Nodal Defects and Their Influence on Wave Propagation in Juvenile Wood of *Tectona grandis*

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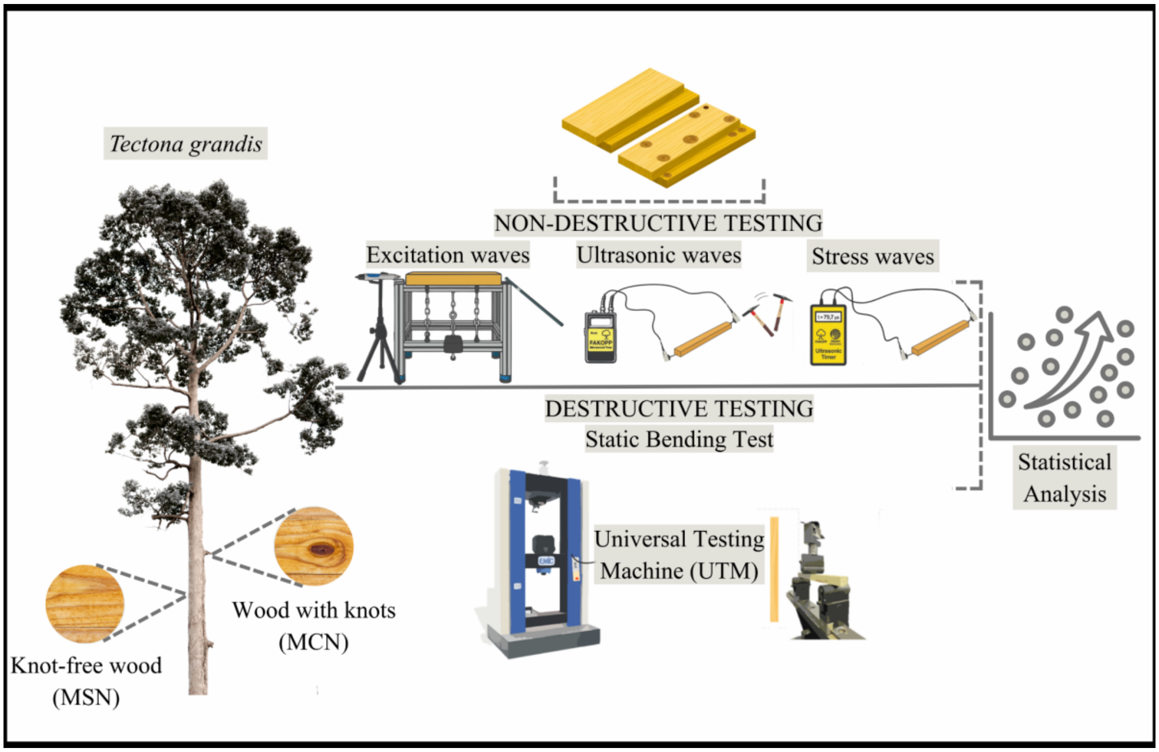
GRAPHICAL ABSTRACT



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Acoustics plays a significant role in the classification of a wide range of products in wood science and technology, from standing trees to structural elements. The study of wood acoustics involves the use of mechanical waves that are sensitive to several factors, including sample dimensions, intrinsic characteristics of the wood species, and the presence of defects. This study aimed to estimate the modulus of elasticity in juvenile wood of *Tectona grandis* using three different non-destructive wave-based evaluation methods: ultrasound, impulse vibration, and stress waves, with the goal of identifying the most suitable technique for predicting this mechanical property. Additionally, the study evaluated the impact of knots on wave propagation velocity and, consequently, on the estimation of the modulus of elasticity. Specimens measuring 20 × 20 × 300 mm (width, thickness, and length, respectively) were used, totaling 42 samples divided into two groups: with knots and without knots. The results indicated that all evaluated methods were effective and exhibited strong correlations with the estimated modulus of elasticity. Furthermore, the presence of knots in young, fast-growing teak wood did not significantly influence wave propagation.

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Keywords: Non-destructive testing; Acoustic properties; Structural anisotropy; Internal irregularities; Teak

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INTRODUCTION

Wood grading is a fundamental step in the valorization process, as it determines whether the material is suitable for structural applications (Burgers *et al.* 2019). This process is based on well-established characteristics that can be obtained through non-destructive measurements, enabling the identification of reliable indicators of mechanical performance. Consequently, there is a growing demand for efficient wood characterization methods and analytical approaches that contribute to reducing material losses.

Although technical standards describe procedures for evaluating the mechanical strength of wood through static tests, interest in dynamic methods that preserve sample integrity has increased in recent years (Fathi *et al.* 2020). This shift is driven by the need for industries to assess wood batches prior to commercialization. In this context, non-destructive testing methods have become essential tools, as they allow material characterization without damaging the specimens or compromising their final use, while also enabling greater efficiency in industrial-scale grading (Bresolin and Pravia 2021; Afoutou *et al.* 2024).

