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Variation of the Electrical Resistivity of Peruvian Tropical Woods

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Abstract

This study investigated the electrical resistivity of 105 timber species from the Peruvian tropical forest; with a focus on promoting sustainable use by considering the wood's equilibrium moisture content (EMC). Employing a non-destructive method, it correlated the wood's physical properties with its electrical resistivity, uncovering an inverse exponential relationship between resistivity and EMC, with resistivity values ranging from 0.0244 x 10^9 Ωm to 26.0104 x 10^9 Ωm across different cutting directions (longitudinal, tangential, and radial). These findings allowed for the classification of the woods into five groups based on their moisture balance and electrical resistivity, from very high to very low. This classification aids in identifying the appropriate and sustainable use of these timber species in various applications, highlighting the study's contribution to sustainable forest management.

Keywords: Balance, humidity, longitudinal, resistivity, timber species, transversal.

1. INTRODUCTION

In the Peruvian Amazon forests, a vast diversity of native timber species is identified, with 237 forest species recognized as commercially usable (MINAGRI, 2019). However, of this wide range, only a limited fraction is effectively exploited in the market. This selection is based on various factors such as the quality of the wood, market demand and the feasibility of its sustainable extraction. This selective approach to exploitation is highlighted in recent studies (Domínguez Liévano, 2022; Cabanillas-Pardo et al., 2023; Welling et al., 2023). The most common way to measure, the moisture content of wood is using its electrical properties (Aira-Zunzunegui et al., 2022).

Correlation of moisture content with electrical resistivity provides guidance for identifying the moisture content distribution of wood elements (Hafsa et al., 2023), that is, the functional relationship between electrical resistance and moisture content provides a solid basis for non-destructive measurements of moisture content (Welling et al., 2023). Therefore, the inverse relationship between moisture content and electrical resistance is the most used method and consists of introducing two electrodes into the wood and using a hygrometer to measure the moisture content based on its electrical resistance (Rosales-Solórzano, 2015; Hafsa et al., 2023).

It is important to study the conductivity of wood due to the possibilities of diverse applications that have to do with electricity. Knowing to what extent and under conditions wood behaves as an insulator defines its field of application. It is necessary to mention that the study of the resistivity that wood presents with respect to humidity is based on the operating principle of xylohygrometers (Fernández-Golfín Seco, 2010; Běťák et al ., 2023).

A crucial factor contributing to the increase in moisture-related electrical conductivity is the nature of the water contained in the wood. Non-potable water, loaded with elements such as mineral salts, chlorine, fluorine and others, can interact with the metabolites of wood, modifying its electrical resistance. These interactions can result in an increase or decrease in resistivity depending on the specific chemical composition of the water and its reaction with the wood components (Kwon et al., 2013).

It is important to note that wood contains secondary metabolites such as gums, latex and resins, which can alter its electrical properties. The presence of these compounds, together with the quality of the water absorbed, plays a significant role in the electrical conductivity of wood. Therefore, the type of water and its interaction with these metabolites must be considered when evaluating conductivity (Glass & Zelinka, 2010).

Wood is considered to be an insulator of electric current; this characteristic depends on factors, in order of priority, such as moisture content , electrolytic substances inside and the direction of the grain (Bär et al., 2019), also indicate that the moisture content (MC) of wood is the most important factor in relation to the resistance it offers to the passage of an electric current.

The electrical resistance of wood shows a direct relationship with the moisture content in the range of 5 to 30% (Běťák et al., 2023). Beyond this point, especially after the 30% threshold where fiber saturation is reached, the resistance tends to stabilize. In addition, an inverse variability with specific weight and greater resistance in the transverse direction compared to the longitudinal direction has been observed (Tuset & Duran, 1979; Glass & Zelinka, 2010).

Wood is considered to be in a dry state when its moisture content is in equilibrium with the ambient humidity and is generally defined as air dry with a moisture content of 12-20% depending on the regional climate (Kollmann, 1959). Although wood cannot be completely anhydrous due to its hygroscopicity, its electrical resistance under low humidity conditions is high enough to be classified as an insulator. Kollmann (1959) determined that, within the hygroscopic range, electrical resistance decreases logarithmically with increasing moisture content. This phenomenon continues until the wood reaches the saturation point of the fibers, a point at which the resistivity drops drastically, increasing its conductivity up to five times, as it approaches total saturation, which demonstrates the strong dependence of electrical resistance on the wood with respect to the presence of humidity (Glass & Zelinka, 2010).

