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DETERMINATION OF THE ACOUSTIC ABSORPTION COEFFICIENT IN WOODS USED FOR CHORDOPHONES

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Resumo

Determinação do coeficiente de absorção acústica em madeiras utilizadas para cordofones. O objetivo deste estudo foi caracterizar a absorção sonora de 13 espécies de madeira utilizadas por *luthiers* no Peru, por meio da medição de seus coeficientes de absorção sonora utilizando um tubo de impedância acústica construído de acordo com as normas ASTM C384. As densidades, os teores de umidade e outras propriedades acústicas das amostras foram determinadas. Os resultados mostraram que os coeficientes de absorção sonora variaram de 0,037 a 0,119 em baixas frequências, de 0,019 a 0,063 em frequências médias e de 0,033 a 0,112 em altas frequências. Concluímos que as espécies de madeira palisangre (*Brosimum rubescens*) e palo azufre (*Symphonia globulifera)* apresentaram boas qualidades de absorção acústica para a construção do fundo e das laterais de cordofones.
Palavras-chave: Luthier, timbre da madeira, som, frequência fundamental.

Abstract

The aim of this study was to characterize the sound absorption of 13 wood species used by luthiers in Peru by measuring their sound absorption coefficients using an acoustic impedance tube built according to the ASTM C384 standards. The densities, moisture contents, and other acoustic properties of the samples were determined. The results showed that the sound absorption coefficients ranged from 0.037 to 0.119 at low frequencies, 0.019 to 0.063 at mid frequencies, and 0.033 to 0.112 at high frequencies. We concluded that the wood species palisangre (*Brosimum rubescens*) and palo azufre (*Symphonia globulifera*) exhibited good acoustic absorption qualities for the construction of the backs and sides of chordophones.
Keywords: Luthier, wood tone, sound, fundamental frequency.

INTRODUCTION

As an engineering material, wood possesses physical, mechanical, and chemical properties that are widely recognized owing to its traditional uses. However, it also exhibits acoustic properties that, although less well known, are essential for various applications, particularly in manufacturing musical instruments. Solid wood is the traditional raw material employed in constructing these instruments because of its unique acoustic qualities and bound carbon content, which enhances its fiber structure. A detailed understanding of these properties is fundamental for creating higher-value and higher-quality products, optimizing the use of natural resources, and enabling the exploration of new species for this purpose (NASIR *et al*., 2022; ZHA *et al*., 2023).

A lack of information on the acoustic properties of wood limits its use in the musical instrument manufacturing industry in Peru. Moreover, this is an artisanal activity conducted throughout the country in a series of workshops that use either imported or native timber, often without rigorous evaluation. As Dinulică *et al.* (2021) also point out, not every wood species possesses optimal acoustic properties, and not all wood from a single tree is suitable from an acoustic standpoint.

Acoustic absorption, understood as the ability of wood to interact dynamically with the surrounding air, depends on the air penetrating its structural elements, such as fibers, pores, and interstices, which then vibrate and dissipate acoustic energy. This capacity varies according to the wood's orthotropic structure and density (GUIMAN *et al*., 2023; MANIA *et al*., 2023).

Previous studies have highlighted the influence of the physical properties of fibers on acoustic absorption, particularly at high frequencies. Oldham *et al.* (2011) demonstrated that the porosity and compaction of natural fibers in cylinders with a thickness of 50 mm resulted in excellent acoustic absorption properties, particularly at frequencies above 1000 Hz. The density and fiber type also play decisive roles in determining the acoustic quality of wood. Bucur (2016) observed that sapwood exhibited higher absorption coefficients than heartwood, whereas Kang *et al.* (2020) noted that heartwood was more efficient at absorbing sounds at high frequencies. These studies demonstrate the importance of considering the anatomical and physical variables of wood in the development of acoustic materials, particularly for applications in musical instrument manufacturing.

In addition, another study investigated the possibility of using treated natural fibers to manufacture acoustic absorbent materials, considering their abundance and biodegradability. Proposals have been made to apply the Delany-Bazley physical model to perform simulated acoustic absorption studies, as in the work of Berardi (2017) and Gokulkumsar *et al.* (2019). These approaches can be applied to research on wood for chordophones (CAO *et al.*, 2018).