Wave propagation techniques have proven to be an effective approach for estimating wood properties and they are widely used in the industry to grade logs, lumber, and veneers (Ross 2015). Acoustic tomography and ultrasonic waves have also been applied to estimate wood stiffness constants, although the agreement with static measurements may vary according to the method and analytical approach employed (Alves *et al.* 2015). Studies conducted by Papandrea *et al.* (2022), Duong *et al.* (2022), Zhang *et al.* (2022), Silva *et al.* (2023), Carvalho *et al.* (2023), and Virgen-Cobos *et al.* (2022) applied wave-based tests to determine modulus of elasticity values. Accurate interpretation of these results requires understanding the factors that influence wave behavior in wood, which must be considered in the analyses (Bucur 1983).

Knots are natural features resulting from branch growth and insertion and are particularly common in fast-growing species (Ruan *et al.* 2024). Their influence on mechanical strength is associated with the proportion of the cross-sectional area they occupy, as well as their number, type, size, and distribution along the length and across the cross-section of the structural element (Barbosa *et al.* 2019). The nodal region is characterized by changes in fiber orientation, local density variations, and specific anatomical modifications, which may either generate stress concentrations or act as partial structural compensation mechanisms, thereby affecting the mechanical performance of wood (Lyu *et al.* 2023; Zhang *et al.* 2024). Thus, the way the knot connects to the surrounding tissues directly influences stress redistribution under static loading. Moreover, this interaction may alter material continuity for mechanical wave propagation, affecting dynamic parameters used in estimating the modulus of elasticity.

Tectona grandis plays a prominent role in the international market and is commonly cultivated in short-rotation plantations in Brazil. Rapid early growth in these systems promotes intense branching and a higher occurrence of knots in the first growth rings, resulting in wood with high structural heterogeneity (Ruan *et al.* 2024). Considering that a large portion of current teak production comes from young stands, it is essential to understand how these characteristics influence both mechanical behavior and the reliability of non-destructive methods applied to technological grading.

The present study aimed to evaluate whether the presence of knots influences mechanical wave propagation in juvenile wood of *Tectona grandis*, analyzing the potential effects on the dynamic parameters used to estimate mechanical properties.

Based on this context, we hypothesized that (i) all methods provide reliable estimates of the static modulus of elasticity, although with different predictive accuracies, (ii) the influence of knots on wave propagation differs among impulse excitation, stress wave, and ultrasonic testing methods, and (iii) the presence of knots affects mechanical wave propagation in juvenile wood of teak.

EXPERIMENTAL

Study Area and Material Collection

The study was conducted at the Laboratory of Wood Experimentation and Multiple Uses, which is part of the Department of Forest and Wood Sciences at the Federal University of Espírito Santo, Alegre, ES, Brazil. *Tectona grandis* wood from an 11-year-old plantation was used. Dynamic wave propagation tests and static bending tests were performed. The samples had dimensions of 20 × 20 × 300 mm (width, thickness, and length, respectively), in accordance with ISO 13061-3 (2014), totaling 42 specimens divided into two treatments: without knots (MSN) and with knots (MCN). In the without-knot group (MSN), the specimens were free from any visible defects. In the knot group (MCN), the specimens contained knots of varying sizes, ranging from small to large, distributed along the length of the pieces.

The moisture content and apparent density of the specimens were determined according to ASTM D4442-20 (2020) and ASTM D2395-17 (2017), respectively. Three non-destructive wave propagation methods were employed: vibration or impulse excitation, stress waves, and ultrasound.

Excitation Vibration

The specimens were subjected to the characterization of flexural and longitudinal vibration modes. An adjustable bar support, an impact hammer, a directional sensor, and dedicated software were used. Figure 1 illustrates the experimental setup during testing, showing the longitudinal and flexural configurations, respectively. The impulse excitation technique followed the procedures described in ASTM E1876 (2021).

The Sonelastic testing system was used to determine the elastic moduli based on the natural vibration frequencies of the specimens. The frequencies were excited by the impact hammer, and the acoustic response was captured by a sensor. The signal was then mathematically processed using a Fourier transform to obtain the corresponding frequency spectrum. Subsequently, the dynamic elastic moduli were calculated by considering the specimen geometry, mass, dimensions, and the frequencies obtained from the equipment, as presented in Eq. 1.

