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VERTICAL AND RADIAL VARIATION IN WOOD ACOUSTICAL AND PHYSICAL PROPERTIES OF *Ailanthus altissima*

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ABSTRACT

This study investigated the vertical and radial variability of wood acoustical and physical properties in *Ailanthus altissima* (ailanthus tree), a species with potential applications in musical instrument construction. However, there is limited information about the variation within the stem in these properties, which is essential for assessing its suitability in acoustically demanding applications. In this context, wood density, dynamic modulus of elasticity, damping coefficient, acoustic conversion efficiency, and tangential and radial shrinkage were analyzed across three stem heights and three radial positions. Results revealed significant variation within the stem, with density and dynamic modulus of elasticity increasing from the base to the middle before declining at the top, while acoustic conversion efficiency showed an inverse trend. Radially, acoustic conversion efficiency was highest near the pith and decreased significantly toward the middle and outer parts of the stem, with no significant difference between these outer zones. The damping coefficient was lowest at the bottom logs, increased significantly at the middle, and slightly decreased at the top. Radially, the damping coefficient was lowest near the pith, increased toward the middle, and reached the highest values near the bark. Shrinkage increased significantly from pith to bark but showed minor axial variation, with similar values at the base and middle, and a significant decrease at the top of the stem. Importantly, density could be used as an indicator for acoustic conversion efficiency, enabling indirect assessment of acoustic performance. These variations highlight the potential of selecting specific stem regions to balance sound transmission and structural support, suggesting that *Ailanthus altissima* (ailanthus tree) could replace traditional woods for the backs and sides of stringed instruments.

Keywords:, *Ailanthus altissima,* wood acoustics, vibration damping, acoustic properties, mechanical properties of wood, radial and axial variation, musical instrument wood

INTRODUCTION

Ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) is a native genus from China and belongs to the family Simaroubaceae (Miller 1990, Panayotov *et al.* 2011). This species is commonly known as the tree of heaven (Ferreira *et al.* 2013, Panayotov *et al.* 2011) and may reach a height of 30 m (Hu 1979). This species is allelopathic (Heisey 1997) and has a wide global distribution mainly in the U.S.A., Europe, and North Africa (Enescu *et al.* 2016). This tree is considered an invasive species in many regions (Sladonja *et al.* 2015). The tree of heaven wood is easy to work with tools and is mainly used for pulp and paper, fuel, particleboard, cabinetwork, musical instruments, and turnery (Ferreira *et al.* 2013, Sladonja *et al.* 2015).

Both density and modulus of elasticity are essential factors in judging the quality of wood and are used in lumber grading (Barnett and Jeronimidis 2009) as well as in evaluating the structural integrity and safety of

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trees, which is important for assessing the risk of a tree failing (Vojáčková *et al.* 2021); therefore, knowing both values is a good indicator of wood quality. Although the classical (destructive) methods for determining both values are still used today, there are many other methods based on non-destructive testing that have proved their reliability for assessing both quality indicators. These nondestructive techniques permit the assessment of wood while retaining the material's integrity, hence aiding in conservation and resource evaluation (Arriaga *et al.* 2023). They include methods for assessing mechanical behavior, such as longitudinal resonance, flexural vibration, time of flight (stress waves), and ultrasound (Horáček *et al.* 2012, Hassan *et al.* 2013, Hassan and Tippner 2019, Shi *et al.* 2025), while others are semi-destructive but are used for in-place density evaluations such as Pilodyn 6J and Resistograph (Kloiber *et al.* 2014). Wood species selection is an important aspect in designing musical instruments. In general, several vibrational properties that are evaluated non-destructively could be used to assess woods for their suitability in musical instrument manufacturing such as specific dynamic elastic modulus, damping characteristics, radiation ratio, and acoustic conversion efficiency (Wegst 2006).

Generally, wood properties variability can be found among tree genera and within the single stem of the same species. These patterns of variation depend greatly on the species, habitat type, growth conditions, and geographical location (Zobel and Buitjeenen 1989, Hassan 2020). These variations also exist between the branch and the trunk of the trees (Hassan *et al.* 2020). Accordingly, knowing the patterns of difference in wood properties within trees is essential when converting them into final products and in tree breeding programs (Zobel and Buitjeenen 1989).

Most of the research on the variability within the stems of various species is focused on anatomical features, physical characteristics, chemical constituents, and classical mechanical properties (Hudson *et al.* 1998, Lachenbruch *et al.* 2011, Machado *et al.* 2014, Hassan 2020); however, in the literature, little is known about the vibrational properties variation trends within stems (Roohnia *et al.* 2011). A significant unresolved issue in the literature is how axial and radial positions within a tree stem affect the physical and acoustical properties important for making musical instruments. Since ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) wood is used for musical instrument manufacturing, it is therefore the acoustical and dynamic properties variations within the stem that should be well documented in the literature.