In light of the above, the Laboratory of the Department of Forest Industries at the Universidad Nacional Agraria La Molina in Lima, Peru, has been developing nondestructive testing methods for ten years to apply them to musical instrument manufacturing, especially chordophones. As part of these investigations, The objective of the present study was to determine the acoustic absorption of sound in tonal woods, highlighting the importance of density and porosity for the sonority of these materials.

MATERIAL AND METHODS

Collection of Plant Material

The wood samples comprised 13 species, including nationally traditional woods such as caoba (*Swietenia macrophylla*), cedro (*Cedrela odorata*), estoraque (*Myroxylon balsamum*), palisangre (*Brosimun rubescens*), diablo fuerte (*Prumnopitys harmsiana*), and nogal (*Juglans* sp.). National exotic species, including ulcumano (Retrophyllum rospigliosii), dialium (Dialium guianense), shihuahuaco (*Dipteryx odorata*), and palo azufre (*Symphonia globulifera*), were selected from a pool of 68 species using techniques commonly used by luthiers. In addition, imported species, such as spruce (*Picea engelmannii*), palisandro (*Dalbergia latifolia*), and arce (*Acer saccharum*) were selected.

The samples were provided by Industrial Amazónica Zapote S.A. – IMAZA and were identified at the Faculty of Forestry Sciences of the National Agrarian University La Molina (UNALM) in Lima, Peru, at the Laboratory of Physical and Mechanical Properties of Wood, where density and moisture content were determined. The acoustic parameters were evaluated at the Acoustics Laboratory of the Department of Physics and Meteorology of the Faculty of Sciences at UNALM.

The determination of density and moisture content followed the procedures established by the Peruvian Technical Standards NTP 251.010 (2004) "WOOD. Method for Determining Moisture Content" and NTP 251.011 (1980) "WOOD. Method for Determining Density." Exceptions were made for ulcumano (*Retrophyllum rospigliosii*), nogal (*Juglans* sp.), arce (*Acer saccharum*), caoba (*Swietenia macrophylla*), and cedro (*Cedrela odorata*), whose moisture content was measured using an electronic detector.

Specimen Size and Orientation

Owing to the heterogeneity and quality of the standard wood strips (selected) from longitudinal (quarter-sawn) cuts, three samples were prepared from each species. These samples were discs measuring 9.8 cm in diameter and 0.3 cm in thickness, as shown in Figure 1.

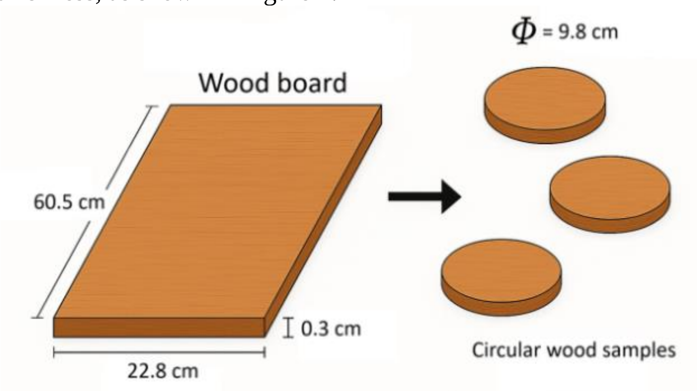

Figure 1. Procedure for obtaining circular wood samples.
Figura 1. Processo de obtenção das amostras circulares de madeira.
Source: Authors, 2025.

Sound Absorption Coefficient

This study was conducted in accordance with ASTM C384 (2004) and was supported by its equivalent ISO 10534-1:1996, which is the standard test method for measuring the acoustic impedance and absorption of materials using the impedance tube method. The tube was constructed at the Acoustics Laboratory of the Department of Physics and Meteorology of the Faculty of Sciences at UNALM, as shown in Figure 2. The coefficient was determined based on the generation of a standing wave between the specimen (circular wood sample) and a speaker emitting the wave, with the setup positioned vertically in accordance with the cited standards. The ambient temperature was controlled at 19 ± 1 °C, and the average moisture content was 10.8%.

Description of the Impedance Tube

Following the ASTM C384 and ISO 10534-1 standards, the impedance tube was designed and built using a straight PVC tube with a diameter of 10.2 cm, a length of 1 m, and a wall thickness of 4 mm, configured to operate vertically. This orientation facilitates a more precise movement of the microphone because it does not rely on floor-mounted support, which would otherwise increase the acoustic attenuation within the tube, as shown in Figures 2-A and 2-B.