The moisture content significantly influences the conductivity of wood, this being a predominant factor in electrical resistance (Glass & Zelinka, 2010). Although the species, density and morphology of the wood have appreciable effects on its ohmic resistance, these characteristics usually exert a variability that, although not negligible, turns out to be of comparable or smaller magnitude compared to the effects produced by humidity. It is relevant to mention that the internal surface of the wood also plays a role in its conductivity, but it is largely modulated by the presence of water in the cellular structure (Kollmann, 1959; Glass & Zelinka, 2010).

Therefore, detailed knowledge about the variations in electrical resistivity between different timber species can play a fundamental role in the accurate calibration of hygrometers, which in turn improves the accuracy in measuring the moisture content of specific species. Beyond technical precision, this information can promote more diversified forestry use. By valuing and exploiting a greater variety of timber species, pressure on the few currently exploited species can be reduced, thus promoting more balanced management of forest resources. This approach not only adds commercial value to lesser-known species, but also aligns logging practices with sustainability principles. Ultimately, this strategy contributes to the sustainable use of forests, balancing economic needs with ecosystem conservation.

The main objective of this study was to determine how the electrical resistivity of Peruvian tropical woods varies with the equilibrium moisture content and to classify them by groups for their sustainable use. This approach not only seeks a better economic valuation and understanding of species previously marginalized in forest exploitation, but actively integrates them into forest management plans. By diversifying primary products from Peru's tropical forests, this strategy could mitigate the negative environmental impact of overexploitation of preferred species, promoting a more balanced and responsible exploitation of timber resources.

2. MATERIALS AND METHODS

The indirect non-destructive method was used, taking advantage of the previously studied physical properties of the wood and correlating them with the electrical resistivity, which was calculated or estimated using demonstrated and validated mathematical equations (Dietsch et al., 2015; Luo et al ., 2019; Běťák et al., 2023).

Electrical resistance is the property of a material that opposes the passage of electric current and we can calculate it using the following formula (Kollmann, 1959; Fernández-Golfín Seco, 2010; Glass Zelinka, 2010).

$$R = \frac{rl}{S} \tag{1}$$

Where:

R = Electrical resistance (ohms)

r = Resistivity of the material (ohms×cm or ohms×m)

S = Section of the resistive element (cm^2 om ^{2})

l = Length of resistance element (cm^2 om ^{2})

Resistivity is designated by the lowercase letter r (r) and is measured in ohms per meter (Ω×m or Ω×cm).

$$r = \frac{RS}{l} \qquad (2)$$

Where:

R = is the resistance in ohms,

S = Cross section in cm²

l = Length in cm

The humidity of the wood is the factor that most influences its resistivity. Therefore, the electrical resistance of wood increases as the moisture content decreases (Xu et al., 2019). Therefore, Stamm (1927) arrived at the following relationship between resistivity and moisture content: For moisture < PSF.

$$\log r = c^{-ah} \text{ either} r = De^{-bh} \qquad (3)$$

Where:

a, b, c and D = Constants

Researchers during the 1930s to 1950s found accurate resistivity results at moisture ranges between 8-18% (Kollmann, 1959; Glass & Zelinka, 2010), but Rosales-Solórzano (2015) calculated that the equilibrium moisture content of wood varies between 9.81-18.34%. The equation is:

$$r = 1.78\text{x}10^{13}\, e^{-0.736\text{h}} \qquad (4)$$

Where:

r = Resistivity of the material (ohms×cm or ohms×m)

e = Epsilon

h = Equilibrium moisture content of wood (%)

Resistivity studies, which investigate the behavior of wood with respect to moisture, strongly support the effectiveness of modern resistance meters. Knowing the resistivity curve and humidity evolution, it will be enough to measure the resistivity to determine the humidity levels (Fernández-Golfín Seco, 2010; Běťák et al., 2023).

Although humidity is the dominant factor in the electrical resistance of wood, as established in previous studies, the influence that species, grain direction and density have on this property should not be underestimated (Glass & Zelinka, 2010). Density, in particular, affects resistivity so that it is greater in the longitudinal direction compared to the transverse direction (Vigonote Peña & Martínez Rojas, 2006). In a completely dry state and at room temperature, the electrical resistance of wood can be as high as 1 016 Ωm, but decreases to approximately 104 Ωm when the wood is saturated with moisture (Fernández-Golfín Seco, 2010). Therefore, although resistivity measurement is primarily used to determine moisture levels, interpretation of these values must be done considering the species and density of the wood for adequate accuracy.