A detailed understanding of this variation is crucial for optimizing wood choices for musical instruments, where specific acoustic properties are desired. Additionally, knowledge of the vibro-acoustic properties of wood and their distribution within the stem is also important from a tree-safety assessment point of view. The vertical (apical) variation is of particular interest because wood formed at different heights in the stem is subjected to varying growth rates, which may affect characteristics such as density and anatomical structure, ultimately affecting the acoustic and dynamic mechanical properties. Moreover, apical variation can be influenced by several factors, including mechanical stresses and gravitational loads. Understanding these variations is not only important for evaluating wood quality but also has practical implications for tree risk assessment. This approach is essential for determining any risks or hazards that may be connected to the tree, particularly in locations where trees are close to buildings or human activity (Cristini *et al.* 2021). Until now, there are no reports that have discussed the wood vibrational properties variations from pith to bark or from the base toward top within the ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) stem. Only one report discussed the anatomical variation within another species of iron wood (*Acacia excelsa* Benth.) (Mohammed and Nasroun 2012). Therefore, to fill this gap in the literature, this study aimed to examine the effect of different radial and vertical positions and their interaction within ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) stems on wood acoustical and physical properties.

Materials and methods

Three ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) trees grown in Alexandria, Egypt were cut at 25 cm above ground level, free from any visible mechanical defects and biological infections. The growth characteristics of the three trees are presented in Table 1.

Table 1: Mean values of some growth characteristics of ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) trees used in this study.

Tree number	DBH (cm)	Total tree height (m)
No. 1	51,91	9,5
No. 2	55,73	10,3
No. 3	47,77	11,0

DBH is the diameter at breast height outside bark.

To analyze vertical variability, the merchantable stems were sequentially divided into three distinct sections along the height of the stem, beginning 25 cm above ground level. These sections are designated as L_1 (from the base to 35 % of the stem's height), L_2 (from 35 % to 75 %), and L_3 (above 75 % of the stem's height). Likewise, for radial variation examination, three sampling positions were selected from the pith towards the bark: D_1 (from the pith to 35 % of the stem's radius), D_2 (from 35 % to 75 %), and D_3 (above 75 % of the stem's radius).

For each selected section (L_1, L_2, and L_3), discs were extracted and subdivided into four quarters, as illustrated in Figure 1. The properties under consideration were measured for each quarter, and the values were then averaged to represent the radial position from pith to bark (D_1, D_2, and D_3). This methodology resulted in a comprehensive dataset, encompassing a total of 180 specimens for each tested property (e.g., L_1D_1, L_1D_2, L_1D_3, and so on). It is important to note that statistical analysis indicated no significant variations among the three trees, consequently, discs were uniformly taken from all three trees to accurately represent each property under consideration.

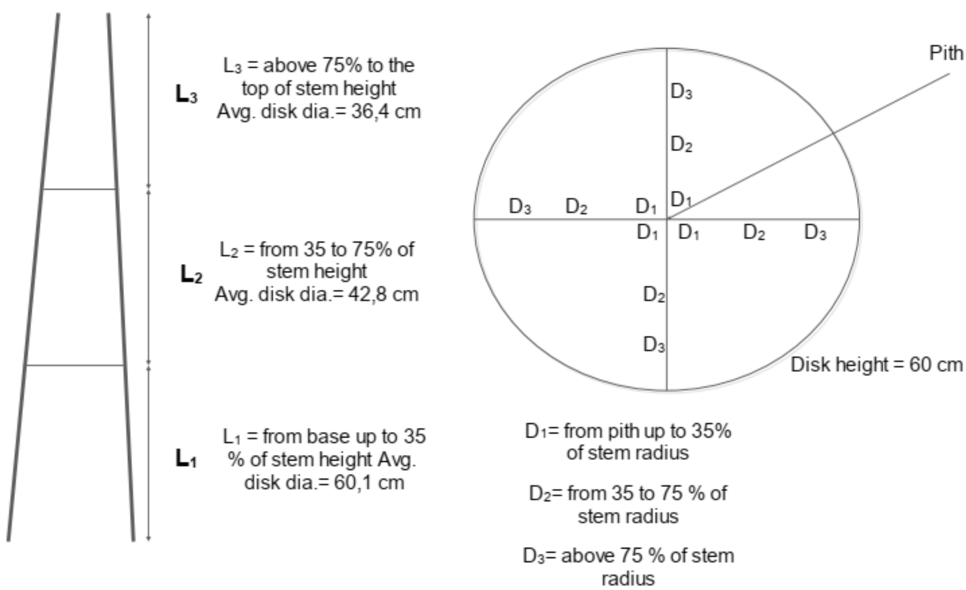

Figure 1: Vertical and radial stem sampling procedure.

Density and vibrational properties assessment

Before testing, the moisture content inside the wood samples was controlled to be 12 % under fixed temperature and relative humidity conditions. Density was determined following the International Organization for Standardization, ISO 13061-2 (2014). The dynamic elastic modulus in the longitudinal direction was evaluated on short rectangular beams with a dimension of 20 mm x 20 mm x 500 mm (R x T x L) and calculated using Equation 1. A small steel hammer was used to tap the beam's end and the longitudinal vibration signal was received from the other end and analyzed using a Fast Fourier Transformation (FFT) (Fakopp Enterprise Bt., Ágfalva, Hungary).

$$E_d = (2Lf)^2 \rho \qquad (1)$$

Where E_d (Pa) is the dynamic modulus of elasticity, L (m) is the specimen's length, f (Hz) is the longitudinal resonance frequency, and ρ (kg/m^3) is the wood density.