The 10.2 cm tube diameter presented a challenge owing to a non-planar wavefront. However, the estimated deformation was less than 5%, which was compensated for by the reduced attenuation inside the tube. In addition, the ratio of the wall thickness to the tube diameter was less than 4%, and the ratio between the cross-sectional areas of the microphone and tube was less than 2%. The tube was reinforced along its length using clamps and polyethylene foam to prevent deformation and vibration. Its interior was kept clean, smooth, and free of porosity in compliance with the standards mentioned above.

The design of this tube enabled operation within the recommended detection frequency range of 231–1988 Hz, according to ASTM C384. The laboratory environment was maintained using an air conditioning and humidity control system. The temperature inside the tube was monitored by using thermometers placed at three different points along the length of the tube. A high-sensitivity Virtins Technology VT RTA 168 B Dayton MM-6 omnidirectional electret condenser microphone (diameter: 0.12 cm) was used along with a Rohde & Schwarz HMO72 70 MHz/2 MB digital oscilloscope.

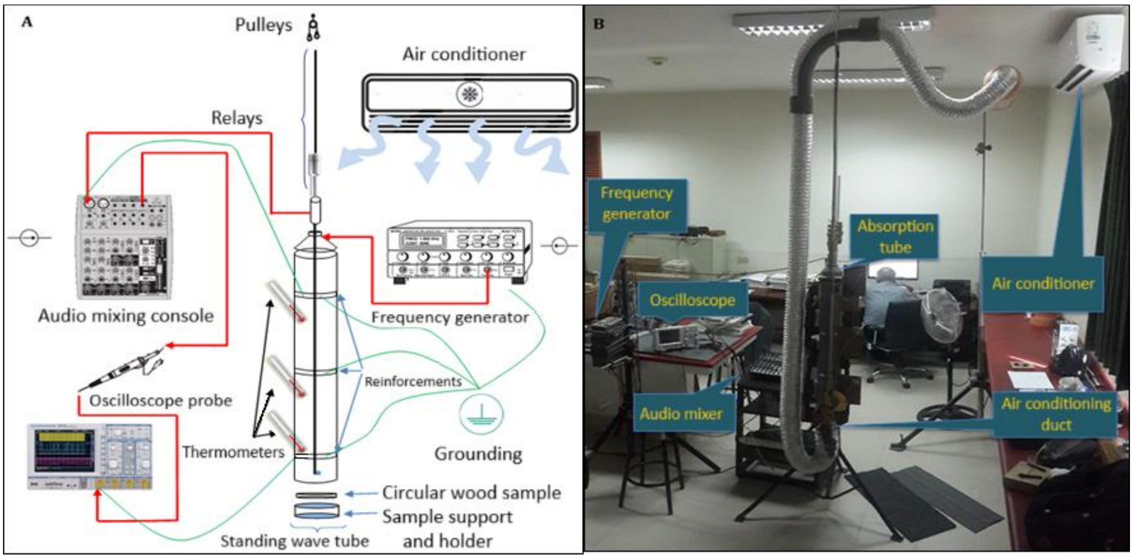

Figure 2. Acoustic absorption tube. A: Installation diagram. B: Installed absorption equipment.
Figura 2. Tubo de absorção acústica. A: Diagrama de instalação. B: Equipamento de absorção instalado.
Source: Authors, 2025.

Measurement Procedure

The procedure involved emitting an acoustic wave from a small loudspeaker at one end of the tube, generating a wave that traveled along the tube and struck the specimen perpendicularly. The wave was then reflected, producing a standing wave along the tube at different resonance frequencies. Measurements were taken using a movable microphone, which recorded the positions of the maximum and minimum sound pressure levels in volts (V_{max} and V_{min}) using an oscilloscope. In the present study, the longitudinal-radial (LR) face was used as the surface of incidence of acoustic waves for both coniferous and broadleaf species.

Figure 3 shows a diagram of the standing wave pattern, in which the correspondence between the standing wave and concentrations of particles, nodes, and antinodes can be observed, defining the location of the minimum points relative to the surface of the sample at x = 0 m. The antinodes were located half a wavelength away from the nodes. The voltages recorded by the microphone and their respective distances from the surface of the specimen determined the standing-wave pattern.