Due to the peculiarity of its structure, wood does not present the same properties in its classic longitudinal, radial and tangential directions (Kollmann, 1959; Hwang et al., 2021). This is also confirmed by other researchers who state that the resistivity in the tangential direction is twice that in the longitudinal direction and, on the other hand, the resistivity in the radial direction is approximately 10% lower than in the tangential direction (Kollmann, 1959 ; Fernández-Golfín Seco, 2010; Glass & Zelinka, 2010; Hwang et al ., 2021).

$$r_t = 2r_1 \qquad (5)$$

$$r_r = \text{r}_t - 10\% r_t \qquad (6)$$

Where:

r_t= tangential resistivity

r_r= Radial resistivity

r_l= Longitudinal resistivity

It is important to know the characteristics of wood to use it in a responsible and balanced manner, so that we can meet our current needs without compromising the ability of future generations to meet their own needs, considering economic, social and environmental aspects (Yu et al., 2021).

Electrical conductivity is the ability of a material to conduct electric current. Physics defines it as the inverse of the resistance of an electrical circuit (Iglesias & Reis, 2021). Now Fernández-Golfín Seco (2010) mentions that conductivity is the study of the behavior of wood as a passive element of an electrical circuit.

Electrical resistance is the ability of wood to prevent the flow or oppose the passage of conductive electric current (Aira-Zunzunegui et al., 2022). Resistivity (r) is the specific electrical resistance or volumetric resistivity of each wood to oppose the passage of an electric current (Tuset & Duran, 1979; Glass & Zelinka, 2010).

Equilibrium moisture content (CHE). It is the moisture content that wood reaches when it is exposed to constant environmental conditions for an adequate time (Glass & Zelinka, 2010; Rosales-Solórzano, 2019). Knowledge of the electrical resistivity in the CHE of wood of various species is important for the development of applications of wood as an insulating or conductive material (Xu et al., 2019). Furthermore, today it is reiterated that the most common way to measure the moisture content (MC) of wood is using modern resistance sensors whose manipulation requires precision and skill (Dietsch et al., 2015; Běťák et al ., 2023).

2.1. Population and sample

In this study, 307 different species recorded for sawn wood production were identified. Of these, 200 species had complete technological studies, constituting the reference population for our research. Within this set, we focused specifically on Peruvian tropical species, selecting 105 different species that belong to five physical categories of wood and that have been the subject of previous physical studies (Meléndez Cárdenas & Valenzuela Andrade, 2017; Rosales-Solórzano, 2019). This selection of 105 species represents more than 50% of the initial population of 200 species, exceeding the minimum threshold of 10% required for scientific validity according to Coll -Serrano et al. (2022). This level of representativeness ensures the validity of the sample for analysis.

Furthermore, to evaluate the relationship between two quantitative variables in our study, the Correlation Coefficient (R) was considered. An R-value was considered significant if it was greater than or equal to 0.7 (positive) or less than or equal to -0.7 (negative), following the criteria established by Córdova-Zamora (2003) and Coll -Serrano et al. (2022). This measure will help us determine the strength and direction of the association between the variables under study.

2.2. Data collection techniques and instruments

The technique used to develop the research was divided into three stages:

First stage. Collection of technological information from wood physics publications by Rosales-Solórzano (2015, 2018, 2019) available in the National Library of Peru and Google Scholar.

Second stage. In order to estimate the electrical resistivity in the longitudinal direction of the wood of the 105 tropical forest species, a mathematical model was generated. This model is based on the basic density (DB) and equilibrium moisture content (CHE) values of each species. The model formulation is based on equation (8), adapted from the research of Stamm (1927), Fernández-Golfín Seco (2010), and Rosales-Solórzano (2019). The mathematical model (7) developed allows a precise estimation of the electrical resistivity, thus contributing to a better understanding of the physical properties of these timber species:

$$CHE = -4{,}141 \ln(DB)+9{,}8993 \qquad (7)$$

Where:

DB = Basic density of wood (g/cm^3 or kg/m^3)

CHE = Equilibrium moisture content of wood (%)

$$r = 1{,}78x1013\ e\ \text{-}0{,}736\ CHE \qquad (8)$$

Where:

e = Epsilon (2.7183)

r = Electrical resistivity of wood (Ω×m or Ω×cm)

To estimate the direction of the cross section in its tangential and radial section of the wood, equations (9 and 10) proposed by Stamm (1927), Kollmann (1959) and Glass & Zelinka (2010) were used:

$$rt = 2rl \qquad (9)$$

$$rr = rt - 10\%rt \qquad (10)$$

Where:

rt = Tangential resistivity (Ω×m or Ω×cm)

rr = Radial resistivity (Ω ×mo Ω ×cm)

rl = Longitudinal resistivity (Ω×m or Ω×cm)

Third stage. To classify the electrical resistivity of tropical woods according to their equilibrium moisture content, the methodology proposed by Arostegui Vargas (1982) and Rosales Solórzano (2018) was used, based on the basic density of the wood. This approach supports a more sustainable use of these species. It was structured by inserting the electrical resistivity values within each range of the five levels of basic density of wood (Arostegui Vargas, 1982) and within the five levels of equilibrium humidity (Rosales Solórzano, 2018). Finally, the groups were named with Roman numerals to differentiate them with their respective levels for location and classification (Table 1).