The damping coefficient (*Tan δ*) in longitudinal mode-shapes was determined by measuring the logarithmic decrement (*LD*) of two successive peaks in the time domain extracted from the measured FFT spectrum (Fakopp Enterprise Bt., Ágfalva, Hungary) and calculated using Equation 2 (Brémaud 2012). The acoustic conversion efficiency, *ACE*, ($m^4 \cdot kg^{-1} \cdot s^{-1}$) was calculated according to Equation 3 (Brémaud *et al.* 2012, Hassan and Tippner 2019).

$$Tan\ \delta = \frac{LD}{\pi} \qquad (2)$$

$$ACE = \frac{\sqrt{E_d / \rho^3}}{tan\delta} \qquad (3)$$

Dimensional stability determination

The shrinkage values in the tangential (β_T) and radial (β_R) directions were calculated from green to oven-dried state according to the International Organization for Standardization, ISO 3061-13 (2016).

Statistical analyses

Two-way analysis of variance followed by Fisher's least significant test (F_{LSD}) was used to detect the effect of the three vertical and radial positions on the tested vibrational and physical properties of ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) wood at 0,05 level of significance. Pearson's correlation analysis was used to examine the strength of the relationships among the density and E_d and the vibrational properties.

RESULTS AND DISCUSSION

The results for each wood property have been tested by analysis of variance (ANOVA) and presented in Table 2.

Table 2: Summary of ANOVA for the effect of height, radial positions from pith to bark, and their interaction.

Source of variation	d.f.	F-value					
		Density	E_d	Tan δ	ACE	β_T	B_R
Vertical Level (VL)	2	95,31*	254,9*	28,30*	36,64*	101,71*	255,6*
Radial Position (RP)	2	53,26*	140,6*	8,41*	17,99*	152,4*	216,1*
VL X RP	4	1,28^{NS}	3,78*	3,15*	5,20*	0,29^{NS}	1,72^{NS}

NS not significant; * Significant at 0,05 level; *Tan δ* is damping coefficient; β_T and β_R are tangential and radial shrinkage, respectively.

The mean values of density at the three radial and axial positions within the ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) stems are presented in Table 3. In general, knowing the wood density is important for strength and biomass predictions (Repola 2006).

Table 3: Density variation within ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) stem.

Longitudinal position	Radial position			Overall mean
	D_1	D_2	D_3	
L_1	516,72±27,3^{de}	565,8 ±23,2^{b}	530,41±19,7^{cd}	537,64^{A}
L_2	546,65±29,9^{c}	603,46±39,9^{a}	564,97±21,7^{b}	571,69^{B}
L_3	472,2±44,3^{f}	523,76±30,2^{de}	507,84±25,9^{e}	501,26^{C}
Overall mean	511,85^{X}	564,3^{Y}	534,4^{Z}	

Values in kg/m³; Lowercase letters (a, b, c, d, e, f) indicate significant differences within each column (D_1, D_2, D_3) and within each row (L_1, L_2, L_3). Uppercase letters (A, B, C) denote significant differences among overall mean values for longitudinal positions (L_1, L_2, L_3), while (X, Y, Z) denote significant differences for radial positions (D_1, D_2, D_3); ($p < 0,05$).

The analysis of variance showed that both vertical and radial sampling positions significantly affected the density values within the stem (Table 2), while their interaction was not significant ($P > 0,05$). This indicates that density varied independently along the radial and longitudinal axes of the stem. Similarly, Kiaei and Farsi (2016) found that both radial and vertical positions significantly influenced density in mimosa tree (*Albizzia julibrissin* (Durazz.) Willd.) with no significant interaction between them. The density increased radially from D_1 (from pith to 35 % of stem radius) to D_2 (from 35 to 75 % of stem radius) then decreased at D_3 (above 75 % of stem radius); however, the density at the D_3 position was still higher than that measured at D_1. Some studies have reported an increase in the density values from pith to bark within the stems of some tree species, for example, in pilón (*Hieronyma alchorneoides* L.) and white mahogany (*Vochysia guatemalensis* J.D. Smith) (Butterfield *et al.* 1993); lampong (*Shorea leprosula* Miq.) and white lauan (*Shorea parvifolia* Dyer) (Bosman *et al.* 1994); and canadian poplar (*Populus euramericana*) (Kord *et al.* 2010).

An inconsistent trend of wood density variation from pith to bark within bootlace tree (*Eperua falcata* Aubl.) and wapa (*Eperua grandiflora* (Aubl.) Benth.) stems was observed by McLean *et al.* (2011). In another study, Machado *et al.* (2014) reported that there was an increase from 10 % to 50 % in radial position from the pith, then a relative stabilization was observed in up to 90 % of stem radius in blackwood (*Acacia melanoxylon* R.Br.)

