustic strength above $1.40 \text{ MPa s m}^{-1}$ with acoustic radiation above $7 \text{ m}^4 \text{ kg}^{-1} \text{ s}^{-1}$ for a high ACE above $1000 \text{ m}^4 \text{ kg}^{-1} \text{ s}^{-1}$ for *T. superba* and *C. patens* and low around $674 \text{ m}^4 \text{ kg}^{-1} \text{ s}^{-1}$ for *H. floribunda*. All these species have a medium stability in service and a low propensity to deformation due to their shrinkage anisotropy. In view of these results, the wood of these species can be used in both structural and acoustic works specifically in sound insulation, art sculpture and instrument making.

Key words: Specific modulus, internal friction, sound velocity, acoustic radiation, acoustic impedance, acoustic conversion efficiency, insulation, musical instrument.

INTRODUCTION

Wood is a material of choice that is found in almost all sectors of socio-economic development. The appreciation of its quality is then defined according to its adequacy to the envisaged uses. Each characteristic of wood can thus

answer a given quality provided that it is associated with an application. The notion of wood quality covers all the properties that condition the technological aptitudes. The mechanical, physical, chemical and acoustic properties

as well as the aesthetic aspect still make wood a preferred material in instrument making, the manufacture of art objects, interior constructions (concert halls), sound insulation, the construction of structures entirely of wood (Bucur, 2006; Wegst, 2006; FPL, 2010; Brémaud, 2012). In the special cases of miscellaneous carving and artisanal and semi-industrial manufacture of musical instruments and art objects, not all wood species are eligible (Wegst, 2006). The case of the royal treasures of Abomey returned to Benin in November 2021 and which did not suffer any visible deformation despite the constraints and rigors of the climate is a typical example of the professionalism of the makers and the efficient use of the material wood. In Benin and Africa in general, these trades are threatened because of the progressive disappearance of the holders of endogenous knowledge in the field but also because of the non-availability of appropriate wood species for the realization of these objects and the absence of documentation and reliable scientific information on the species.

Deforestation, climate change, overexploitation, agriculture, demographic pressure, livestock, vegetation fires, etc. are the factors that contribute to the disappearance of these woody species. From 1990 to 1995, a total loss of 298 thousand hectares of Beninese forest cover was recorded (FAO, 2010). For the World Bank Group, citing national statistics, there appears to be a loss of 5.9 to 7.6 million hectares of forest, a decrease in area of 14% and a deforestation rate of 1.4% per year between 2005 and 2015 (World Bank Group, 2020). This decrease in vegetation cover has led to threats to many plant species, some of which are increasingly disappearing from their natural ecosystems. Among these endangered forest species in Africa are those whose wood is used as a basic material for carving, instrument making and other crafts. In studying the importance of biodiversity and tropical forests in South Benin, Adjovi et al. (2017) stratified the different uses of wood in our forests and noted, without being exhaustive, that for South Benin, about 13 species of wood are used in carving, 09 species for furniture making, 04 species of wood in light carpentry, 02 in formwork, 05 for boat building, two for mortar making and three for drumming. This study revealed that among the objects carved or manufactured are: tam-tams, masks, statuettes, mortars, decorative objects, handles, etc. The actors involved in this socio-economic activity include carvers, tradition keepers, dealers, art museum curators, etc. Among the species cited in carving and instrument making in Benin and other African countries (Schmelzer, 2006; Kimpouni, 2009; Lemmens, 2012), are the woods of *Terminalia superba*, *Cleistopholis patens* and

Holarrhena floribunda for which this work determined physical, mechanical and acoustic properties. The main properties determined are density, modulus of elasticity, shear modulus, modulus of specific rigidity, internal friction, speed of sound, acoustic radiation coefficient, acoustic conversion efficiency, and acoustic impedance. The knowledge of these parameters will make it possible to fill the documentary gap which characterizes the Beninese wood species and to better indicate the various uses of these wood species in instrument making.

MATERIALS AND METHODS

Plant

In this study, trees of these species were identified and collected in the Pahou Forest and the Lama in Benin (Table 1). These are dense humid forests specifically of the Guinean-Congolese zone. This zone is the wettest in Benin and is located in its southern part in the Dahomey-Gap and extends from the coast to the latitude of the Commune of Djidja. The climate is sub-equatorial with a bimodal rainfall regime. There are four seasons, including two rainy seasons and two dry seasons. Annual rainfall varies from 900 mm in the west to 1,300 mm in the east. The dominant soil is ferrallitic and deep.

The study area covers the sites of occurrence of the materials and methods. After identification of the species of trees concerned in the field, on each marked and felled individual; a round of wood of 70 cm length was taken by species at man height (1 m 30). For the determination of physical, mechanical and acoustic properties, the sampled logs were cut into bars in the form of prismatic specimens 500 mm x 20 mm x 20 mm in the orthotopic directions of the wood (Photo 1). Thus, we worked on 3 feet of *C. patens*, 2 feet of *T. superba* collected in Pahou and 5 feet of *H. floribunda* collected in Lama in Benin. From these plants we extracted 50 prismatic specimens without defects of *H. floribunda*, 80 specimens of *T. superba* and 85 of *C. patens*.

Vibration measurement

Measurements of physical and mechanical parameters were made by the vibratory method developed by CIRAD-forest and whose operation was described in the work of Brancheriau (2002, 2006), Brancheriau and Baillères (2002), Brémaud (2006, 2008), Traoré et al. (2010), Brémaud et al. (2012), Roohnia (2016), Hounlonon et al. (2017, 2021), Sproßmann et al. (2017), Saadnia et al. (2018a, b) and Ahmed and Adamopoulos (2018). It is based on the spectral analysis of beam vibration natural frequencies and fast Fourier Transforms (FFTs) programmed under the Beam Identification by Non-destructive Grading (BING) software version 9. The test setup is the one presented in the work of Hounlonon et al. (2021), the principle of which is as shown in Figure 1 (Saadnia et al., 2018a, b).

The basic physical, mechanical and acoustic characteristics determined are density, modulus of elasticity and shear, and the internal friction coefficient. The most important physical property

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determined is the density which indirectly gives the density of the sample.

In the range of mechanical properties, we have the modulus of elasticity and shear according to Timoshenko's theory and the modulus of elasticity according to Bernoulli. While it is proven that the most elaborate method is Timoshenko's, the modulus of elasticity according to Timoshenko and the modulus of elasticity according to Bernoulli of 1st order (mode 1) are not very different and are of the same order of magnitude (Brancheriau, 2002; Brémaud, 2006), we focused in terms of mechanical properties on the modulus of elasticity according to Bernoulli mode 1 to extract the acoustic properties (Ahmed and Adamopoulos, 2018). At the end of the vibratory or acoustic properties, the properties of primary interest in structural mechanics such as the speed of sound and internal friction have been determined.

If the acoustic properties of wood, such as the sound level, quality and color of xylophone bars and soundboards, are determined by the mechanical properties of the material from which they are made, this is justified by the fact that sound is produced by the material's own vibration. According to Wegst (2006), the properties on which the acoustic performance depends are mainly the density, the Young's modulus and the damping coefficient. They determine the speed of sound in the material, the natural frequencies and the intensity of acoustic radiation. The most important acoustic properties for the selection of materials with applications in acoustics such as musical instruments and building interiors are the velocity V of sound in the material, the acoustic impedance z , the acoustic radiation coefficient K and the loss coefficient $\tan\delta$ and the acoustic conversion coefficient ACE (Wegst, 2006; Brémaud, 2012; Ahmed and Adamopoulos, 2018).

The speed of sound in a structural material depends on the modulus of elasticity and density. In wood, the speed of sound also varies with the direction of the grain because the transverse modulus of elasticity is at least twenty times lower than the longitudinal value. Across the grain, the speed of sound is about one fifth to one third of the longitudinal value (FPL, 2010). It is given, according to the work of Ahmed and Adamopoulos (2018), Saadnia et al. (2018a, b), Roohnia (2016), Brémaud (2006), Wegst (2006), Holz (1996a), and James (1961), by relation (Equation 1).

$$V = \sqrt{\frac{E}{\rho}} = 2lf \tag{1}$$

where V (m s^{-1}) is the speed of sound; E (Pa) is the modulus of elasticity, ρ is the density (kgm^{-3}), l (m) is the length of the specimen, and f (Hz) is the resonant frequency.

E is the modulus of elasticity of the first mode of vibration according to Bernoulli's model (Brancheriau, 2002; Brémaud, 2006). According to this theory, the specific Young's modulus of the n^{th} mode is given by relation (Equation 2).

$$\frac{E}{\rho} = f_n^2 \times \frac{4\pi^2}{m_n^4} \times \frac{AL^2}{I} \tag{2}$$

where A : area of the straight section ($A=b \times h$) L : length; I : moment of inertia ($I = \frac{bh^3}{12}$) for a rectangular section of base b and height

h ; $m_1 = 4.730$; $m_2 = 7.8532$; $m_3 = 10.9956\dots$, with a very large slenderness (L/h) sufficient to neglect the influence of shear and rotational inertia.

The independence of E to the frequency increase (in the audible range) requires taking into account the influence of shear and rotational inertia in model of Timoshenko (Hearmon, 1958; Bordonné, 1989) which is a more elaborate model (Brancheriau, 2002; Brémaud, 2006).