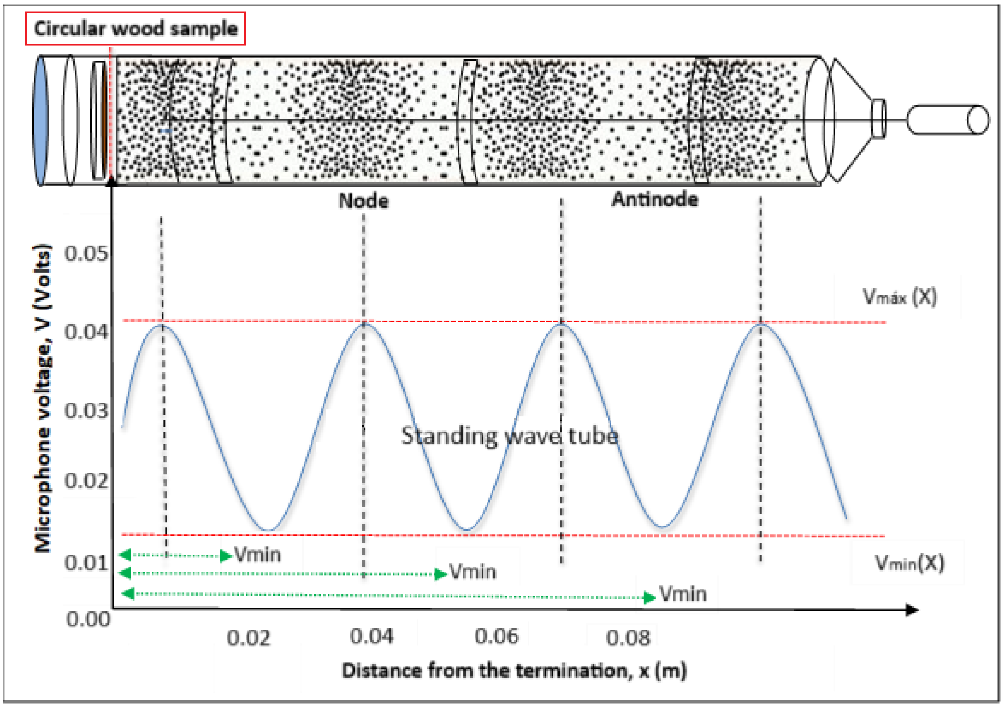

Figure 3. Diagram of the standing wave pattern.
Figura 3. Diagrama do padrão de onda estacionária.
Source: Authors, 2025.

Relationships for Determining the Absorption Coefficient

The different maxima of the standing wave have (SWR) nearly the same value; however, the minimum voltage values show a positive slope due to greater attenuation of the medium on the reflected wave, on the order of 0.2%. A SWR can be defined, according to Equation (1), as follows: (BARANEK, 1996).

$$SWR(x) = \frac{V\max}{V\min} \quad (1)$$

where SWR(x) is the SWR at position (x), V_{max} is the maximum voltage (V), and V_{min} is the minimum voltage (V).

The SWR(x) relationship can be linearly extrapolated to the surface of the sample (x = 0) to obtain SWR(0) in accordance with the technical standard. The normal reflection coefficient (CR) was determined using the following Equation (2).

$$CR = \frac{(SWR(0)-1)}{(SWR(0)+1)} \quad (2)$$

where α_n is the acoustic absorption coefficient of the material, as expressed in Equation (3).

$$\alpha_n = 1 - CR^2 \quad (3)$$

Another important factor that affects acoustic absorption is porosity, which is measured by the capacity of the wood to absorb fluids such as water and is related to the penetration of acoustic waves into the wood. Porosity can be determined using a porosimeter or. alternatively, by applying Equation (4), which considers the ratio between the density of a sample and the average cell wall density of 1.56 g·cm⁻³, with values ranging from $0 \leq P \leq 1$ (SIAU, 1995).

$$P = \frac{\rho}{(1+0.01M)}\left(\frac{1}{1.56} + 0.01M\right) \quad (4)$$

where ρ is the density at 12% moisture content and M is the moisture content in %.

RESULTS

Table 1 presents the data on wood density, moisture content, and porosity. The measured moisture contents of the samples ranged from 7.5% to 12.4%, and the porosity values ranged from 0.31 to 0.74.

Table 1. Evaluated wood species and their respective values of moisture content (%), density (g/cm³) and porosity.
Tabela 1. Espécies de madeira avaliadas e seus respectivos valores de teor de umidade (%), densidade (g/cm³) e porosidade.