To determine the longitudinal modulus of elasticity (E), the vibration frequencies in the longitudinal (fl) and flexural (ff) directions were used in the calculations, following the standard procedures established by ASTM E1876 (2021),

$$E_{dyn} = \frac{4m\, L^2\, fl^2}{bt} K \tag{1}$$

where E_{dyn} is the modulus of elasticity (Pa) determined from the longitudinal vibration mode, m is the specimen mass (g), L is the specimen length (mm), b is the specimen width (mm), t is the specimen thickness (mm), f_l is the fundamental longitudinal vibration frequency (Hz), and K is the correction factor.

$$T_1 = 1 + 6.585\,(1 + 0.0752\mu + 0.8109\mu^2) - \left(\frac{t}{L}\right)^2 - 0.868\left(\frac{t}{L}\right)^4 - \left[\frac{8.34\,(1+0.2023\mu+2.173\mu^2)\left(\frac{t}{L}\right)^4}{1+6.338\,(1+0.1408\mu+1.536\mu^2)\left(\frac{t}{L}\right)^2}\right] \tag{2}$$

$$E_{dyn} = 0.9465\left(\frac{m f_f^2}{b}\right)\left(\frac{L^3}{t^3}\right) T_1 \tag{3}$$

Let $T_1 = 1/f$ be the fundamental vibration period obtained from the fundamental frequency measured in the acoustic tests. Then, the dynamic modulus of elasticity (E_{dyn}) was determined according to Eqs. (2) and (3).

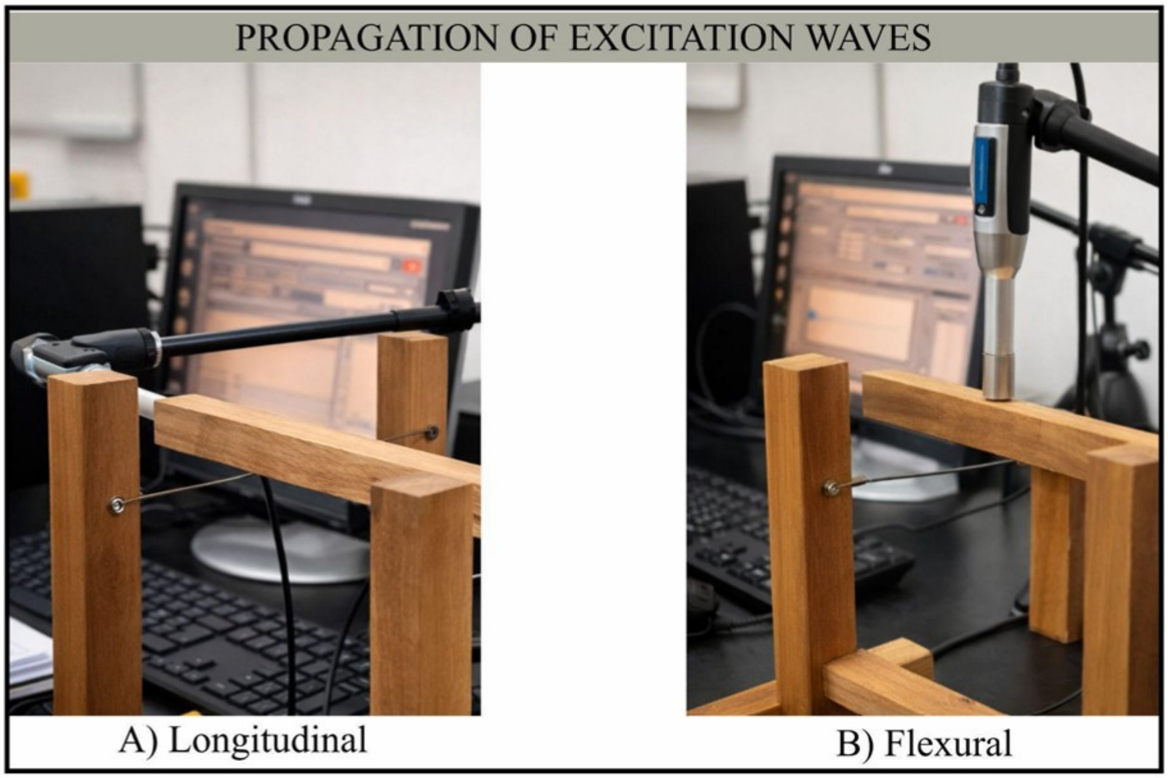

Fig. 1. Methodology used for the excitation wave propagation test to obtain the (A) longitudinal and (B) flexural modes

Ultrasonic Waves

Ultrasonic wave propagation tests were performed using a V-Meter MK IV (James Instruments) equipped with a 500 kHz longitudinal transducer. The same specimens used in the other tests were employed, with dimensions of 20 × 20 × 300 mm. The equipment detects the acoustic pulse emitted by transducers positioned on each transverse face of the specimen. These transducers transmit electrical pulses to a piezoelectric crystal, which converts them into ultrasonic waves.