The acoustic impedance or mechanical impedance z (Wegst,

2006; Roohnia, 2016) of the material is given by the product of the velocity V (m s^{-1}) of sound in the material by its density ρ (kg m^{-3}). It can also be expressed as a function of density and Young's modulus. The impedance z is expressed in MPa s m^{-1} by the relation (Equation 3).

$$z = V\rho = \frac{E}{V} = \sqrt{\rho E} \tag{3}$$

The acoustic radiation coefficient K ($\text{m}^4 \text{kg}^{-1} \text{s}^{-1}$) reflects the acoustic radiation damping (Wegst, 2006). This parameter is conceptually different from internal frictional damping (Roohnia, 2016). Noted K , it depends on the elastic modulus (Pa) and density (kgm^{-3}), the influence of which is higher than in the case of specific modulus (Wegst, 2006; Roohnia, 2016). It is expressed by relation (Equation 4).

$$K = \sqrt{\frac{E}{\rho^3}} = \frac{V}{\rho} \tag{4}$$

The inverse of this coefficient is called the anti-vibration parameter according to Yoshikawa (2007).

The Acoustic Conversion Efficiency ACE defines the efficiency with which vibrational energy is transformed into sonic energy and has been accepted as an overall estimate of acoustic properties (Aizawa et al., 1998; Rujinirun et al., 2005; Roohnia et al., 2011). It is the ratio of the radiation ratio to the damping coefficient or internal friction (Brémaud, 2008; Aizawa et al., 1998; Yano et al., 1992; Obataya et al., 2000; Roohnia, 2016) and the acoustic conversion efficiency, expressed in $\text{m}^4 \text{kg}^{-1} \text{s}^{-1}$, is formulated by relation (Equation 5).

$$ACE = \frac{K}{\tan \delta} \tag{5}$$

High radiation damping combined with low internal friction damping means that less sound energy is consumed in the internal friction and more is emitted as sound radiation to the environment - exactly what is expected from musical instrument soundboards.

The transmission parameter or relative acoustic conversion efficiency was also defined which according to Yoshikawa (2007) is given by expression (Equation 6).

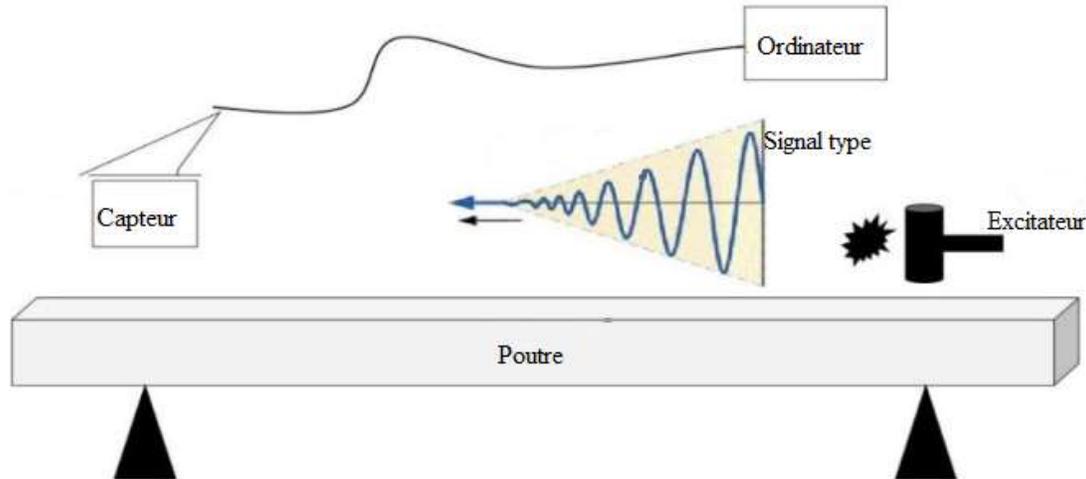
$$\alpha = \frac{\sqrt{E}}{\tan \delta} \tag{6}$$

Internal friction is the term used to refer to the mechanism that causes the dissipation of vibrational energy from a body (FPL, 2010; Roohnia 2016), that is, internal dissipation of acoustic waves (Roohnia, 2016). When a solid is stretched, some of the mechanical energy is dissipated as heat (FPL, 2010). As a result, the damping capacity often referred to by the mechanism that causes it as 'internal friction' is also referred to as 'damping due to internal friction' or 'loss coefficient' (Roohnia et al., 2015; Wegst, 2006; Roohnia, 2016). Internal friction is the property of solid materials that reflects the transformation of mechanical energy into heat under cyclic stress (Brancheriau et al., 2010). The loss coefficient measures the degree to which vibrational energy is dissipated by internal friction in a material. It is given by $\tan\delta = \delta/\pi$ where δ is

Table 1. Observations on the wood species studied.

Plantation	Species	Observations
Pahou	<i>Holarrhena floribunda</i>	Species of varying frequency in the forest. It is normally found in deciduous relics, forest plantations, forest edges, and wet/riverine forests (Orwa et al, 2009).
	<i>Terminalia superba</i>	Exotic species more or less planted in the forest
	<i>Cleistopholis patens</i>	Species confined to the swampy part of the forest
Lama	<i>Holarrhena floribunda</i>	Native species
	<i>Terminalia superba</i>	Common species in the formation
	<i>Cleistopholis patens</i>	The species has not been identified in the forest

Source: Authors

**Figure 1.** Principle of data acquisition.
Source: Adapted from Saadtnia et al. (2018a).

the logarithmic decrement (Newland, 1989; Bodig and Jayne, 1993; Wegst, 2006; Roohnia, 2016). During this study, the internal friction is collected, following the development of the work of Brancheriau (2002) and Brancheriau and Baillères, 2002; Brancheriau et al., 2010, 2011) along with the physical-mechanical and vibrational properties in a raw text file.

The data collected or calculated were tabulated and processed in Excel to give the results of descriptive statistics represented by the mean and standard deviation of each parameter and presented subsequently.

RESULTS AND DISCUSSION

Preliminary investigations among some carvers in the lake regions of Benin, in the communes of Cotonou and surroundings, in Pobè, Kétou, Dassa, Parakou, Djougou and Natitingou have revealed that in carving, the woods

most used are among others: *Ricinodendron heudelotii*, *Tectona grandis*, *H. floribunda*, *T. superba*, *C. patens*, *Triplochiton scleroxylon*, *Milicia excelsa*, *Anogeissus leiocarpa*, *Khaya senegalensis*, *Terminalia catapa*, *Gmelina arborea*, etc.

This finding reflects the work of Adjovi et al. (2017) who found in their work in South Benin that the top 13 most used wood species in carving are *G. arborea*, *Pterocarpus erinaceus*, *T. grandis*, *Diospyros mespiliformis*, *K. senegalensis*, *M. excelsa*, *Eucalyptus* species, *Daniellia oliveri*, *Khaya grandifoliola*, *Azadirachta indica*, *Vitellaria paradoxa* and *Triplochiton scleroxylon*. Of these thirteen species, the most used for the manufacture of dugouts is *T. scleroxylon*, *Erythrophleum africanum*, *Cola* spp., *M. excelsa*, *Anarcadium occidentale*.

Table 2. Thickness and diameter of *C. patens*.

Wood	Bark thickness (cm)	Diameter (cm)	Observation
CP1	0.5	18.1-19	Pungent smell, presence of red heartwood in the wine not very differentiated
CP2	0.3	11.2-23.2	Pungent odor
CP3	0.4	23.0-24.8	Pungent odor

Source: Authors

Table 3. Thickness and diameter of *H. floribunda*.

Bark thickness (cm)	Diameter (cm)
0.1	9-9.5
0.1	8.7-9
0.1	10.4-10.9
0.1	9.8-10.2
0.2	9.7-10.9

Source: Authors

Table 4. Density, average modulus of elasticity and shear modulus of the studied species.

Wood species	Density (kg m ⁻³)	Modulus of elasticity Bernoulli mode 1 (MPa)	Timoshenko modulus of elasticity (MPa)	Timoshenko shear modulus (MPa)
<i>Terminalia superba</i>	467±41	8305±1716	8504±1783	1008±681
<i>Cleistopholis patens</i>	360±44	6126±1014	6254±1036	850±823
<i>Holarrhena floribunda</i>	536±36	7957±929	8181±980	915±729

Source: Authors

Dendrometric parameters of *C. patens*, *T. superba*, and *H. floribunda*

The bark thickness and diameters of the three *C. patens* woods are summarized in Table 2. The two *T. superba* trees used show good stiffness with straight shafts, white wood. The heartwood and sapwood are not differentiated. The bark thickness of these trees is 0.2 cm with a diameter between 21.5 and 22.8 cm for one and 22.9 and 23.2 cm for the other. For the five feet of *H. floribunda* wood, the bark thickness varies between 0.1 and 0.2 cm shown in Table 3.

Physical, mechanical and acoustic properties of the wood species studied

The physical-mechanical properties of the materials used in instrument making determine the acoustic properties of the instruments. With wood being a multifunctional material, certain physical-mechanical properties determine the acoustic performance. Among these parameters is density, Young's modulus, and the loss or damping coefficient or internal friction (Wegst, 2006). By combining

the basic physical-mechanical properties (Table 4) with the acoustic models, we have determined the acoustic properties shown in Table 5.

Table 4 shows a similarity of Timoshenko and Bernoulli mode 1 moduli of elasticity confirming the observations of Brancheriau (2002) and Brémaud (2006). Compared to *Ricinodendron heudelotii*, all three species have higher densities, moduli of elasticity and shear. *R. heudelotii* is a light wood with a density of 130 to 300 kg m⁻³, soft and brittle with a modulus of elasticity of 3700 to 4800 MPa and a shear of 2.2 to 3.2 MPa (Tchoundjeu and Atangana, 2007). This species is highly prized in the sculpture of Guèlèdè masks, various statuettes and other art objects such as canes and tom-toms (Akpovo and Fandohan, 2021).