SPECIES	MOISTURE CONTENT (M) (%)	DENSITY (ρ) (g/cm^3)	POROSITY (P) $0 \leq P \leq 1$
Arce (*Acer saccharum*)	9.1	0.56	0.62
Caoba (*Swietenia macrophylla*)	10.8	0.61	0.59
Cedro (*Cedrela odorata*)	11.2	0.47	0.68
Diablo Fuerte (*Prumnopitys harmisiana*)	12.4	0.65	0.56
Dialium (*Dialium guianense*)	11.3	0.98	0.33
Estoraque (*Myroxylon balsamum*)	10.8	0.87	0.41
Nogal (*Juglans* sp.)	8.2	0.57	0.61
Palisandro (*Dalbergia latifolia*)	7.5	0.56	0.62
Palisangre (*Brosimun rubescens*)	9.9	1.01	0.31
Palo Azufre (*Symphonia globulifera*)	10.2	0.71	0.52
Shihuahuaco (*Dipteryx odorata*)	11.4	0.93	0.37
Spruce (*Picea engelmanii*)	11.1	0.39	0.74
Ulcumano (*Retrophyllum rospigliosii*)	9.4	0.44	0.70

Source: Authors, 2025.

The results obtained for the acoustic absorption coefficient within the resonance frequency range of 506–1977 Hz for the 13 evaluated species are presented in Table 2. The results are interpolated using fourth-degree polynomials to produce sinusoidal trends. The coefficients of variation are listed in Table 2 and range from 3.4% to 10.8%.

Table 2. Acoustic absorption coefficients by resonance frequency ranges (Hz), standard deviation, and coefficient of variation (%) for the 13 evaluated wood species.
Tabela 2. Coeficientes de absorção acústica por faixas de frequência de ressonância (Hz), desvio padrão e coeficiente de variação (%) das 13 espécies de madeira avaliadas.

	1st	2nd	3rd	4th	5th	6th	7th	8th
	506–613 (Hz)	775–800 (Hz)	956–995 (Hz)	1166–1190 (Hz)	1359–1384 (Hz)	1552–1584 (Hz)	1701–1790 (Hz)	1930–1977 (Hz)
Arce	0.109	0.037	0.041	0.047	0.038	0.067	0.065	0.068
(Acer saccharum)	3.4 %	6.6 %	5.5 %	10.5 %	8.9 %	10.8 %	10.4 %	9.8 %
Caoba	0.072	0.049	0.048	0.029	0.019	0.033	0.084	0.076
(*Swietenia macrophylla*)	6.7 %	9.2 %	8.9 %	10.5 %	6.5 %	9.4 %	7.9 %	9.5 %
Cedro	0.096	0.037	0.032	0.035	0.039	0.066	0.077	0.083
(Cedrela odorata)	4.9 %	9.1 %	9.3 %	8.5 %	9.9 %	9.6 %	10.2 %	9.9 %
Diablo fuerte	0.099	0.040	0.038	0.062	0.051	0.072	0.060	0.070
(Prumnopitys harmsiana)	4.7 %	8.4 %	9.9 %	10.3 %	10.4 %	10.8 %	5.6 %	9.7 %
Dialium	0.119	0.040	0.036	0.031	0.020	0.046	0.079	0.101
(Dialium guianense)	4.9 %	9.7 %	9.5 %	8.2 %	9.4 %	9.6 %	10.4 %	9.1 %
Estoraque	0.103	0.030	0.037	0.019	0.031	0.084	0.047	0.075
(*Myroxylon balsamum*)	3.5 %	10.0 %	4.8 %	9.7 %	7.7 %	9.1 %	6.3 %	10.4 %
Nogal	0.100	0.032	0.030	0.020	0.038	0.078	0.067	0.094
(Juglans sp.)	3.7 %	9.4 %	10.5 %	10.2 %	8.3 %	9.9 %	10.3 %	7.61 %