The specimen length was determined based on the wavelength ($\lambda = V_{wave}$ / frequency), as prescribed by ABNT NBR 58000 (2007), which establishes a minimum length of 3λ. This recommendation was followed in the present study. Using Eq. 4, the modulus of elasticity was calculated based on apparent density and ultrasonic wave velocity, both adjusted to 12% moisture content.

$$MOEd = \frac{\rho V^2}{g} \tag{4}$$

where *MOEd* is the dynamic modulus of elasticity, or elastic constant (MPa), g is the acceleration due to gravity, assumed to be 10 $m \cdot s^{-2}$, ρ is the apparent density at 12% moisture content ($kg \cdot m^{-3}$), and V is the wave propagation velocity ($m \cdot s^{-1}$).

Stress Wave

Stress wave propagation tests were performed using a Microsecond Timer device FAKOPP (Fig. 2). This test consists of activating a transducer through an impact applied with a small hammer, thereby generating a mechanical wave. The wave is received by a sensor located at the opposite end of the specimen, allowing the travel time to be recorded. Knowing the distance traveled by the wave, the propagation velocity was determined. Measurements were performed using direct transmission. For the calculation of the dynamic modulus of elasticity (Ed), Eq. 4 was also applied.

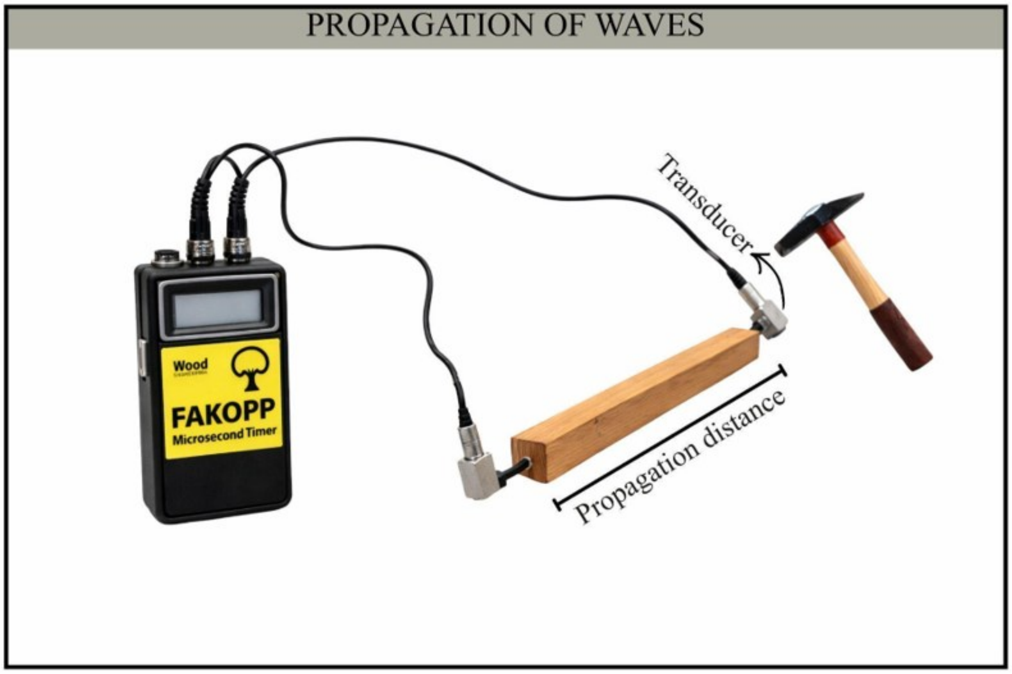

Fig. 2. Schematic representation of the stress wave propagation test setup, showing the Fakopp Microsecond Timer, transducers, impact hammer, and the wave propagation distance measured along the wood specimen

Static Bending

To evaluate the accuracy of the proposed methods, the specimens were subjected to static bending tests to determine the modulus of elasticity. The tests followed the procedures established by ISO 13061-3 (2014) and were performed using an EMIC DL 10000 universal testing machine.

Statistical Analysis

The data were subjected to the Shapiro–Wilk test to assess normality and the Bartlett test to evaluate homoscedasticity. When significant differences were identified for any dependent variable. Student's t-test was applied for mean comparisons. All tests were conducted at a 95% confidence level. Measures of dispersion expressed as standard error were provided to better characterize the confidence interval obtained for each analyzed variable. MiniTab 19 software was used for all statistical procedures. Subsequently, Pearson's correlation analysis (r) was performed to evaluate the adequacy of the linear regression model.

RESULTS AND DISCUSSION

No statistically significant differences were observed between the MSN (knot-free wood) and MCN (wood with knots) groups for the evaluated properties (Table 1). This result contradicts the initial hypothesis, as knots were expected to interfere with wave propagation by disrupting fiber continuity, which may cause signal dispersion, attenuation, and reduced propagation velocity in anisotropic materials such as wood (Palma *et al.* 2018).