The comparison of Bernoulli mode 1 specific moduli and Timoshenko specific dynamic modulus, for all our samples of slenderness L/h of the order of 25, presents in the case of our three species good correlations (Figure 2) confirming the observations of Brémaud et al. (2012), Brémaud (2006) and Brancheriau (2002).

The results of the internal friction obtained (Table 5) for these three species are in the range of the values obtained by Brancheriau et al. (2006) for species of good

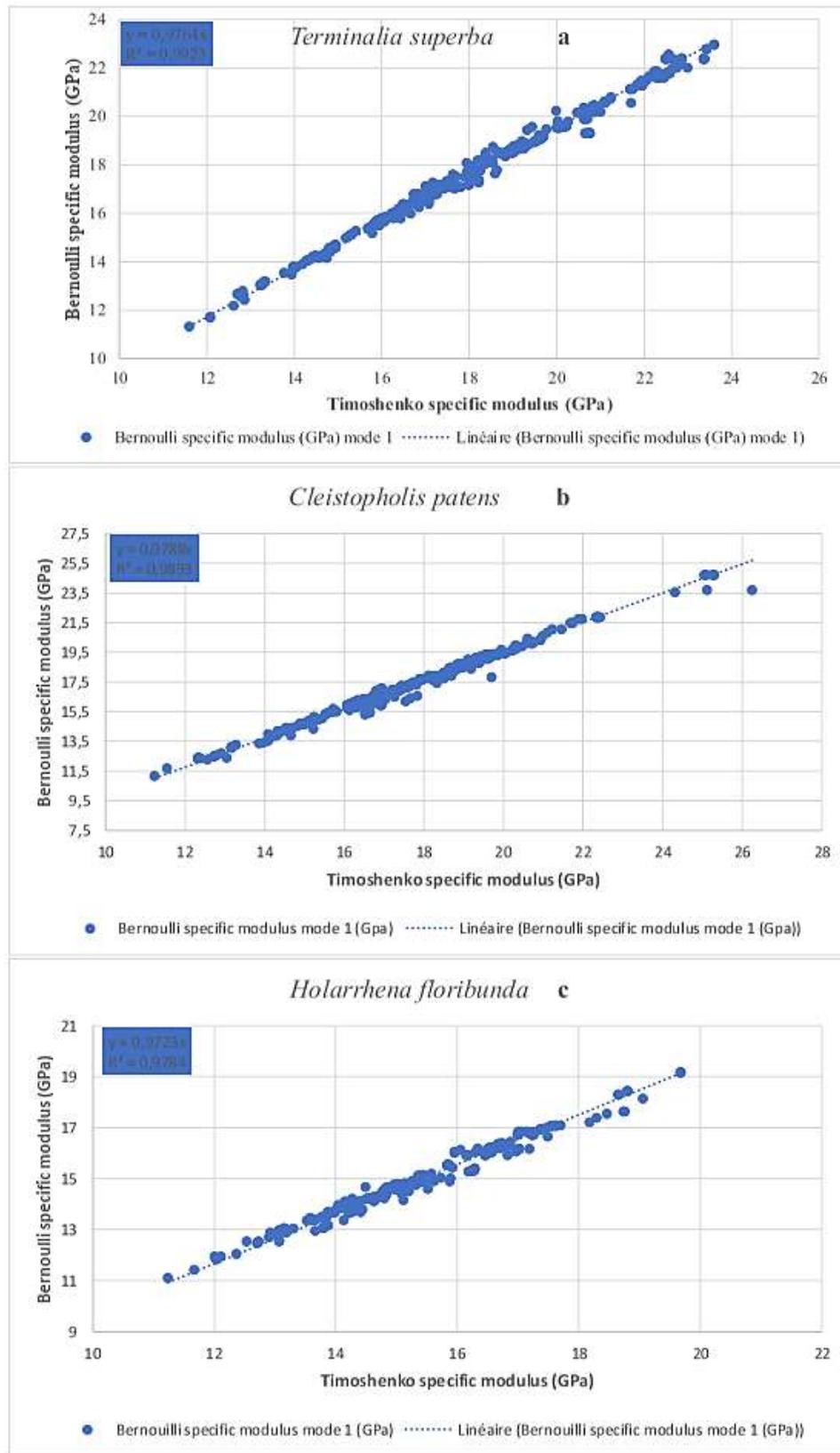


Figure 2. Comparison of Bernoulli mode 1 specific moduli to Timoshenko specific modulus for *T. superba* (a); *C. patens* (b); *H. floribunda* (c).
Source: Authors

Table 5. Specific modulus and average acoustic properties of the studied species.

Wood species	Specific modulus (MPa m ³ kg ⁻¹ or GPa)	Internal friction tan δ (10 ⁻²)	Speed V (m s ⁻¹)	Impedance z (MPa s m ⁻¹)	Sound radiation coefficient K (m ⁴ kg ⁻¹ s ⁻¹)	Acoustic conversion efficiency ACE (m ⁴ kg ⁻¹ s ⁻¹)
<i>Terminalia superba</i>	18±3	1.05±0.50	4188±322	1.96±0.29	9.00±0.69	1039±454
<i>Cleistopholis patens</i>	17±2	1.10±0.43	4141±279	1.47±0.18	11.81±1.79	1242±506
<i>Holarrhena floribunda</i>	15±1	1.23±0.46	3868±178	2.07±0.14	7.25±0.67	674±267

Source: Authors

acoustic quality whose internal friction is located between 0.82 and 1.26×10^{-2} . From Table 5, it appears that, *C. patens* has the highest value of ACE and K, *T. superba* has the highest specific stiffness and the highest speed of sound while *H. floribunda* has the highest values of internal friction and acoustic impedance.

Density and modulus of elasticity

The modulus of elasticity and density are important acoustic parameters (Brémaud, 2012; Wegst, 2006; Roohnia, 2016; Ahmed and Adamopoulos, 2018) especially since they are determinant in the specific modulus of stiffness. The modulus of elasticity increases globally with density as already found in the work of Sproßmann et al. (2017). While the species *T. superba* correlates well with both parameters, *C. patens* and *H. floribunda* correlate less well as shown in Figure 3.

The density of wood used in instrument making covers a wide range from 300 to 1400 kg m⁻³ (Wegst, 2006). For example, the mass of the back and sides of a body or part of the body of an instrument is a function of the density of the wood used and can be controlled by acting on the thickness of the panels. A guitar body with high panel mass reduces the resonant frequency and increases the radiating area in phase, acoustically improving the midrange and extending the duration of the sound (Gore, 2011).

Our three species tested here have a density of 467 ± 41 kg m⁻³ for *T. superba*, 360 ± 44 kg m⁻³ for *C. patens*, 536 ± 36 kg m⁻³ for *H. floribunda*. Values that remain, for example, in the realm of soundboard resonance woods whose density varies 300 to 500 kg m⁻³ (Wegst, 2006; Ahmed and Adamopoulos, 2018). It is true that according to the same authors the woods of the bottoms and sides of violin and piano action have densities of 600 to 900 kg m⁻³; woods of high density for wind instruments, xylophone bars and violin hump; woods of high density of the order of 750 kg m⁻³ are used as electric guitar neck (Wegst, 2006; Ahmed and Adamopoulos, 2018). The back and sides of guitars, for example, are traditionally made of wood of the same species of wood for aesthetic reasons regardless of the stiffness and density of the material (Gore, 2011). According to Gore (2011), cited by Ncube and Masilinga (2017), wood species on the sides

should be heat flexible with a density of 550 to 800 kg m⁻³; the density of 550 kg m⁻³, is more favorable for the back and sides of guitars. The properties for example required for guitar neck woods are strength, stiffness and dimensional stability over time against moisture gradient (Sproßmann et al., 2017). In view of these authors, *H. floribunda* and *T. superba* in their range of variation would offer usable samples in guitar making.

Indeed, depending on the age and level of harvesting, the density of the wood, as well as other wood parameters, of each of these species can vary widely. The values of the densities found remain within the range of the data of the Tropix 7 database which obtained 540 ± 70 kg m⁻³; of PROTA quoting Kimpouni (2009), 370 to 730 kg m⁻³ for *T. superba*. *C. patens* also has its average density close to that of PROTA citing Lemmens (2012) who found a density ranging from 290 to 500 kg m⁻³.

Of the three species studied, *H. floribunda* has the best density. However, the results of the literature remain almost empty on its physical-mechanical characteristics. Indeed, the work done so far remains in the field of life and earth sciences (Schmelzer, 2006; Bayala et al., 2006; Orwa et al., 2009). However, it is also used in kitchen framing (Leciak and Bah, 2008). According to Schmelzer (2006) quoted by PROTA, this wood species is used in Benin to build granaries, beds or children's cribs; its wood is resistant to attack by *Prostephanus truncatus*. For carving, stools and other carved seats, *H. floribunda* is considered the best wood (Schmelzer, 2006; Orwa et al., 2009). Recent work in Ghana by Antwi et al. (2022) showed that branch and trunk wood have similar densities close to those in our work. This study found a density of 467.53 ± 70.87 kg m⁻³ for branch wood and 457.40 ± 70.46 kg.m⁻³ for *H. floribunda* trunk wood.

The average Bernoulli dynamic modulus of each of these species as presented in Table 4 shows that they have moduli in the range of instrument making that runs from 6000 to 40000 MPa (Wegst, 2006; Ahmed and Adamopoulos, 2018).