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	506–613 (Hz)	**775–800 (Hz)**	**956–995 (Hz)**	**1166–1190 (Hz)**	**1359–1384 (Hz)**	**1552–1584 (Hz)**	**1701–1790 (Hz)**	**1930–1977 (Hz)**
Palisandro	0.094	0.046	0.060	0.045	0.063	0.089	0.069	0.064
(Dalbergia latifolia)	7.4 %	7.8 %	9.4 %	9.2 %	8.7 %	2.3 %	7.6 %	10.3 %
Palisangre	0.128	0.052	0.052	0.036	0.030	0.084	0.083	0.109
(Brosimun rubescens)	8.6 %	7.1 %	8.7 %	10.4 %	8.2 %	10.1 %	9.7	8.4
Palo azufre	0.100	0.045	0.037	0.029	0.038	0.063	0.060	0.112
(Symphonia globulifera)	8.2 %	9.9 %	9.9 %	5.3 %	10.1 %	9.4 %	7.9 %	7.1 %
Shihuahuaco	0.117	0.055	0.048	0.041	0.052	0.085	0.077	0.057
(*Dipteryx odorata)*	10.0 %	9.2 %	9.3 %	9.4 %	7.5 %	9.5 %	8.0 %	9.7 %
Spruce	0.091	0.039	0.025	0.023	0.027	0.085	0.083	0.094
(Picea engelmannii)	8.4 %	5.8 %	7.3 %	8.5 %	10.43 %	10.2 %	10.2 %	9.7 %
Ulcumano	0.109	0.036	0.042	0.025	0.050	0.096	0.072	0.094
(Retrophyllum rospigliosii)	7.4 %	9.6 %	9.5 %	7.2 %	10.8 %	9.9 %	10.6 %	10.5 %

Source: Authors, 2025.

Figure 4 shows the behavior of the acoustic absorption coefficients as a function of the incident wave frequency for the studied species. The values ranged from 0.032 to 0.117 for frequencies around 500 to 700 Hz, 0.020 to 0.063 for frequencies between 800 and 1400 Hz, and 0.033 to 0.112 for frequencies from 1500 to 1900 Hz.

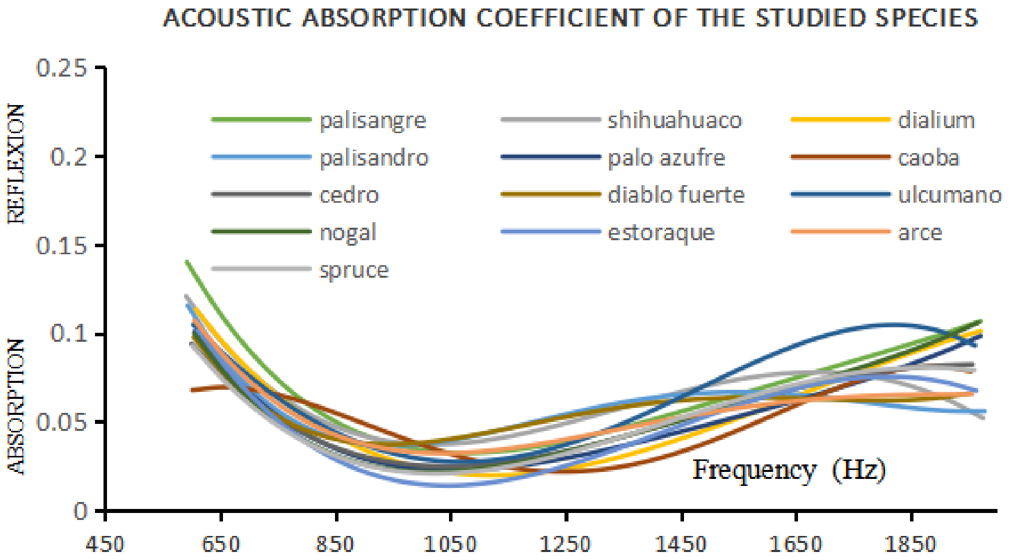

Figure 4. Distribution of the acoustic absorption curves of the specimens. The absorbed energy is shown to be around 15%, while up to 85% of the incident radiation energy is reflected.
Figura 4. Distribuição das curvas de absorção acústica das amostras. A energia absorvida é da ordem de 15%, enquanto até 85% da energia da radiação incidente é refletida.
Source: Authors, 2025.

A similar behavior can be observed among caoba, palo azufre, and palisangre (Figure 5), with absorption coefficients below 0.15 at low frequencies around 600 Hz, up to 0.10 at mid frequencies between 900 and 1400 Hz, and up to 0.12 at high frequencies above 1500 Hz. In the case of caoba, the average absorption coefficients ranged from 0.07 at low frequencies to a maximum of 0.08 at high frequencies. This enabled us to conclude that palisangre and palo azufre exhibited better acoustic absorption qualities than caoba, which was used as a reference, as also noted by the luthiers.