Data presented in Table 3 showed that density increased axially from L_1 (from base to 35 % of stem height) to L_2 (from 35 % to 75 % of stem height) then a significant decrease was observed at L_3 (above 75 % of stem height). Some studies have reported that the density values decreased from the base toward the top, for example, in canadian poplar (*Populus euramericana*) (Kord *et al.* 2010); spanish elm (*Cordia alliodora* (Ruiz & Pav.) Oken) and rain tree (*Samanea saman* (Jacq.) Merr.) (Tenorio *et al.* 2016); ironwood (*Casuarina equistifolia* L.) (Chowdhury *et al.* 2007); oriental beech (*Fagus orientalis* Lipsky) (Topaloglu and Erisir 2018); and silver birch (*Betula pendula* Roth) (Repola 2006). Other studies have recorded an increase in wood density from base to top in some tree species, such as in blackwood (*Acacia melanoxylon* R.Br.), especially from 35 % to 65 % of stem height (Machado *et al.* 2014).

In contrast, in a study performed by Githiomi and Kariuki (2010) on rose gum (*Eucalyptus grandis* W.Hill), the researchers found a decrease in density from the base to the breast height followed by an increase up to 60 % of stem height, then a decrease to 80 % of stem height. Within the blue gum (*Eucalyptus globulus* Labill.) stem, Miranda *et al.* (2015) found that the density decreased from the base to breast height followed by a gradual increase to 11,3 m then a slight decrease was observed. Generally, the main reason for density variation within a single stem or among stems of different tree species is the cell wall thickness and the percentage of thick-walled cells such as fibers (Panshin and De Zeeuw 1980; Bosman *et al.* 1994). Furthermore, the wood density could be controlled through some silvicultural practices such as adequate pruning, thinning, and tree spacing (Zobel and Buitjeenen 1989).

For the dynamic modulus of elasticity (E_d), the analysis of variance indicated that the vertical positions, radial positions, and their interaction had a significant effect on E_d. In the current study, the trend of E_d variation within the stems was similar to that found with wood density, where the E_d increased from D_1 to D_2 then a significant decrease was observed at D_3; however, *Ed* at D_3 remained higher than at D_1 (Table 4).

Table 4: Dynamic modulus of elasticity (E_d) within ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) stem.

Longitudinal position	Radial position			Overall mean
	D_1	D_2	D_3	
L_1	10861,3±637,1^e	12541,4±483,1^b	11772,9±489,1^d	11725,2^A
L_2	12169,9±534,9^c	13494,7±436,4^a	12410,1±718,7^{bc}	12691,5^B
L_3	9432±624,9^g	11534±635,9^d	10190,7±417,3^f	10385,5^C
Overall mean	10821^X	12523,3^Y	11457,9^Z	

Values in $N.mm^{-2}$; Lowercase letters (a, b, c, d, e, f) indicate significant differences within each column (D_1, D_2, D_3) and within each row (L_1, L_2, L_3). Uppercase letters (A, B, C) denote significant differences among overall mean values for longitudinal positions (L_1, L_2, L_3), while (X, Y, Z) denote significant differences for radial positions (D_1, D_2, D_3); ($p < 0,05$).

These results observed across all studied heights, were consistent with the findings of Machado *et al.* (2014) on blackwood (*Acacia melanoxylon* R.Br.), who found that the modulus of elasticity values increased from 10 % to 50 % of the radial distance from pith then decreased up to 90 % radial position.

For the vertical variation, there was a significant increase in the E_d from L_1 to L_2 then a significant decrease at L_3. The highest values of E_d were recorded at L_2 sampling height (12691,5 $N \cdot mm^{-2}$) and the lowest values were recorded at the L_3 position (10385,5 $N \cdot mm^{-2}$). Some studies have reported an increase in modulus of elasticity from the base to the top, as observed in mimosa tree (*Albizzia julibrissin* (Durazz.) Willd.) trees (Kiaei and Farsi 2016). Conversely, other studies have indicated a decrease in modulus of elasticity from the base to the top. For example, in cadamba (*Neolamarckia cadamba* (Roxb.) Bosser), the highest values were found at the base and the lowest at the top, with insignificant variation between the base and the middle logs (Mahmud *et al.* 2017).

Although most of the previous studies and the current study indicated that the modulus of elasticity values varied at different heights within the stems of various tree species, in a study on blackwood (*Acacia melanoxylon* R.Br.) the MOE did not vary significantly with stem height (Machado *et al.* 2014).