Indeed, *T. superba* has a mean modulus of 8305 ± 1716 MPa; *C. patens* (6126 ± 1014 MPa) and *H. floribunda* (7957 ± 929 MPa).

If it is true that the acoustic properties are decisive in the choice of a type of wood in acoustics, it will be taken into account the dimensional stability of the species studied, *T. superba* has the highest modulus of elasticity

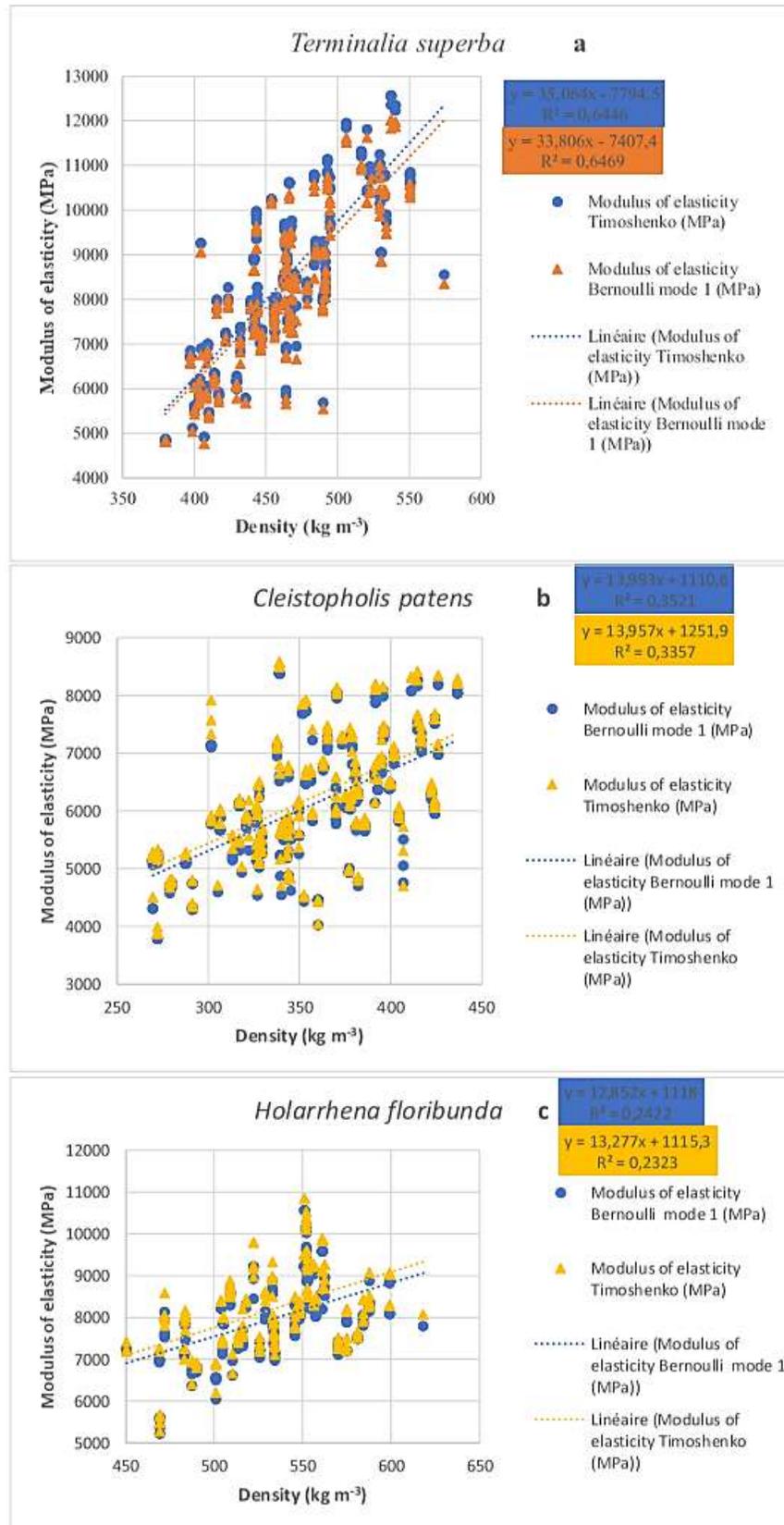


Figure 3. Variation of the modulus of elasticity with density for *T. superba* (a); *C. patens* (b); *H. floribunda* (c).
 Source: Authors

and shear.

Regarding modulus of elasticity *T. superba* has lower moduli than Tropix 7 (11750 ± 2480 MPa) but in the range of PROTA (Kimpouni, 2009) which varies from 3625 to 16660 MPa. *C. patens* has, according to PROTA citing Lemmens (2012), a modulus of elasticity in the range of 6080 to 8230 MPa which is not much different from our values for the same species. *H. floribunda*, according to the work of Antwi et al. (2022), has a static modulus of elasticity of 8213.83 ± 116.23 MPa for the branches and 8654.96 ± 108.30 for the trunk. These values show that the mechanical stiffness of *H. floribunda* wood from Benin is similar to that from Ghana.

Treated woods, as well as, pure species can be suitable for the manufacture of soundboards for moduli of about 6000 to 19000 MPa; violin backs and sides for a modulus of about 8000 to 19000 MPa, wind instruments for about 7000 to 18000 MPa, piano mechanics for about 14000 to 19000 MPa and for xylophone bars from 12000 to 20000 MPa (Wegst, 2006; Ahmed and Adamopoulos, 2018). Therefore, all our woods can be used in soundboard making; *T. superba* and *H. floribunda* for violin backs and sides and wind instruments.

Also, coupling density and stiffness modulus, *T. superba* and *H. floribunda* can be used as back and side woods for guitars following the classification of Sproßmann et al. (2017) which categorized woods from 700 to 1100 kg m⁻³ and 9000 to 18000 MPa as back and side woods, and woods from 1000 to 13000 kg m⁻³ and 14000 to 26000 MPa as guitar fret woods.

Yoshikawa (2007), in Japan, working on the wood species traditionally used for making stringed instruments (*Picea abies*, *Picea sitchensis*, *Paulownia tomentosa*, *Morus alba*, *Acer platanoides*, *Acer* sp., *Pterocarpus indicus* and *Dalbergia nigra*) and substitute species used in the same manufacture (*Pinus albicaulis*, *Tsuga* species, *Sequoia sempervirens*, *Thuja plicata*, *Cinnamomum camphora*, *Zelkova serrata*, *Cupressus sempervirens*, *Pyrus communis*, *Prunus serotina*, *Juglans nigra*, *Pterocarpus dalbergioides*, and *Ochroma pyramidale*) density, modulus of elasticity, and velocity values for the two groups of 260 to 873 kg m⁻³; 6300 to 20000 MPa; 3130 to 5300 m s⁻¹ and 380 to 710 kg m⁻³; 2800 to 22000 MPa; 3500 to 5400 m s⁻¹. These values crossed with our average values recorded in the two previous tables predispose our wood species to certain potentialities in instrument making of stringed instruments whereas in the light of the work of Traoré et al. (2010) on veneer (*Pterocarpus erinaceus* Poir.) the density and the modulus of elasticity of these studied species remain weak and unsuitable for the manufacture of xylophone bars.

Speed of sound

The speed of sound is directly related to density and

modulus of elasticity. The speed of sound in wood and any hygroscopic material decreases with increasing temperature or humidity and is proportionally influenced by density and modulus of elasticity (Tsoumis, 1991). The velocity of sound, in wood, reflects the speed of transmission of the energy received thus woods with high velocity and low damping coefficient better facilitate the transmission of vibration energy (Ahmed and Adamopoulos, 2018). Materials with high sound propagation velocities, that is, low densities for high relative stiffness or low internal friction are the best facilitators of energy transfer (Bourgeois, 1994; Gore, 2011).

For the wood samples we tested, *T. Superba* has a velocity (4188 ± 322 m s⁻¹); *C. patens* (4141 ± 279 m s⁻¹); *H. floribunda* (3868 ± 178 m s⁻¹). In the literature, it is reported that, the highest velocities of sound propagation, are obtained in the longitudinal direction followed significantly by a lower velocity in the radial direction and by a lower velocity in the tangential direction (Kúdela and Kunštár, 2011). Several acoustic parameters are necessary for wood selection in instrument making. In the case of velocity, the range of desired values for the woods used varies from 3000 to 6500 m s⁻¹. Often woods of high celerity are used as resonance woods (Wegst, 2006). Woods for piano action, violin bows, xylophone bars, violin backs and sides, and wind instruments have low velocities (Ahmed and Adamopoulos, 2018). Thus, all three species studied have velocities that are in the range of velocities (Wegst, 2006) thus showing suitability for making different musical instruments. The speed of sound, of *P. kesiya* and *Pterocarpus angolensis*, used in guitar making in Zambia, is 4481 and 3799 m s⁻¹, respectively, while that of *Picea abies* is 4894 m s⁻¹ (Ncube and Masilinga, 2017). Hilde et al. (2014) found a velocity of 5600 m s⁻¹ (with variation from 5200 to 6300 m s⁻¹) for spruce and 3500 m s⁻¹ for pine. The high modulus of rigidity of *P. sitchensis* and its relatively low density prevail of a high sound velocity (Bourgeois 1994). It is expected that resonance woods have a high sound velocity around 3000 m s⁻¹ although velocities of 4000 to 6500 m s⁻¹ are preferred for soundboards (Wegst 2008). In this range, all our three wood species have good resonance potential. For instruments with impulsive excitation, the parameters of sound decay are particularly important (Hase, 1987; Holz, 1996b; Brancheriau et al., 2006; Aramaki et al., 2007; Chaigne and Doutaut, 1997; Wegst, 2006). Spruce, often used as a high quality wood in instrument making, has a low density of 450 kg m⁻³ and a very high specific modulus of elasticity of 26 to 36 GPa, arguing for a sound speed above 6000 m s⁻¹ (Haines, 2000; Bucur, 2006; Yano et al., 1990, 1992). Combining speed with density and, referring to Figure 4 (Wegst, 2006) of sound speed versus density, *T. superba* and *C. patens* can be used in the manufacture of soundboards while *H. floribunda* would be a candidate for the manufacture of violin backs and sides or wind