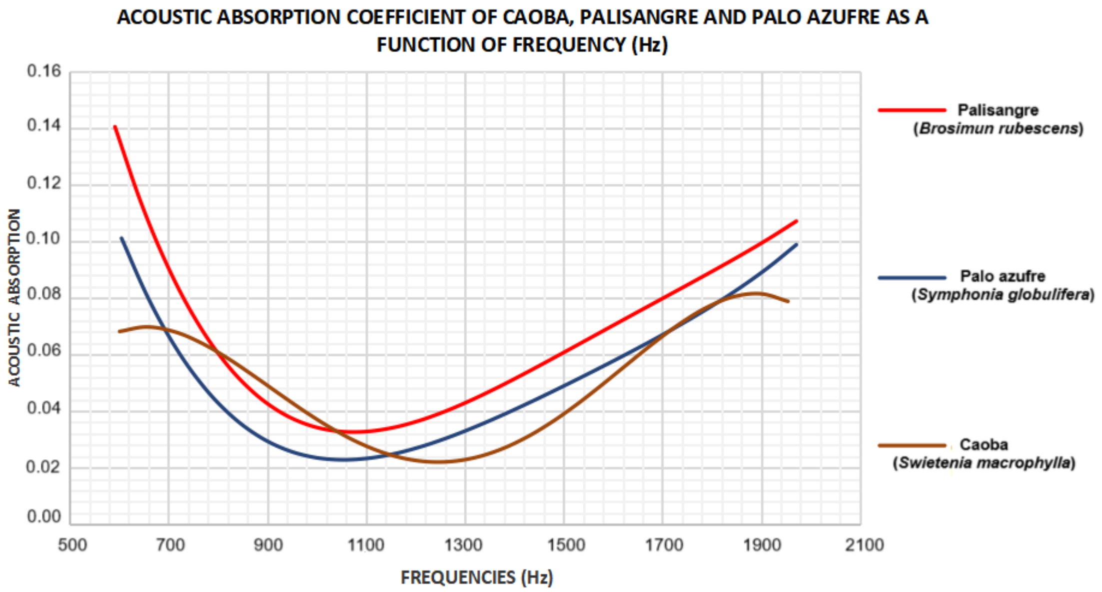

Figure 5. Absorption curve of caoba, palisangre and palo azufre.
Figura 5. Curva de absorção de caoba, palisangre e palo azufre.
Source: Authors, 2025.

Figure 6 shows a 3D graph of absorption, porosity, and frequency. Notably, absorption did not depend heavily on porosity but was influenced by the acoustic frequency. This behavior might be related to the specimen thickness (0.3 cm), reflecting the acoustic properties of the wood used in chordophones, as they are typically used at that thickness.