The occurrence of knots is common in young plantation-grown teak wood, particularly under short-rotation management. High stand densities adopted to promote initial height growth influence branch development and the proportion of live and dead branches. However, self-pruning may be insufficient, requiring timely silvicultural pruning to produce clear, knot-free stems (Víquez and Pérez 2005; Vongkhamho *et al.* 2020; Lima *et al.* 2021).

Table 1. Values of the Variables Determined from Dynamic Tests, with Natural Frequency Obtained from Impulse Excitation Tests and Wave Propagation Velocity Obtained from Ultrasonic and Stress Wave Tests

Sample	ρ (kg/m³)	Tests			
		Impulse Excitation Longitudinal	Flexural Impulse Excitation	Ultrasound	Stress Waves
		f_{long} (Hz)	f_{flex} (Hz)	V (m/s)	VD (m/s)
MSN	632 ± 62 [a]	7410 ± 714 [a]	963 ± 84 [a]	4662 ± 399 [a]	4366 ± 389 [a]
MCN	637 ± 50 [a]	7339 ± 543 [a]	934 ± 62 [a]	4603 ± 348 [a]	4063 ± 348 [a]

Note: ρ is the apparent density of the wood; f_{lon}g is the longitudinal frequency; f_{xlex} is the flexural frequency; V is the ultrasonic wave propagation velocity; and VD is the stress wave propagation velocity

The mean apparent density values (~632–637 kg/m³) are consistent with those reported for juvenile teak from commercial plantations. Studies conducted by Silva-Albuês *et al.* (2024) and Ruan *et al.* (2024) indicate that the density of young *Tectona grandis* typically ranges between 550 and 700 kg/m³ depending on site conditions and silvicultural management. Thus, the material analyzed in this study presents physical characteristics representative of plantation-grown juvenile teak.

The mean static modulus of elasticity (MOE ≈ 9.2 GPa for both treatments) falls within the range reported for juvenile teak wood. Studies involving plantations aged between 8 and 15 years commonly report MOE values ranging from approximately 8 to 12 GPa, with stiffness increasing as tree age advances and the proportion of juvenile wood decreases (Silva-Albuês *et al.* 2024; Papandrea *et al.* 2022).

Comparative analyses between clear and knotty wood in fast-growing species, such as that presented by Ruan *et al.* (2024), show that significant reductions in stiffness are generally associated with large knots or high knot-to-cross-section ratios. In the present study, the absence of statistically significant differences between MSN and MCN suggests that the knots evaluated exhibited low structural severity and were not sufficient to compromise the global elastic behavior of MSN specimens.

The small difference observed between treatments (3.6%) indicates that the presence of knots had a limited influence on the modulus of rupture (MOR) and was insufficient to significantly alter the bending behavior of the wood. This finding suggests that the knots present in the specimens were not severe enough to compromise the maximum stress sustained by the material prior to failure, indicating that, under the conditions evaluated, MOR was predominantly governed by the intrinsic characteristics of the wood.

Table 2. Modulus of Elasticity is Determined from Dynamic and Static Tests for Wood with Knots and Knot-free Wood

	MOEd (GPa)				Static	
	Impulse Excitation		Ultrasonic Waves	Stress Waves	MOE (GPa)	MOR (GPa)
	Longitudinal	Flexural	Longitudinal	Direct		
MSN	12.48 ± 2.09[a*]	11.89 ± 2.03 [a]	13.75 ± 2.23 [a]	12.07 ± 2.02 [a]	9.19 ± 1.31 [a]	0,0945 ± 0,0142 [a]
MCN	12.41 ± 1.71 [a]	11.32 ± 1.51 [a]	13.52 ± 2.04 [a]	10.94 ± 2.93 [a]	9.27 ± 1.24 [a]	0,0911 ± 0,0118a

The MOR values obtained in the present study were higher than those reported for teak wood from young plantations. Seta *et al.* (2023) reported values ranging from 77.2 to 80.2 MPa for 15-year-old clonal teak subjected to different thinning and pruning regimes, whereas Nugroho *et al.* (2024) found a mean value of 72.0 MPa for 20-year-old clonal material. These differences reinforce that the mechanical performance of wood is not determined solely by the presence of natural defects, but is strongly influenced by factors such as genetic material, growth conditions, silvicultural practices, wood density, sampling position, and testing procedures (Marini *et al.* 2021). Therefore, the absence of a significant difference between specimens with and without knots indicates that, when knots are of low severity, their effect on MOR may be less pronounced than the influence of the wood's intrinsic characteristics and the conditions under which it developed.

Dynamic moduli were consistently higher than the static modulus, which reflects the instantaneous elastic response captured by acoustic methods and the absence of time-dependent viscoelastic effects during loading (Bucur 2023). Similar findings have been reported by Fathi *et al.* (2020) and Silva *et al.* (2023) in studies involving fast-growing species.