Table 1. Wood classification ranges according to moisture levels related to basic density to promote its sustainable use.

Classification by humidity groups		Equilibrium Moisture Content (CHE)	DB (g cm -3)
Group A	Very low (MB)	< 11.1	> 0.75
B Group	Low (B)	11.1 - 12	0.60 – 0.75
Group C	Medium (M)	12.01- 13.6	0.40 – 0.60
Group D	High (A)	13.61 – 14.8	0.30 – 0.40
Group E	Very high (MA)	> 14.8	< 0.30

Source: Rosales Solórzano (2018).

CHE = Equilibrium moisture content; DB = Basic density

2.3. Statistical analysis

To determine the statistical significance of the variability of electrical resistivity as a function of equilibrium moisture content, analysis of variance (ANOVA) was applied. This analysis was performed using statistical software. Package for the Social Sciences (SPSS) version 26 that facilitated the evaluation of the differences between the electrical resistivity groups identified in the third stage. With a confidence level of 95%.

3. RESULTS AND DISCUSSION

In Table 2, the analysis of variance (ANOVA) of the variability of the electrical resistivity of 105 forest species as a function of the equilibrium moisture content of the wood highlights that Fc > Ft (0.05), therefore, The null hypothesis is rejected at 95% statistical probability. This indicates that the electrical resistivity of Peruvian forest species versus the equilibrium moisture content of the wood to promote its sustainable use is different, corroborating what several authors (Kollmann, 1959; Tuset & Duran, 1979; Fernández-Golfín Seco, 2010; Glass & Zelinka, 2010) stipulate. Likewise, an exponential correlation coefficient is recorded ($R = 0.840$; $P < 0.05$), which shows that the relationship between electrical resistivity and the equilibrium moisture content of the wood is significantly adjusted, having a degree of association. High, confirming what Fernández-Golfín Seco (2010), Glass & Zelinka (2010), Xu et al. (2019) and Coll-Serrano et al. (2022) mention.

Table 2. Analysis of variance of electrical resistivity variability of 105 forest species as a function of the equilibrium moisture content of the wood.

Source of variation	Degrees of freedom	Sum of squares	mean squares	F c	F t (0.05)	Worth critic of F
Regression	1	473947427.93	473947427.93	245.95	3.09	4.76E-29
Waste	103	198483050.73	1927019.91			
Total	104	672430478.66				
R2 = 0.702		R = 0.840				

F = Fisher; Fc = Fisher calculate; Ft = Fisher tabulate.

The electrical resistivity of the wood was related exponentially and inversely to the equilibrium moisture content (CHE), according to equation 1 (Kollmann, 1959; Fernández-Golfín Seco, 2010; Glass & Zelinka, 2010; Rosales Solórzano, 2018), confirming what was stipulated by Luo et al. (2019) and Xu et al. (2019) (Figure 1). Therefore, for example, a very soft wood like *Ochroma pyramidale* (Cav. ex Lam.) Urb. (topa) with 18.34% CHE had 0.0244×10^9 Ω m of longitudinal resistivity, 0.0488×10^9 Ω m of tangential resistivity, and 0.0439×10^9 Ω m of radial resistivity of the wood, while a very hard wood like that of *Tabebuia billbergii* (Bureau & K. Schum.) Standl. (guayacan) with 9.81% CHE had 13.0052×10^9 Ω m of longitudinal resistivity, 26.0104 $\times10^9$ Ω m of tangential resistivity, and 23.4094×10^9 Ω m of radial resistivity of the wood. It is known that the electrical resistivity of wood is very sensitive to water absorption, dropping drastically as the CH increases in the wood (Hafsa et al., 2023), however, the results show a high variability of the CHE of the different species, leading to an exponential variation of the electrical resistivity of the forest species as shown by Kollmann (1959), Skaar (1988), Fernández-Golfín Seco (2010), Glass & Zelinka (2010) and Sotomayor Castellanos et al. (2022) in their studies.