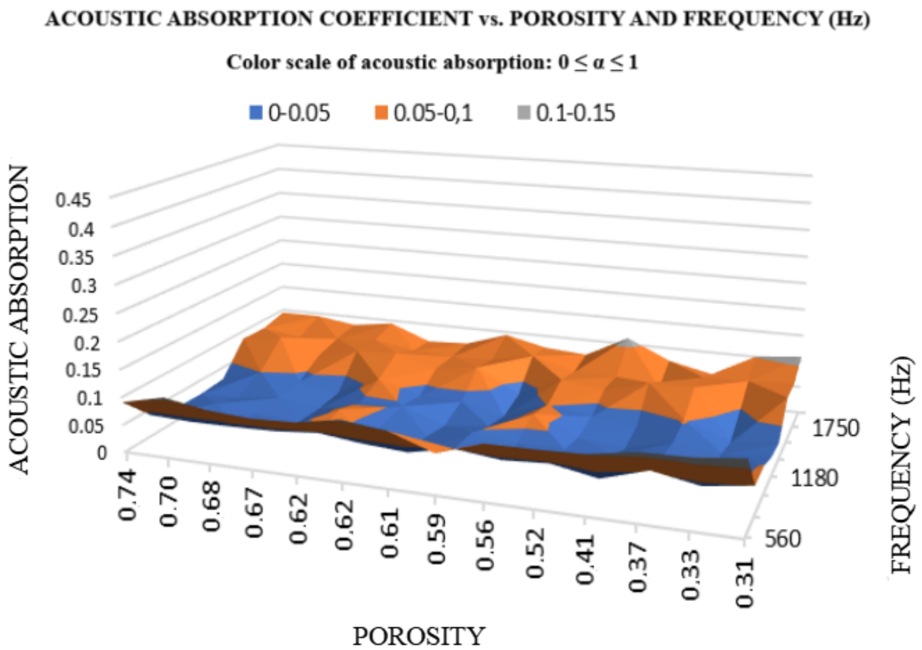

Figure 6. Behavior of the absorption coefficient as a function of porosity and acoustic wave frequency for samples 3 mm thick.
Figura 6. Comportamento do coeficiente de absorção em função da porosidade e da frequência da onda acústica, para amostras de 3 mm de espessura.
Source: Authors, 2025.

DISCUSSION

The results obtained in the present study revealed important characteristics of the wood used in chordophones, especially regarding acoustic absorption and its dependence on factors such as the porosity, thickness, and frequency of the incident wave.

In a study on acoustic absorption in spruce (*Picea abies* L. H. Karst) and maple (*Acer pseudoplatanus* L.) woods with different orientations and quality grades (A and D), Guiman *et al.* (2023) found absorption coefficients ranging from 0.15 to 0.27 for spruce and from 0.07 to 0.22 for maple at frequencies of 1000 Hz. These values were comparable to those found in our study, which showed values of 0.11. This similarity suggested that the absorption characteristics of the studied woods fall within the expected range for materials used in musical instruments, although differences in sample thickness may explain the specific variations.

At frequencies between 125 and 500 Hz, the high absorption can be attributed to the low surface density and high porosity on the incident face of the acoustic wave (SMADZEWSKI *et al.*, 2015), as confirmed by Nandanwar *et al.* (2017) in their evaluation of fiber panels. However, our results show that acoustic absorption does not directly depend on porosity, which may be related to sample thickness (0.3 cm). This suggests that for woods with similar thicknesses, other factors, such as the internal structure and wood quality, may play a more significant role.

Eun-suk and Chun-won (2021), when evaluating three low-density wood species, minuana (*Octomeles sumatrana*), balsa (*Ochroma pyramidale*), and paulownia (*Paulownia tomentosa*), found lower absorption coefficients in paulownia, despite its high porosity. This supports the findings of our study, in which porosity was not a determining factor in acoustic absorption, especially when considering the presence of tyloses or resins that may block pores and alter acoustic behavior.

In contrast, Jayamani *et al.* (2013) found lower acoustic absorption values than those obtained in our study for low- and mid-frequencies when investigating wood from the species Jelutong (*Dyera polyphylla*), Selunsor merah (*Tristaniopsis beccarii*), tapinga (*Koompassia excelsa*), and pulai (*Alstonia angustiloba*). This difference in the results may be attributed to the greater thickness of the samples used (2.2 cm), reinforcing the importance of thickness as a determining factor for acoustic absorption.

In summary, this study contributes to understanding the acoustic properties of wood used in chordophones. The wood of palisangre and palo azufre stands out as promising alternatives, offering acoustic absorption indices across a wide frequency range, which can significantly influence the sound quality of musical instruments.

CONCLUSIONS

Based on the results of this study, we concluded that:

- The design of the vertical impedance tube, compared with the horizontal design, demonstrated better performance in position adjustments with greater precision. The values obtained suggested that the results are comparable to those of existing studies. Notably, there is a tendency for values tended to increase for low-frequency measurements, possibly because of the influence of the tube diameter on the geometry of the wavefront.
- The acoustic absorption in the studied woods with 3 mm thickness ranged from 0.020 to 0.117, indicating that absorption contributed little to the loss of incident energy and that most of it was reflected. Additionally, there was a relatively higher contribution at frequencies above 1500 Hz.
- This study indicated that porosity did not significantly influence acoustic absorption in 3 mm thick wood samples.
- Acoustic absorption in the studied woods showed low values between 900 and 1500 Hz, indicating high reflectivity in this range, possibly related to pores blocked by tyloses or resins.
- The wood of palisangre (*Brosimum rubescens*), palo azufre (*Symphonia globulifera*), and mahogany (*Swietenia macrophylla*) exhibit acoustic absorption properties suitable for the manufacture of backs and sides of chordophones.

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