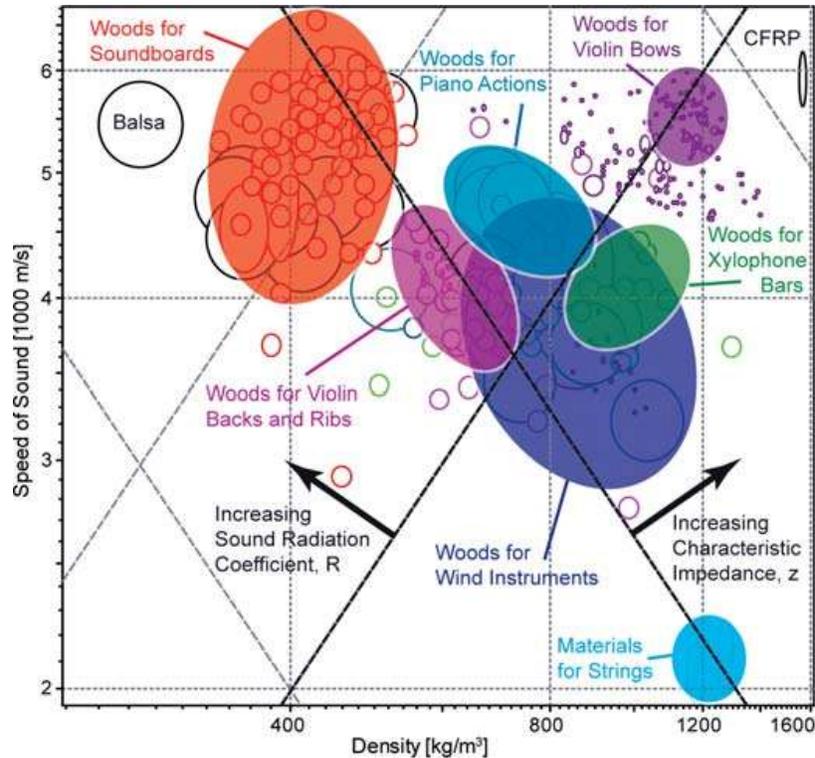


Figure 4. Speed of sound as a function of wood density, graph illustrating the selection of wood in instrument making. Source: Wegst (2006).

instruments. The case of *C. patens* is illustrated by its uses which, according to Lemmens (2012) reported by PROTA, vary from use in carpentry (roofing, doors, beams, dugouts, furniture, veneers, plywood, floats...) to carving musical instruments such as making drums.

Sound radiation coefficient K and acoustic impedance z

Figure 5 shows the variations of K and z as a function of the speed of sound. In general, the acoustic radiation coefficient K and the acoustic impedance z increase when the speed of sound increases. It also shows a good correlation between these different parameters for *T. superba*, *C. patens* and *H. floribunda*.

The sound radiation coefficient is a measure of the vibration in wood when damped by sound radiation. High values of the sound radiation coefficient K are desired for materials used to produce loud sound, and as such, it is very important for its resonance quality (Ahmed and Adamopoulos, 2018). A high radiation coefficient means that there is less energy dissipation due to the inertia of the vibrating body. For resonators, it is desired to resonate the sound by using a lightweight resonator body or top plate with a higher modulus of elasticity. This

parameter for wood in soundboards can range from 7 to 16 $\text{m}^4 \text{kg}^{-1} \text{s}^{-1}$ but slightly lower acoustic coefficients can be accepted for other parts of musical instruments (Roohnia, 2016).

The acoustic radiation coefficients, of the species we studied, are: *T. Superba* ($9.00 \pm 0.69 \text{ m}^4 \text{kg}^{-1} \text{s}^{-1}$); *C. patens* ($11.81 \pm 1.79 \text{ m}^4 \text{kg}^{-1} \text{s}^{-1}$); *H. floribunda* ($7.25 \pm 0.67 \text{ m}^4 \text{kg}^{-1} \text{s}^{-1}$). These values are much higher than those of vène (*Pterocarpus erinaceus*) wood. Thus according to Roohnia (2016), these species can be used in soundboard manufacturing although Wegst (2006) advocates values of $K > 8 \text{ m}^4 \text{kg}^{-1} \text{s}^{-1}$ would be ideal for soundboard manufacturing. The radiation coefficient K , for Sitka spruce and western cedar is about $12 \text{ m}^4 \text{kg}^{-1} \text{s}^{-1}$. These two species have a large sound radiation coefficient which is highly appreciated for producing loud sound (Wegst 2006) as does *Cleistopholis patens* with its sound radiation coefficient of about $12 \text{ m}^4 \text{kg}^{-1} \text{s}^{-1}$.

Wood in music will also need to have a high characteristic impedance to allow for the reflection of sound in the surrounding environment as maple does (Wegst 2006). Like the velocity and the acoustic radiation coefficient K , the acoustic impedance z is related to the modulus of elasticity and density. According to the graphs in Figures 6 to 8, the impedance is related to the density by a linear law while the radiation coefficient is

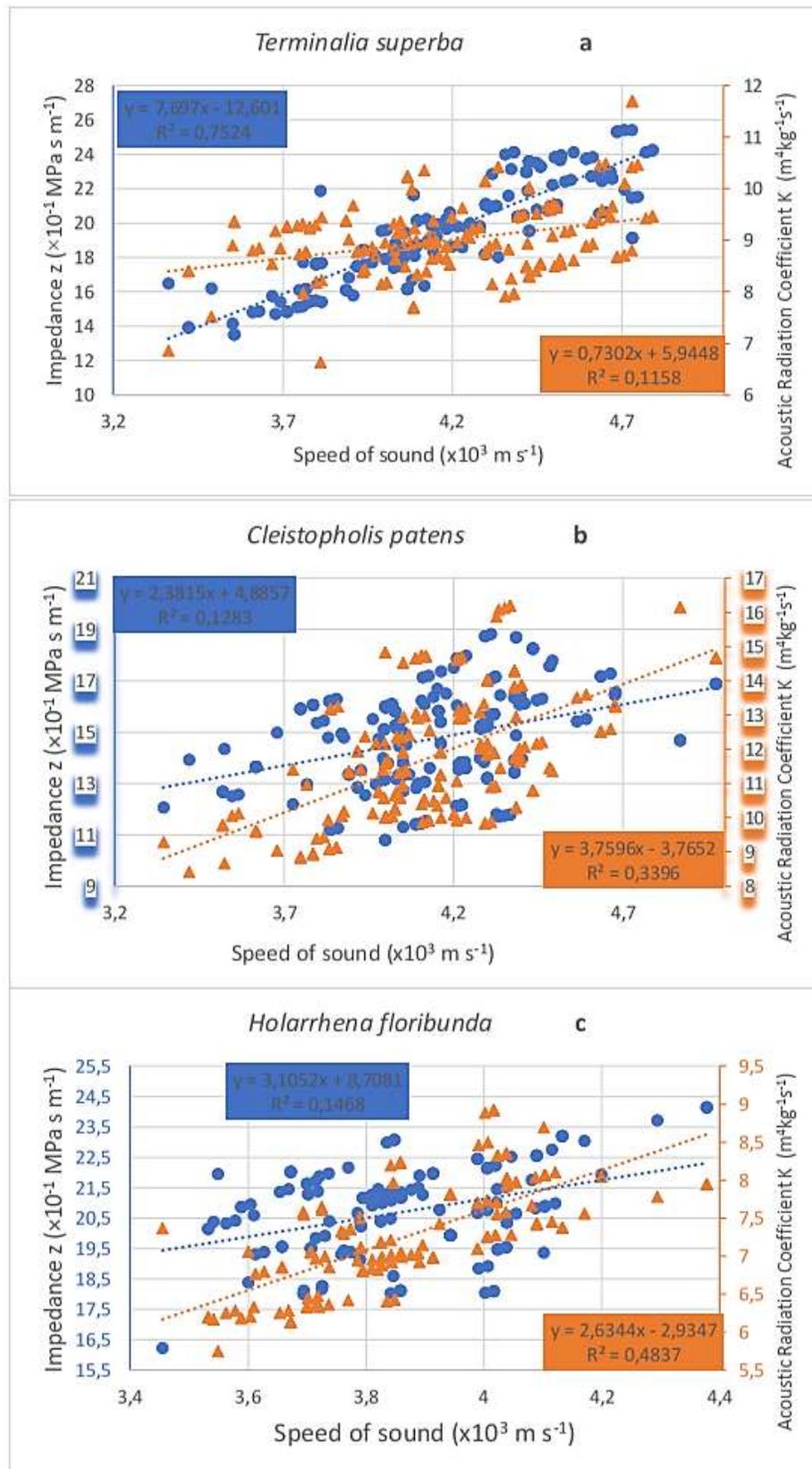


Figure 5. Variation of impedance and acoustic radiation coefficient with speed of sound for *T. superba* (a); *C. patens* (b); *H. floribunda* (c).