Linear regression analyses between MOEd and MOE showed high coefficients of determination, particularly for impulse excitation and stress wave methods ($R^2 < 84\%$).

Table 3. Regression Equations for the Dynamic and Static Moduli of Elasticity and their Respective R² Values

Samples	Test		Equation	R^2 (%)
MSN	Impulse Excitation	Longitudinal	MOE = 1.76 + 0.594 MOEd	88.52
		Flexural	MOE = 2.08 + 0.596 MOEd	84.54
	Ultrasonic Waves	Longitudinal	MOE = 3.13 + 0.433 MOEd	66.74
	Stress Waves	Direct	MOE = 1.92 + 0.587 MOEd	84.16
MCN	Impulse Excitation	Longitudinal	MOE = 1.30 + 0.651 MOEd	89.89
		Flexural	MOE = 0.76 + 0.760 MOEd	85.77
	Ultrasonic Waves	Longitudinal	MOE = 1.75 + 0.547 MOEd	81.82
	Stress Waves	Direct	MOE = 1.07 + 0.716 MOEd	87.54

Similar predictive performance has been reported by Papandrea *et al.* (2022), who demonstrated strong correlations between acoustic measurements and static MOE in standing trees and logs. Likewise, Duong and Ridley-Ellis (2021) and Ferreira *et al.* (2023) highlighted the reliability of stress wave methods for estimating mechanical properties in heterogeneous wood materials.

The impulse excitation method showed the highest predictive performance, with R^2 values exceeding 88% in the longitudinal mode. This result is consistent with Carrasco *et al.* (2017) and Silva *et al.* (2023), who emphasized the high accuracy of this technique due to its sensitivity to natural vibration frequencies and reduced susceptibility to minor internal discontinuities.

Ultrasonic testing exhibited lower predictive performance for knot-free wood (R^2 = 66.74%), although it showed improved stability in the knotty group (R^2 = 81.82%). This variation may be associated with wave scattering and attenuation phenomena in structurally heterogeneous materials such as juvenile wood (Solodov *et al.* 2004; Ettelaei *et al.* 2019; Afoutou *et al.* 2024).

Although the literature frequently associates knots with reductions in stiffness and strength (Zhou *et al.* 2016; Rocha *et al.* 2018), the present results indicate that knots in the analyzed juvenile *Tectona grandis* wood did not significantly affect dynamic parameters or static MOE.

Recent studies suggest that small or well-integrated knots may present adjacent regions with increased local density and anatomical rearrangements that contribute to partial structural compensation (Zhang *et al.* 2024). Such integration may reduce the negative impact typically expected on global stiffness, particularly when the knot does not significantly disrupt the predominant longitudinal fiber orientation.

Furthermore, juvenile wood is characterized by pronounced anatomical heterogeneity, including higher proportions of earlywood, thinner cell walls, and radial variability. These features tend to increase experimental dispersion, potentially masking subtle structural differences associated with knots (Llana *et al.* 2020; Duong *et al.* 2022; Carvalho *et al.* 2023).

CONCLUSIONS

This study investigated the performance of three wave-based non-destructive techniques for estimating the modulus of elasticity of juvenile wood of *Tectona grandis* and whether the presence of knots influences wave propagation. The research presented in this paper provides the technical foundation for using these technologies with *Tectona grandis* wood. The main conclusions are as follows:

1. Ultrasonic waves, stress waves, and impulse excitation methods can be replicated for estimating the modulus of elasticity of juvenile of wood of *Tectona grandis*.
2. The ultrasonic wave propagation method was the most sensitive to the occurrence of knots.
3. Among the evaluated methods, impulse excitation showed the best performance in estimating the modulus of elasticity and the lowest sensitivity to the presence of knots, as evidenced by the highest correlation coefficients for wood with and without knots.
4. The presence of knots in fast-growing juvenile wood did not significantly affect mechanical wave propagation. However, further studies are necessary to better clarify the influence of knots on wave attenuation and the dynamic response of juvenile wood.