As shown in Table 5 revealed that the damping coefficient (*Tan δ*) from pith to bark ranged from 0,0069 to 0,0076, and from base to top the *Tan δ* ranged from 0,0066 to 0,0079. The statistical analysis revealed that the sampling heights and the radial positions from pith to bark, and the interaction between them, had a significant effect on *Tan δ* (Table 2). The F_{LSD} statistical test indicated that *Tan δ* at D_1 varied significantly from D_2 and D_3 where the lowest values of damping were observed near pith at D_1. For the axial variation, the *Tan δ* values varied significantly among the three sampling heights, increasing significantly from L_1 to L_2 before decreasing at L_3. Generally, wood as a raw material has a low damping coefficient compared with many other building materials (Wegst 2006). For example, from a musical acoustics point of view, a low damping coefficient is preferred in the soundboard of stringed musical instruments (Wegst 2006), while higher damping coefficient woods are suitable for the back and sides of stringed musical instruments (Hassan and Tippner 2019).

The results of the current study revealed that the low damping coefficient was observed in the inner part near the pith (D_1) and the base logs (L_1).

Table 5: Damping coefficient (*Tan δ*) variation within ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) stem.

Longitudinal position	Radial position			Overall mean
	D_1	D_2	D_3	
L_1	0,0067±0,0009^c	0,0068±0,0009^c	0,0065±0,001^c	0,0066^A
L_2	0,0075±0,0013^b	0,0078±0,0008^b	0,0085±0,0012^a	0,0079^B
L_3	0,0066±0,0008^c	0,0075±0,0008^b	0,0079±0,0006^{ab}	0,0073^C
Overall mean	0,0069^X	0,0074^Y	0,0076^Z	-

Lowercase letters (a, b, c, d, e, f) indicate significant differences within each column (D_1, D_2, D_3) and within each row (L_1, L_2, L_3). Uppercase letters (A, B, C) denote significant differences among overall mean values for longitudinal positions (L_1, L_2, L_3), while (X, Y, Z) denote significant differences for radial positions (D_1, D_2, D_3); ($p < 0{,}05$).

Table 6 shows the mean values of acoustic conversion efficiency (*ACE*) and their variations within the ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) stem. The range of vertical and radial *ACE* was found to be 1043,8-1304,8 $m^4 \cdot kg^{-1} \cdot s^{-1}$ and 1141-1303,1 $m^4 \cdot kg^{-1} \cdot s^{-1}$, respectively. The analysis of variance indicated that the radial and axial positions had a significant effect on the *ACE*, and their interaction also showed a significant influence (Table 2). The highest axial *ACE* values were observed at (L_1). Radially, the *ACE* at D_1 had the highest values and significantly varied from D_2 and D_3.

In general, *ACE* is an important acoustical parameter for wood selection for musical instruments that combines the internal damping and acoustic constant (Hassan and Tippner 2019). High *ACE* is essential for a high-quality soundboard for stringed instruments.

Table 6: Acoustic conversion efficiency (*ACE*) variation within ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) stem.

Longitudinal position	Radial position			Overall mean
	D_1	D_2	D_3	
L_1	1324,3±154,5^{bc}	1223,7±160,6^{cd}	1366,5±191,1^{ab}	1304,8^A
L_2	1150,9±198,7^b	1004,7±115,3^f	975,9±160^f	1043,8^B
L_3	1434,1±197,4^a	1194,6±192,6^{de}	1116,6±147^e	1248,4^A
Overall mean	1303,1^X	1141^Z	1153^Z	-

Values in $m^4 \cdot$kg-1·s−1; Lowercase letters (a, b, c, d, e, f) indicate significant differences within each column (D_1, D_2, D_3) and within each row (L_1, L_2, L_3). Uppercase letters (A, B, C) denote significant differences among overall mean values for longitudinal positions (L_1, L_2, L_3), while (X, Y, Z) denote significant differences for radial positions (D_1, D_2, D_3); ($p < 0{,}05$).

The mean values of tangential (β_T) and radial (β_R) shrinkage across the three radial and axial positions within the stem are presented in Table 7 and Table 8.

The analyses of variance of both shrinkage properties indicated that both the radial and axial positions had a significant effect on β_T and β_R properties, while their interaction had an insignificant effect (Table 2). The presented data indicated that the tangential shrinkage (β_T) is greater than the radial shrinkage (β_R). Generally, the variation in wood shrinkage is mainly attributed to the microfibril angle in the thickest layer of the wood cell wall (S_2) and the microstructure (Koponen *et al.* 1989).

Table 7: Tangential shrinkage (β_T) within ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) stem.

Longitudinal position	Radial position			Overall mean
	D_1	D_2	D_3	
L_1	10,25±0,56D	11,15±0,41B	12,11±0,40A	$11,17^{A}$
L_2	10,28±0,67D	11,21±0,47B	12,18±0,42A	$11,22^{A}$
L_3	9,04±0,72E	9,98±0,70D	10,73±0,54C	$9,92^{B}$
Overall mean	$9,86^{X}$	$10,78^{Y}$	$11,67^{Z}$	-

Values in (%); Lowercase letters (a, b, c, d, e, f) indicate significant differences within each column (D_1, D_2, D_3) and within each row (L_1, L_2, L_3). Uppercase letters (A, B, C) denote significant differences among overall mean values for longitudinal positions (L_1, L_2, L_3), while (X, Y, Z) denote significant differences for radial positions (D_1, D_2, D_3); ($p < 0,05$).