Source: Authors

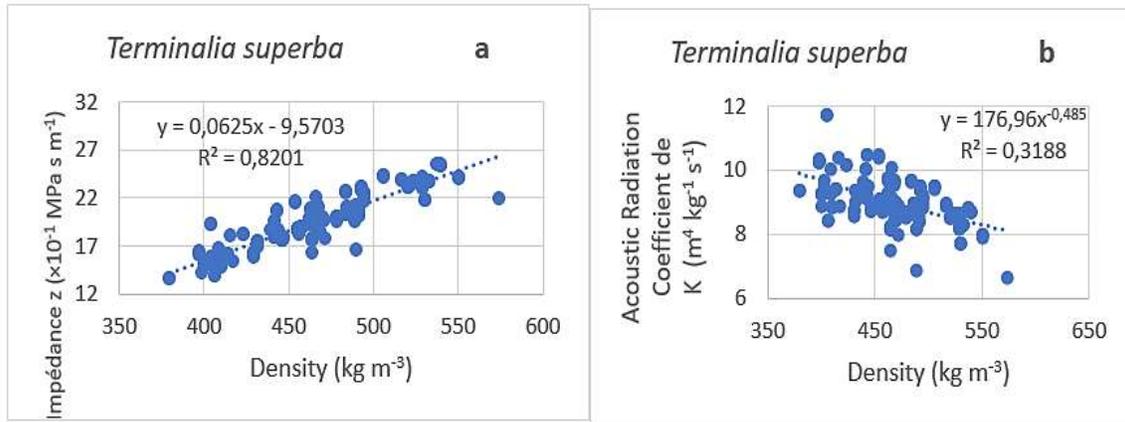


Figure 6. Variation of impedance and acoustic radiation coefficient as a function of density for *T. superba*. Source: Authors

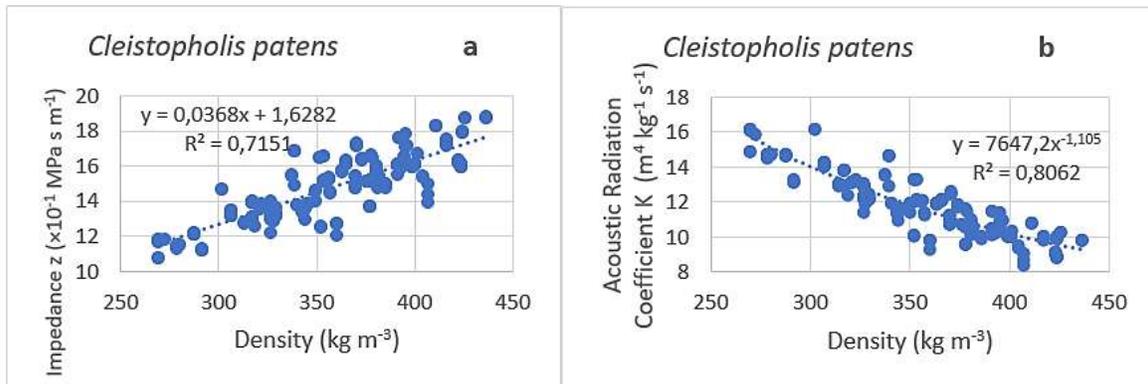


Figure 7. Variation of impedance and acoustic radiation coefficient as a function of density for *C. patens*. Source: Authors

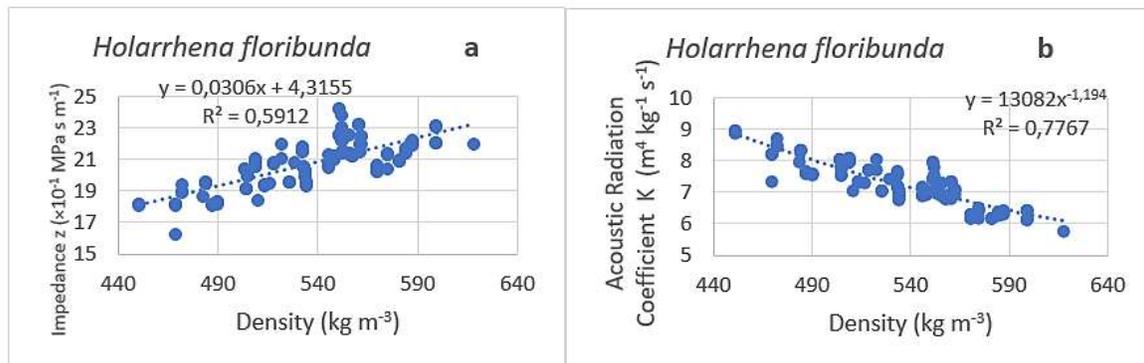


Figure 8. Variation of impedance and acoustic radiation coefficient as a function of density for *H. floribunda*. Source: Authors

related to the density by a power law with strong correlation in both cases.

Impedance is important when the transmission of vibration is from one medium to another as in the case of

musical instruments. For strings, it is a very important quantity and low impedances are highly valued (Wegst, 2006; Hilde et al., 2014) as in the case of sound transmission in air. Values of z between 1.2 and 3.4 MPa s m⁻¹ are required for stringed instruments and high values required for percussion instruments such as xylophones such that resonance will be over a large time period (Hilde et al., 2014). For the three species that are the subject of our study, the average characteristic impedances are for *T. Superba* (1.96 ± 0.29 MPa s m⁻¹); *C. patens* (1.47 ± 0.18 MPa s m⁻¹); *H. floribunda* (2.07 ± 0.14 MPa s m⁻¹). Thus according to Hilde et al. (2014), these species can be used in the manufacture of ropes. Kollmann and Coté (1968) found sound wave resistance values ranging from 2 to 3.7 MPa s m⁻¹ for wood while they found values of 39.5 MPa s m⁻¹ for steel and 25.8 MPa s m⁻¹ for iron (Roohnia, 2016). Excellent sound radiators such as *T. plicata* and *P. sitchensis*, has a low acoustic impedance, 1.683 and 2.165 MPa s m⁻¹. The acoustic impedance of *P. angolensis*, 2.298 MPa s m⁻¹ is similar to that of *Picea* spp. *Acer saccharum* has a sufficiently high impedance of 2.982 MPa s m⁻¹ that allows the wood to act as a reflector and contribute to sound radiation (Wegst, 2006). In contrast, *P. kesiya* for the soundboard impedance 2.733 MPa s m⁻¹, the slightly lower impedance of *P. angolensis* for the back and sides reduces sound deflection according to Ncube and Masilinga's (2017) guitar study in Zambia. These values prove in a general way therefore the low mechanical impedance of wood compared to materials like some metal alloys and the strong potentiality of our wood species to be used both in instrument making and sound insulation.

The impedance of the soundboard is proportional to the acoustic impedance of the material it is made of and also to the square of its thickness. Soundboards of considerable thickness, such as those of pianos for example, have an impedance clearly higher than that of the strings. The achievement of a high sound quality is therefore dependent on a meticulous monitoring of the impedances of the strings and the soundboards (Wegst, 2006). Experimental tests with the dimensioning of different instruments are desirable to further refine the specific observations.

Internal friction $\tan\delta$, acoustic conversion efficiency (ACE), and specific stiffness modulus E/ρ

The internal friction or damping coefficient is a parameter that reflects the energy dissipation in the wood. If the characteristic impedance z indicates the transmission of vibration from one medium to another, the acoustic radiation coefficient K describes the amplitude or loudness while the acoustic conversion efficiency represents the maximum response (Barlow, 1997; Wegst, 2006). ACE is the efficiency of converting vibrational

energy into sound energy and for some musical instruments, better wood rhymes with high ACE (Yano and Minato, 1993). A low $\tan\delta$ is often required as one of the necessary conditions for a wood to be used as soundboards of piano, guitar and other musical instruments (Matsunaga et al., 1999).

For our three species, the internal friction $\tan\delta$ and the acoustic conversion efficiency ACE are respectively for: *T. superba* (1.05 ± 0.50) · 10⁻² and (1039 ± 454) m⁴ kg⁻¹ s⁻¹; *C. patens* (1.10 ± 0.43) 10⁻² and (1242 ± 506) m⁴ kg⁻¹ s⁻¹; *H. floribunda* (1.23 ± 0.46) 10⁻² and (674 ± 267) m⁴ kg⁻¹ s⁻¹. The specific modulus of stiffness of these three species is as follows: *T. superba* (18 ± 3 GPa); *C. patens* (17 ± 2 GPa); *H. floribunda* (15 ± 1 GPa).

The $\tan\delta$ values of the species studied are slightly higher than those of Traoré et al. (2010) for veneer used in Mali for xylophone manufacture. Compared to this same species, the ACEs found here are significantly higher. *T. superba* has a higher specific stiffness than vene wood (Traoré et al., 2010), while the other two species have specific stiffnesses of the same order. Xylophone woods have a very low damping coefficient $\tan\delta$ and a high value of the peak sound radiation ACE, but not of the average sound radiation coefficient K , and harmonic table woods have higher values for ACE and K . (Wegst, 2006). Thus, *T. superba* and *C. patens*, on this basis, are recommendable for soundboards. Working on tropical woods, Brémaud (2012) measured ACE values of 700 to 800 m⁴ kg⁻¹ s⁻¹ generally higher than those of *H. floribunda* but lower than the other two species. Baar et al. (2016), working on the tropical hardwood species *Azelia*, *Intsia*, *Astronium* and *Millettia* species, meeting the criteria for idiophones such as xylophone bars, found a low internal friction of 0.006 to 0.008 and an ACE of about 700 to 800 m⁴ kg⁻¹ s⁻¹ for a specific stiffness around 16.6 to 21.0 GPa. For *Azelia* spp. the internal friction of value 0.0075 found is just like for the other species is lower than the values of our species; its specific rigidity of 16.6 GPa is in the range of that of our species while its ACE of 649 m⁴ kg⁻¹ s⁻¹ is in the range of that of *H. floribunda* but very low compared to those of the two other species here studied.