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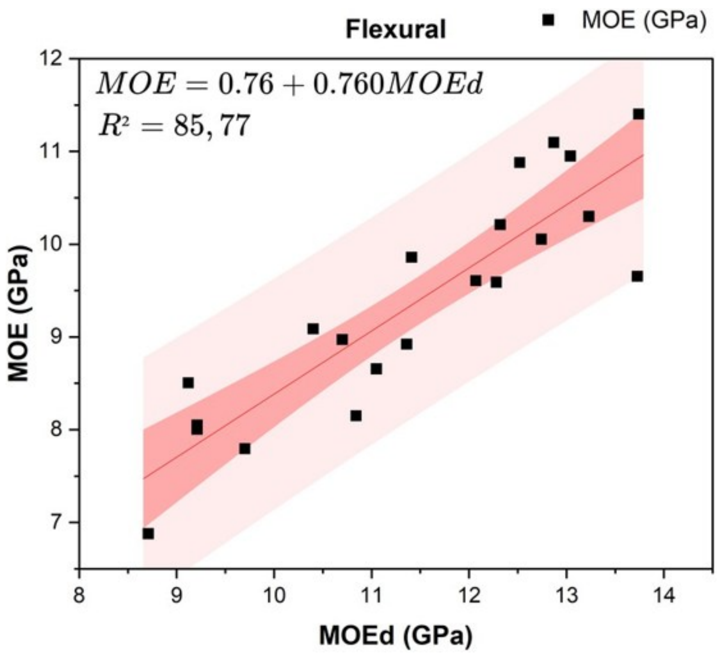
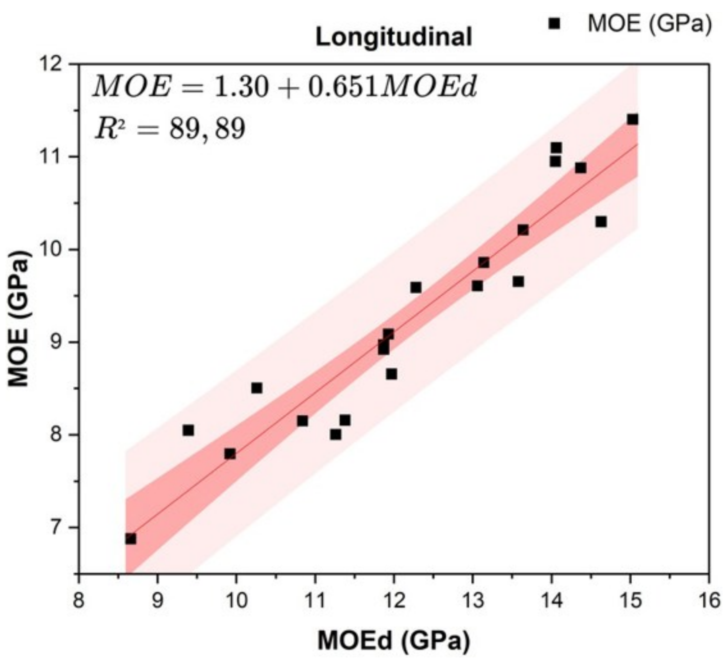
APPENDIX



(A)



(B)

Fig. S1 (A and B). Linear regression between the dynamic modulus of elasticity (MOEd) obtained by impulse excitation in the flexural and longitudinal modes and the static modulus of elasticity (MOE) for juvenile *Tectona grandis* wood with knots (MCN)

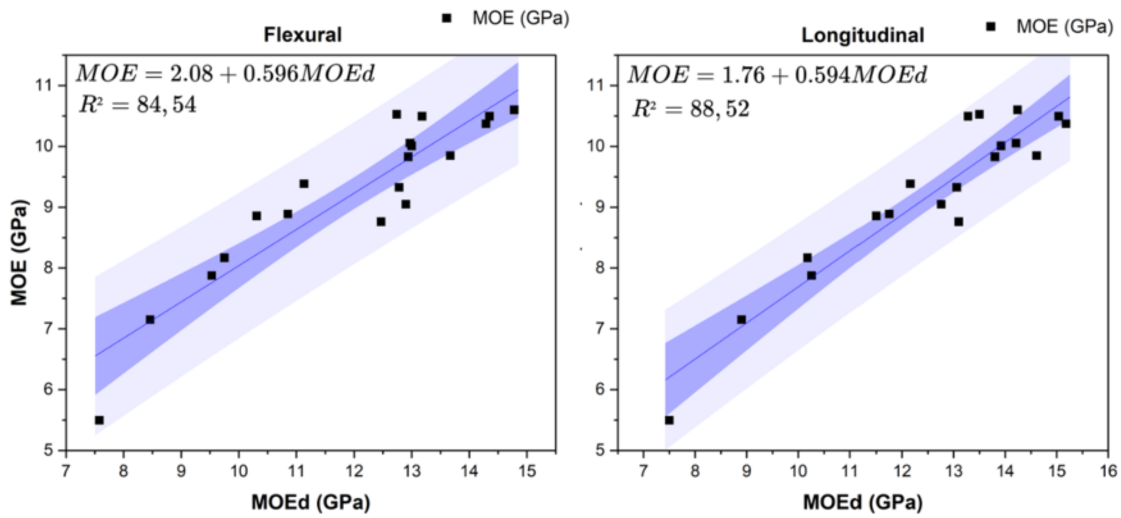


Fig. S2 (A and B). Linear regression between the dynamic modulus of elasticity (MOEd) obtained by impulse excitation in the flexural and longitudinal modes and the static modulus of elasticity (MOE) for juvenile *Tectona grandis* wood without knots (MSN)