Table 3 shows the classification of the electrical resistivity of wood by groups: while the equilibrium moisture content of forest species increases, its electrical resistivity decreases, this corroborates what was mentioned by Kollmann (1959), Vigonote Peña & Martínez Rojas (2006), Fernández-Golfín Seco (2010) and Glass & Zelinka (2010). This means that group IV softwoods or softwoods (*Spondias mombin* L. (ubus), *Macrolobium acaciifolium* (Benth.) Benth. (pashaco), etc.) and V (topa, lupuna , etc.) have low to very low electrical resistivity ($\leq 0.750\times10^9$ Ω m), therefore, they would not be suitable for use as current insulating material electrical. While hard or compact wood species such as group II (*Aspidosperma macrocarpon* Mart. (pumaquiro), *Copaifera officinalis* (Jacq.) L. (copaiba), etc.) and I (*Tabebuia* spp. (tahuari), *Dipteryx odorata* (Aubl.) Forsyth f. (shihuhuaco), etc.) have high to very high electrical resistivity ($> 2{,}580\times10^9$ Ω m), being suitable for use as a non-conductive or insulating material for electric current, thus reaffirming what was mentioned by Fernández-Golfín Seco (2010) and Hafsa et al. (2023). It is also observed that there are other species of group III where *Cedrela* is found. *Odorata* L. (cedar), *Cedrelinga cateniformis* (Ducke) Ducke (screw), *Ocotea quixos* (Lam.) *Kosterm*. (ishpingo), classified with medium electrical resistivity ($0.750–2.580\times10^9$

Ωm), which could also be used as an insulator for electrical installations within wooden furniture constructions (Aira-Zunzunegui et al., 2022). Additional file 1 shows the complete list of the classification of the 105 wood species.

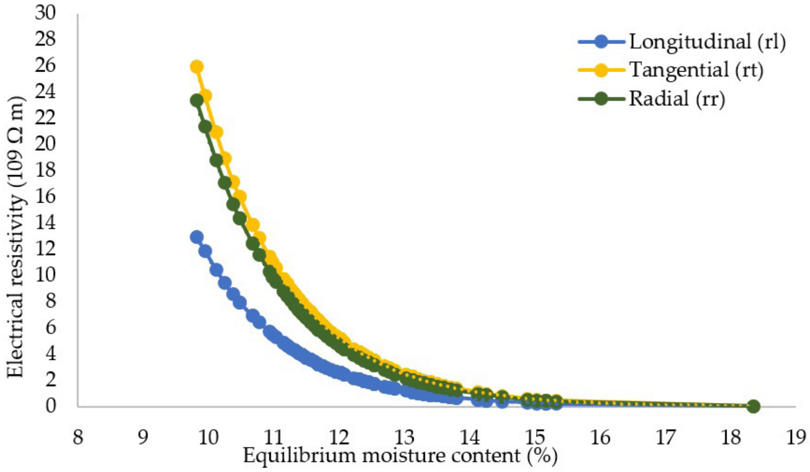

Figure 1. Longitudinal, tangential, and radial electrical resistivity versus equilibrium moisture content (CHE) of wood. Ω = Ohm; m = Meter.

Table 3. Classification of electrical resistivity of wood according to its moisture content balance to promote its sustainable use.

Classification by Electrical resistivity groups		Rank of CHE (%)	Amount of different woods	CHE average (%)	Resistivity range (10^9 Ω m)
Group I	Very high	< 11.1	6	10	≥ 4,890
Group II	high	11.11 - 12	13	12	2,580 – 4,890
Group III	Half	12.01- 13.6	41	13	0.750 – 2.580
Group IV	Low	13.61 – 14.8	32	14	0.312 – 0.750
Group V	Very low	> 14.8	13	16	≤ 0.312

CHE = Equilibrium moisture content

4. CONCLUSIONS

The study has shown that the electrical resistivity of Peruvian tropical woods is indeed related to their equilibrium moisture content. Significant variations in electrical resistivity were observed between longitudinal, tangential, and radial cutting directions, allowing accurate classification of woods into electrical resistivity groups based on their moisture content. With these results, the variation of electrical resistivity as a function of moisture content has been determined, providing a solid basis for the sustainable use of these woods. The creation of a database classified by groups of electrical resistivity (very high, high, medium, low and very low) facilitates the identification of the most appropriate use of each species, thus promoting sustainable practices in forest management. This approach not only contributes to the conservation of forest resources, but also opens new possibilities for the economic valorization and diversification of the use of Peruvian tropical timber species.

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SUPPLEMENTARY MATERIAL

The following online material is available for this article:
Additional file 1. Basic density, equilibrium moisture content, electrical resistivity and classification by electrical resistivity groups of wood from 105 forest species.

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