The internal friction $\tan\delta$ of these three species is not in the range of poor acoustic quality woods with a damping coefficient between 1.52 × 10⁻² and 2.21 × 10⁻² but rather in the range of good acoustic quality woods with $\tan\delta$ between 0.82 × 10⁻² and 1.26 × 10⁻² (Brancheriau et al., 2006). The best perceived acoustic material 'quality' was that of very low internal friction even though the variability of the damping coefficient for wood was restricted to its lowest range between 0.25 × 10⁻² and 0.55 × 10⁻² (Hase, 1987; Brémaud, 2012).

Wegst (2006) argues that resonator woods should have a high ACE unlike other parts of musical instruments. Coupling the ACE with the internal friction, and reading the graph in Figure 9a (Wegst, 2006), the average values of our species indicate that *C. patens* can be used in

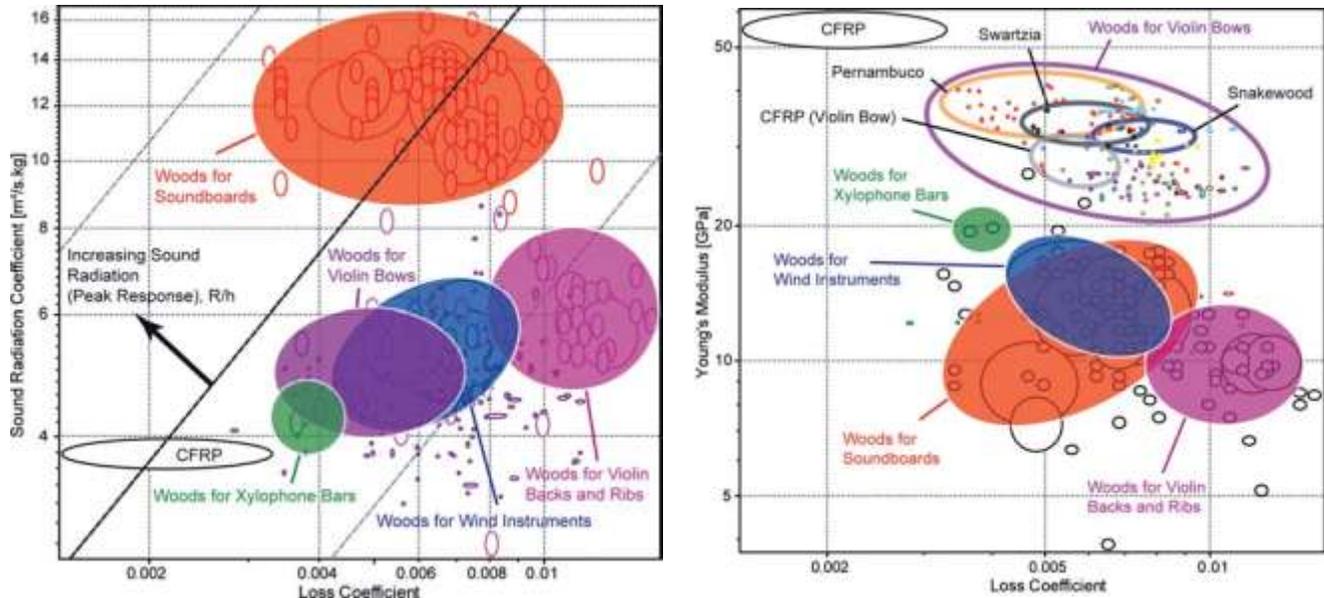


Figure 9. Acoustic radiation coefficient as a function of internal friction (a) and modulus of elasticity as a function of internal friction (b), graphs illustrating the selection of wood in instrument making. Source: Wegst (2006).

making soundboards and *H. floribunda* for violin backs and sides.

According to Wegst (2006), modulus of elasticity can be related to internal friction as shown in Figure 9b. Based on this graph and our average values, the three species studied here would all be candidates for the manufacture of violin backs and sides. Based on the following Figure 9a from Wegst (2006), Roohnia (2016) concluded that light tone woods for resonator soundboards can exhibit ACE beyond $2000 \text{ m}^4 \text{ kg}^{-1} \text{ s}^{-1}$.

In wood acoustics, these species under certain conditions can be used for the manufacture of musical instruments such as woodwinds, percussion instruments, strings and brass bands (Bucur, 2006). Indeed, by combining the acoustic and mechanical properties of wood, we group wood species under the generic term of resonance wood. Woods of high specific modulus (frequency descriptor) find wide application in the manufacture of resonators for musical instruments requiring minimum weight; that is, the utility of specific stiffness is to find wood parts with minimum weight for bending vibration of the body of a sound producing instrument whose primary design constraint is physical deflection or deformation, rather than loading at a point of failure. There are no better materials or materials similar to wood to be combined with or to substitute for wood in these very important acoustical properties to achieve structural wood quality (Bucur, 2006).

The sound produced by a string is barely audible because a single string is capable of moving a small volume of air. So to produce a sound of satisfactory volume for our ears, the string must be coupled with a

resonator that will transmit the vibration energy of the string and radiate the sound. Generally, high ACE woods are known to be excellent soundboards (Brémaud, 2012). Wegst (2006) finds that xylophone bar woods have fairly high values of peak response (maximum response) ACE but not average loudness K. Both their ACE and K are lower than spruce for string soundboards, which corresponds to less radiation damping, and their higher z-impedance would result in less energy loss through the mounts. Numerical simulation showed that the decay time of xylophone bars was governed primarily by internal friction, but very little by losses through the supports (Chaigne and Doutaut, 1997). A high specific modulus may allow radiation at low frequencies (Yano et al., 1994). Fairly light, spruce, with a specific modulus of about 31 GPa, has a moderate characteristic impedance of $2.683 \text{ MPa s m}^{-1}$ (Bucur, 2006), which can promote the transmission of sound in air (Wegst, 2006).

Figures 10 to 12 show for each species, the variation of ACE as a function of $\tan\delta$ and then the variation of internal friction $\tan\delta$ as a function of specific modulus. Overall, ACE follows a power law of internal friction with strong correlation coefficients. The strong dispersion of the specific modulus as a function of internal friction did not allow us to have the exact power law $\tan\delta = 10^{-A} \times (E/\rho)^{-B}$ of Ono and Morimoto (1983), which is the reference. Instead, we have a power law of the form $\tan\delta = (E/\rho)^{-B}$ given the high dispersion of our species, which are tropical wood species.

In general, woods with high specific stiffness E/ρ combined with low damping coefficient $\tan\delta$ are accepted for piano, guitar, and violin soundboards (Matsunaga et

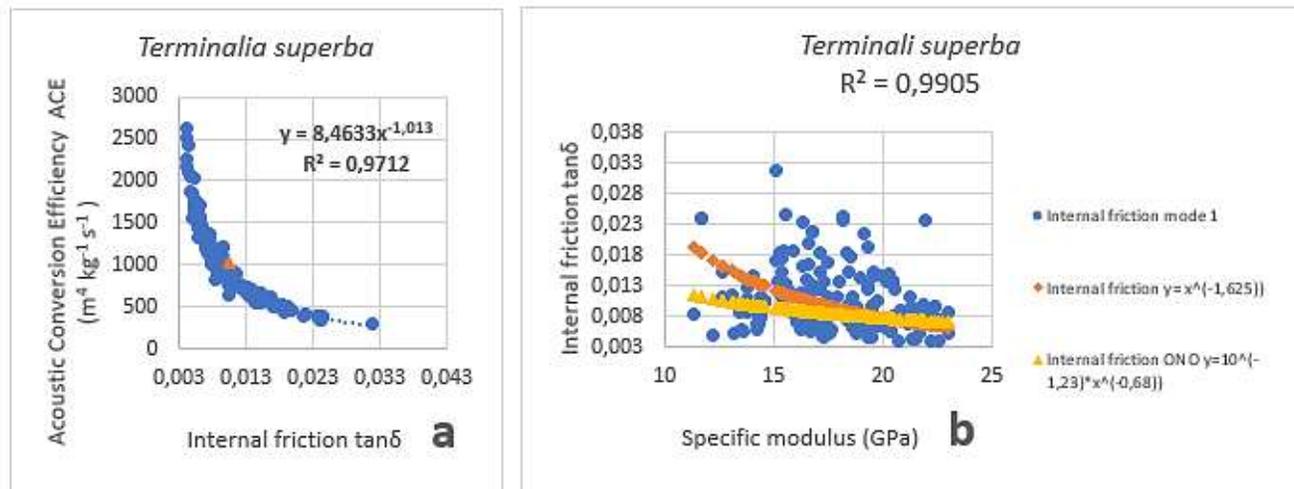


Figure 10. Variation of the Acoustic Conversion Efficiency as a function of internal friction (a) and internal friction as a function of the specific modulus of rigidity (b) for *T. superba*.
Source: Authors