Table 8: Radial shrinkage (β_R) within ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) stem.

Longitudinal position	Radial position			Overall mean
	D_1	D_2	D_3	
L_1	6,48±0,36c	7,51±0,38b	8,06±0,73a	$7,35^{A}$
L_2	6,52±0,36c	7,57±0,39b	8,24±0,42a	$7,44^{A}$
L_3	5,27±0,22e	5,94±0,32d	6,60±0,30c	$5,94^{B}$
Overall mean	$6,09^{X}$	$7,01^{Y}$	$7,63^{Z}$	-

Values in (%); Lowercase letters (a, b, c, d, e, f) indicate significant differences within each column (D_1, D_2, D_3) and within each row (L_1, L_2, L_3). Uppercase letters (A, B, C) denote significant differences among overall mean values for longitudinal positions (L_1, L_2, L_3), while (X, Y, Z) denote significant differences for radial positions (D_1, D_2, D_3); ($p < 0,05$).

It is obvious from Table 7 and Table 8 that the tangential (β_T) and radial (β_R) shrinkage increased significantly from pith to bark. Concerning the radial variation, some studies have reported an increase in shrinkage from pith to bark, for example, in australian pine (*Casuarina equisetifolia* L.) (Chowdhury *et al.* 2007); canadian poplar (*Populus euramericana*) (Kord *et al.* 2010); and teak (*Tectona grandis* L.) (Izekor and Fuwape 2011). Other studies have reported a decreasing trend from pith to bark, for instance, radial and tangential shrinkage in tauria (*Cariniana micrantha* Ducke) (Cruz *et al.* 2019) and at the stem base of sugi (*Cryptomeria japonica* (Thunb. ex L.f.) D.Don) (Yamashita *et al.* 2009).

For the axial variations in β_T and β_R, there was no statistical variation between L_1 and L_2, while L_3 had the lowest values and significantly varied from L_1 and L_2. Some studies found in the literature reported a decrease in shrinkage characteristics from the base to the top of several tree species, for example, in canadian poplar (*Populus euramericana*) (Kord *et al.* 2010); cadamba (*Neolamarckia cadamba* (Roxb.) Bosser) (Mahmud *et al.* 2017); and oriental beech (*Fagus orientalis* Lipsky) (Topaloglu and Erisir 2018). In contrast, some studies reported an increase in shrinkage from base to top, for instance, tangential shrinkage in australian pine (*Casuarina equisetifolia* L.), while the radial shrinkage was not affected by height levels (Chowdhury *et al.* 2007), and in teak (*Tectona grandis* L.) (Izekor and Fuwape 2011).

Relationships among density, dynamic Young's modulus, and the acoustical characteristics

The current study evaluated the density, E_d, and the most important acoustical properties of ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) wood; thus, the relationships among these properties are important for the quality of this wood from a musical acoustics point of view.

The relationships among density, E_d, *Tan δ*, and *ACE* are discussed and shown in Figure 2, Figure 3, Figure 4, Figure 5.

Figure 2 shows that there was no obvious relationship between the density and *Tan δ,* and this relationship is not statistically significant. This lack of relationship may be due to the fact that *Tan δ* is affected by other factors, not just density alone such as wood anatomical features and chemical constituents of cell wall could have a more significant impact on *Tan δ*, constructing the direct association with density to be unclear. These results were in agreement with a study performed by Sidan *et al.* (2010) on *Paulownia*; they found an independent association between the two parameters. In contrast to the findings of the current study, this relationship was found to be moderate and negative (r= -0,64) in barwood (*Pterocarpus erinaceus* Poir.) wood grown in Mali (Traoré *et al.* 2010). This indicating that the strength of this relationship may vary depending on the wood species.

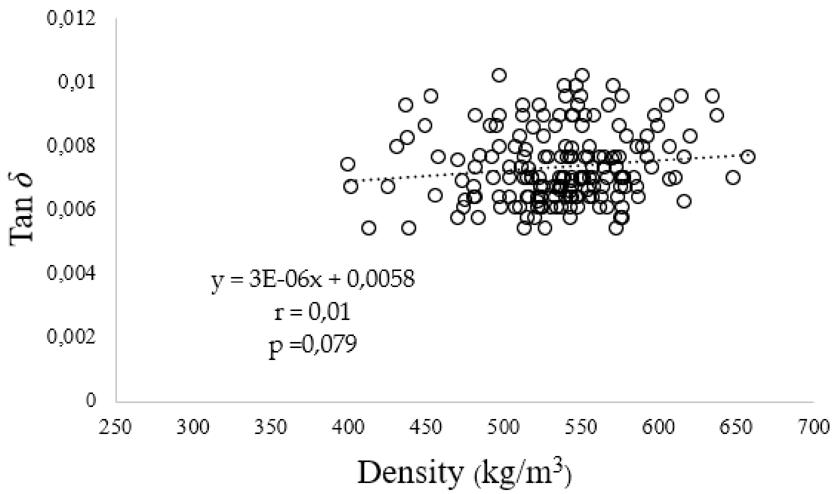

Figure 2: Relationship between density and *Tan δ*.