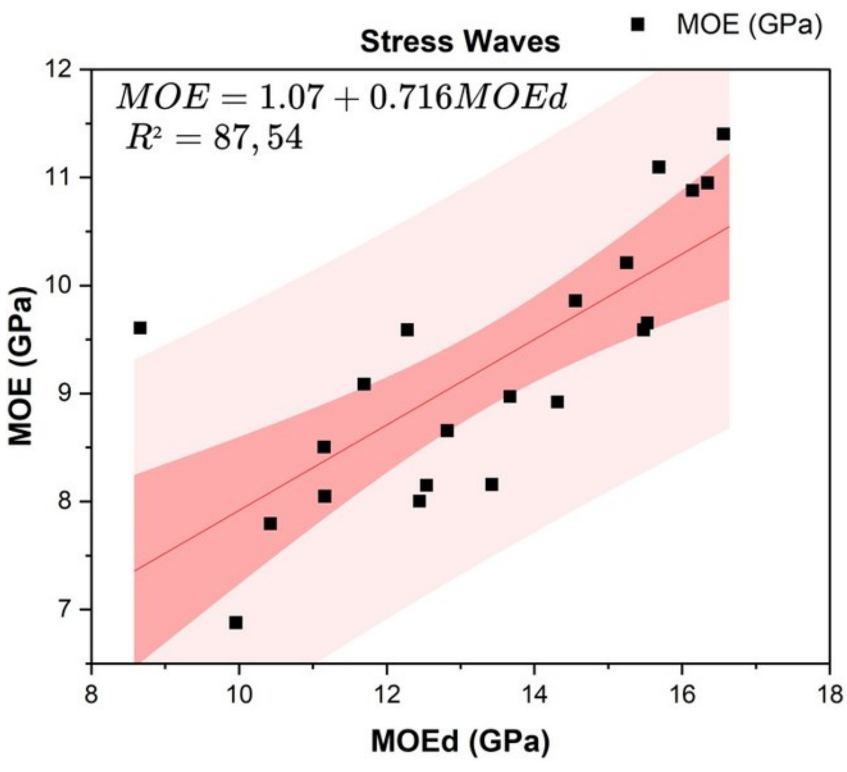


Fig. S3. Linear regression between the dynamic modulus of elasticity (MOEd) obtained by the stress wave method and the static modulus of elasticity (MOE) for juvenile *Tectona grandis* wood with knots (MCN)

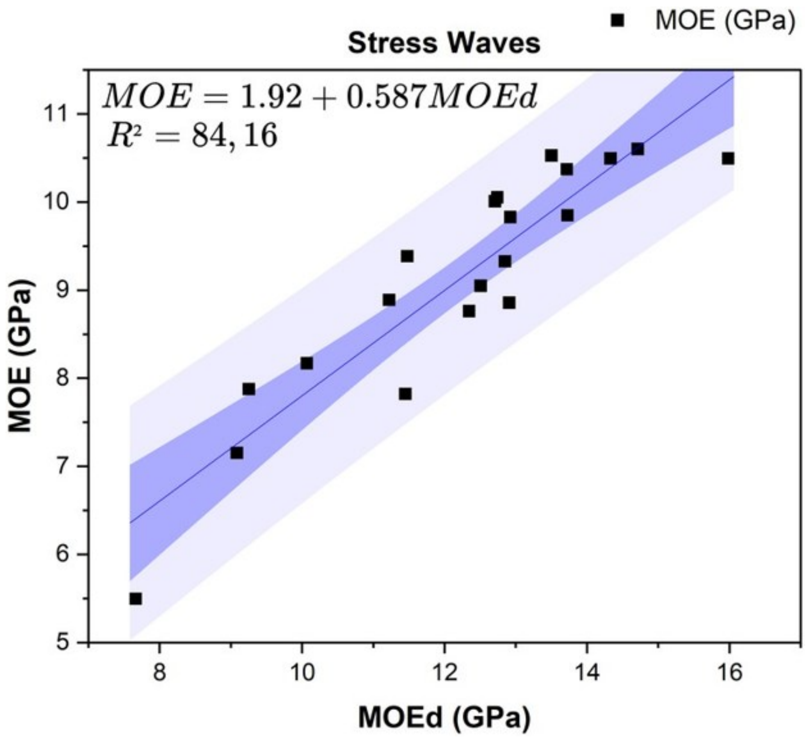


Fig. S4. Linear regression between the dynamic modulus of elasticity (MOEd) obtained by the stress wave method and the static modulus of elasticity (MOE) for juvenile *Tectona grandis* wood without knots (MSN)