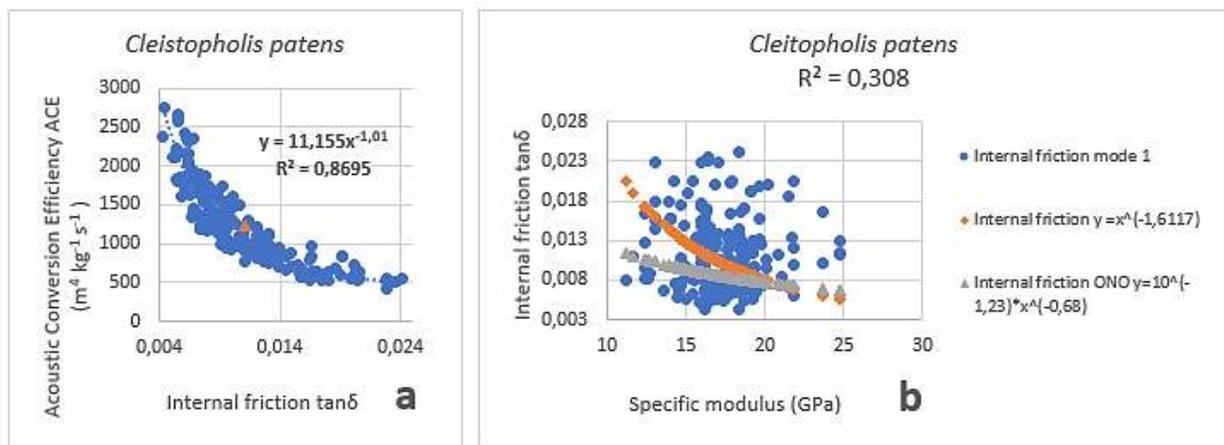


Figure 11. Variation of Acoustic Conversion Efficiency as a function of internal friction (a) and internal friction as a function of specific modulus of rigidity (b) for *C. patens*.
Source: Authors

al., 1996).

The relationship between internal friction $\tan\delta$ and specific stiffness E/ρ is determined by the orientation of the wood elements and can be modeled by considering the microfibril angle or grain angle (Obataya et al., 2000; Brémaud et al., 2011b). Thus the difference observed from the standard form of Ono and Morimoto (1983) can be explained by the fact that our species are tropical species either by the chemical composition or presence of extractives or by the water content of the wood or the presence of compression wood or the structure of the wood (Obataya et al., 2000; Brémaud et al., 2010a, 2011a; Obataya et al., 1998; Sasaki et al., 1988) which

influences the internal friction $\tan\delta$ more than the stiffness modulus E/ρ (Brémaud et al., 2013). Extractables can be without effect as they can decrease, or at times, grow, the internal friction $\tan\delta$ by a coefficient that can reach at most 2 with very little influence on the stiffness modulus E/ρ (Brémaud et al., 2012).

Since the modulus of elasticity generally increases with density, a higher mechanical impedance is recommended for panels of musical instrument body frames or others (Pollens, 1984; Yoshikawa, 2001). Also, high values of the specific modulus of elasticity E/ρ are highly recommended for excellent soundboards (Bucur, 2006; Ono, 1996; Ono and Morimoto, 1984). Because of this,

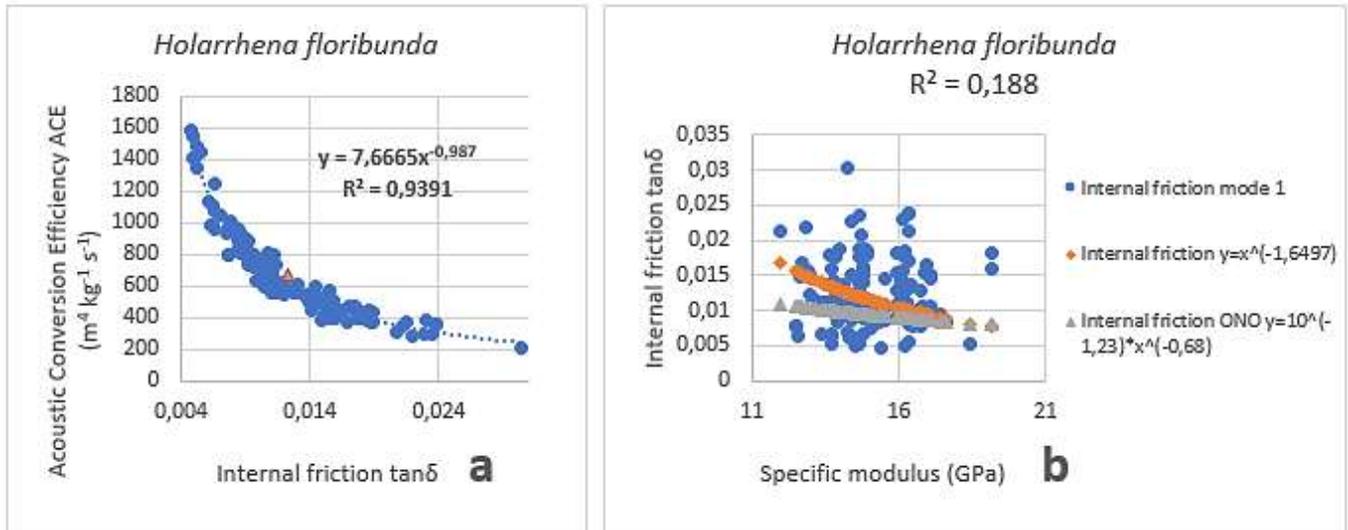


Figure 12. Variation of Acoustic Conversion Efficiency as a function of internal friction (a) and internal friction as a function of specific modulus of stiffness (b) for *H. floribunda*.
Source: Authors

the performance of soundboards and cases cannot be predicted solely from the modulus of elasticity and velocity (Yoshikawa, 2007), internal friction, and others. For Western instruments (marimbas and xylophones), the required wood qualities have been defined as high density, modulus of elasticity, and good moisture-related dimensional stability (Holz, 1996b).

Shrinkability

Shrinkability is a parameter influencing the dimensional stability of wood in both structural and instrumental applications. The physical properties of shrinkage and infradensity of the studied species were researched in the literature. Values of volume shrinkage and radial and tangential shrinkage given the R/T ratio indicate that these species are dimensionally stable in the face of moisture gradient. Indeed, according to Tropix 7, *T. superba* has a tangential shrinkage RT of 6.1%; a radial shrinkage RR of 4.3% for RT/RR ratio of 1.4 for a volume shrinkage coefficient of 0.42% and is required to be medium stable in service. PROTA reporting Lemmens (2012) found that *C. patens* has a radial shrinkage RR of 5.0%, a tangential shrinkage RT of 9.6% for a shrinkage anisotropy RT/RR of 1.9; it is a moderately stable wood in service. The literature is silent on the physical, mechanical and acoustic properties of *H. floribunda*, which remains in the domain of natural sciences (Bayala et al., 2006). However, recent work by Antwi et al. (2022) shows that the branch wood of this species has similar properties to the trunk wood. Antwi et al. (2022) found that branch wood has a tangential shrinkage of $(3.8 \pm$

0.7%), a radial shrinkage of $(2.0 \pm 0.5\%)$ and a shrinkage anisotropy of 1.9 ± 0.2 similar to trunk wood, which has a tangential shrinkage of $3.6 \pm 0.6\%$ and a radial shrinkage of $1.9 \pm 0.2\%$ with a shrinkage anisotropy of 1.9 ± 0.4 . *R. heudelotii* heartwood dries rapidly with little or no degradation. Its tangential shrinkage RT ranges from 4.7 to 5.4% and its radial shrinkage RR ranges from 1.9 to 2.4%. Its shrinkage anisotropy ranges from 2.0 to 2.8. The wood is easy to saw and work, and nails without splitting, but turning and planing are difficult (Tchoundjeu and Atangana, 2007). Thus, the wood of the species studied has, overall, a lower propensity to deformation than the wood of *R. heudelotii*, which nevertheless has the best dimensional stability. These species have good potential for sculptural works requiring low dimensional variation in the face of humidity variations.

Conclusion

At the end of this work, it appears that Benin has many species of wood that can be used in sculpture such as *C. patens*, *T. scleroxylon*, *M. excelsa*, *A. leiocarpa*, *D. mespiliformis*, *H. floribunda*, and *T. superba*. Thus to better value some of them, we determined the most important physical, mechanical and acoustic properties of *T. superba*, *C. patens* and *H. floribunda*. Taking into account their velocity of about 4000 m s^{-1} and basic properties, such as density and modulus of elasticity, these three species offer great potential for instrument making. Based on the densities found, *T. superba* and *H. floribunda* are good candidates for guitar case panels. Because of their modulus of elasticity, all three species

can be used for the manufacture of soundboards; *T. superba* and *H. floribunda* for the back and sides of violins and wind instruments. By combining the speed of sound and the coefficient of acoustic radiation of these three species of wood, it is concluded that the woods of these species are potential resonance woods for the manufacture of soundboards. The specific stiffness of each of these three species is greater than 15 GPa and reinforces their nature as resonance woods. Their acoustic impedance suggests their use in strings. With their internal friction, the three species studied are in the range of wood species with good acoustic quality. *T. superba* and *C. patens* have peak ACE responses above $1000 \text{ m}^4 \text{ kg}^{-1} \text{ s}^{-1}$ while all three wood species have a radiation coefficient above $7 \text{ m}^4 \text{ kg}^{-1} \text{ s}^{-1}$. Compared to the properties *Azelia* spp. *H. floribunda* can be a good substitute in the manufacture of musical instruments especially xylophone bars. Their shrinkage and shrinkage anisotropy predestine them to good use in art sculpture.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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