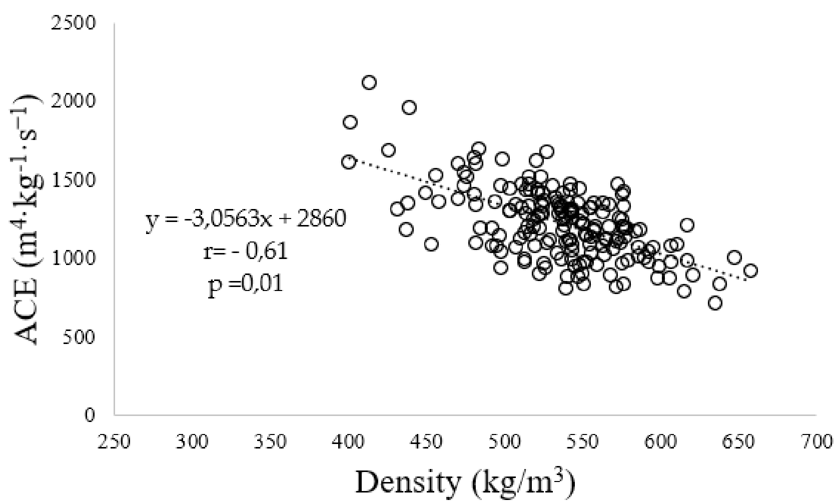

Figure 3: Relationship between density and *ACE*.

Figure 3 shows a strong negative linear relationship (r= -0,61) between density and *ACE*. These results were in agreement with Brémaud (2012) who found a moderate negative relationship with R^2= -0,32 between both parameters. In contrast to this result, Traoré *et al.* (2010) found this relationship to be moderate and positive in barwood (*Pterocarpus erinaceus* Poir.) wood.

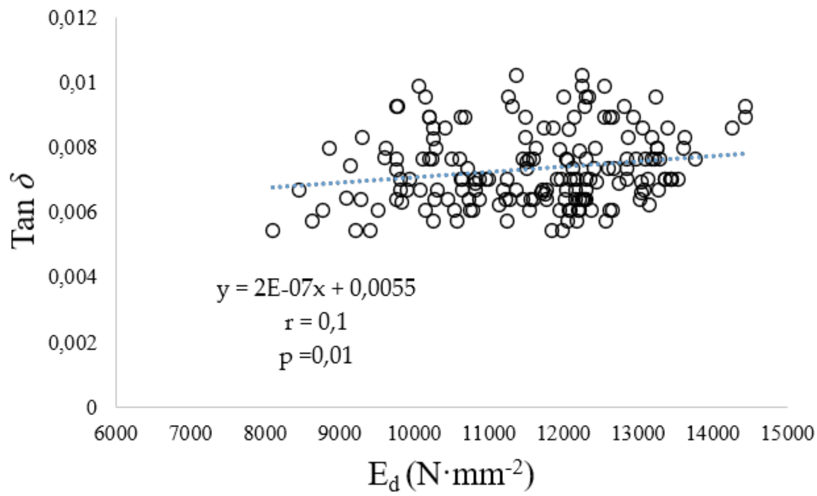

Figure 4: Relationship between E_d and *Tan δ*.

Furthermore, Figure 4 shows an independent association between the E_d and *Tan δ,* while Figure 5 presents a weak to moderate negative correlation between the E_d and *ACE* (r= -0,32). In contrast to the findings of this study, in barwood (*Pterocarpus erinaceus* Poir.) wood a strong negative relationship (r=-0,84) was found between E_d and *Tan δ,* while a strong positive relationship was observed between E_d and *ACE* (r= 0,77) (Traoré *et al.* 2010). Based on the presented results, the wood density could be used for the prediction of *ACE* values.

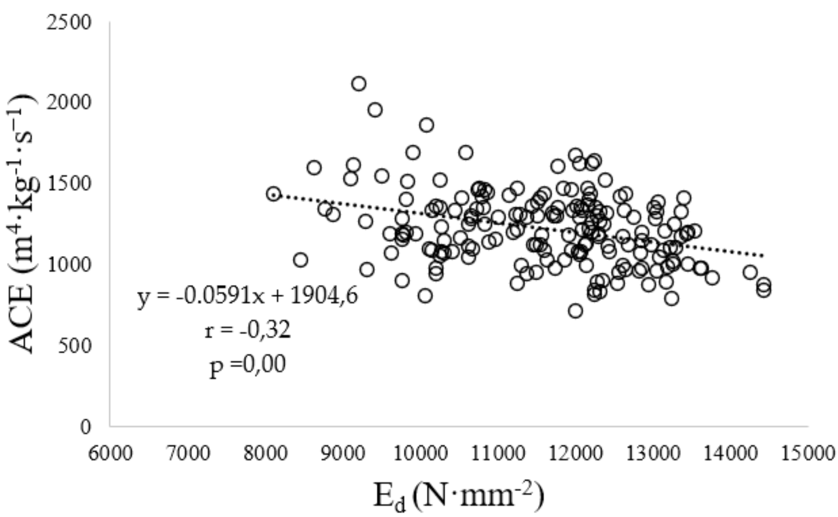

Figure 5: Relationship between E_d and *ACE*.

The results from this study suggest that specific stem regions of ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) could be selected for different components of musical instruments. Following the selection criteria outlined by Wegst (2006), ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) is more suitable for the backs and ribs of stringed instruments rather than soundboards. In general, woods used for soundboards require high specific Young's modulus, high ACE, and low damping, whereas woods for backs and ribs typically exhibit higher damping and lower ACE (Wegst 2006, Brémaud 2012). Traditionally, spruce and cypress are used for soundboards because of their high specific Young's modulus, low density, and low damping, while European maple, khaya wood (*African mahogany*), and Indian and Brazilian rosewoods are commonly used for backs and sides (Haines 1979, Wegst 2006, Hassan and Tippner 2019).

For comparison purposes with acoustical data presented by Carlier *et al.* (2018) on spruce and maple, the average density of ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) (536,9 kg/m³) is closer to that of maple (600 kg/m³), a traditional wood for backs and ribs, than to spruce (approx. 420 kg/m³), the standard for soundboards. Its average damping coefficient (0,0073) is slightly higher than spruce (0,007) but lower than maple (0,01), indicating a moderate capacity for vibration absorption, which is desirable for controlling resonance in backs and sides. Furthermore, its *ACE* (1199 $m^4 \cdot kg^{-1} \cdot s^{-1}$) is substantially lower than that of spruce (1938 $m^4 \cdot kg^{-1} \cdot s^{-1}$) but significantly higher than maple (598 $m^4 \cdot kg^{-1} \cdot s^{-1}$). This positions ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) as an intermediate material that can offer a balance between resonance and damping. When compared to other woods like African mahogany (Khaya) and Indian rosewood (*Dalbergia latifolia* Roxb.) (Haines 1979), ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) exhibits comparable or favorable properties for back and rib applications. The specific Young's modulus is (21,6) also aligns it more with hardwoods used for these components (Haines 1979).

While the overall properties point towards use in backs and ribs, the study also highlights those specific sections, such as those from the inner radial (D_1) and lower/upper axial (L_1/L_3) positions, exhibit higher *ACE* and lower damping, potentially warranting investigation for alternative uses, perhaps even specialized soundboard applications if other criteria can be met. The strong negative correlation between density and *ACE* suggests that selecting lower-density portions of ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) could yield better acoustic efficiency. The increasing scarcity of traditional tonewoods due to overexploitation and conservation efforts necessitates the exploration of alternative, sustainable wood sources. Ailanthus altissima, often considered an invasive species, could represent such an alternative if its properties are well understood and appropriately matched to application requirements. This study provides a foundational dataset for luthiers and researchers to evaluate its potential. The significant intra-stem variability, however, underscores the importance of careful selection of wood from specific locations within the tree to achieve desired acoustic and mechanical performance. Future research should focus on the anisotropic acoustic behavior, long-term stability, and workability of ailanthus tree (*Ailanthus altissima* (Mill.) Swingle), as well as its performance in completed musical instruments.

CONCLUSIONS

The study investigated the vertical and radial variations in wood acoustical and physical properties of ailanthus tree (*Ailanthus altissima* (Mill.) Swingle).

The results revealed significant variations in density, dynamic modulus of elasticity (E_d), and damping coefficient (*Tan δ*) across different stem heights and radial positions. Key findings indicate that:

Density and Ed: Both density and E_d generally increase from the pith outwards to a certain point before decreasing again towards the bark. Axially, these properties tend to be highest in the middle section of the stem and lower at the base and top.

Damping Coefficient (*Tan δ*): The damping coefficient shows an inverse trend to density and Ed, with lower values observed near the pith and at the base of the stem. This suggests that wood from these regions may be more resonant.

Acoustic Conversion Efficiency (*ACE*): *ACE* values were found to be highest in the inner part of the stem (D1 zone) and in the lower and upper stem sections (L_1 and L_3). This indicates that these regions are more efficient at converting vibrational energy into sound.

These variations highlight the importance of considering both axial and radial positions when selecting ailanthus tree (*Ailanthus altissima* (Mill.) Swingle) wood for specific applications, particularly in musical instrument making. The inner part of the lower and upper stem sections appears to offer the most promising acoustic properties for applications requiring high resonance and efficient sound radiation. Further research could focus on the specific anatomical features contributing to these variations and their impact on the perceived sound quality of instruments made from this wood. When comparing the characteristics of this wood species with other traditional woods used in musical instrument manufacturing, the results revealed that it is a potential alternative for backs and ribs of stringed instruments.

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Authorship contributions

K.H.: Conceptualization, data curation, formal analysis, investigation, methodology, resources, software, supervision, validation, visualization, writing – original draft, review & editing. J.T.: Conceptualization, data curation, methodology, software, formal analysis, writing – original draft, review & editing.

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