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Evaluation of Physico-Static and Dynamic Elastic Properties of *Eucalyptus pellita* in Various Thinning Intensities

Noorsyazwani Mansoor[1], Adlin Sabrina Muhammad Roseley[1,2]*, Seca Gandaseca[3], Sabiha Salim[1], Rasdianah Dahali[2] and Lee Seng Hua[4]

[1]*Faculty of Forestry and Environment, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[2]*Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[3]*School of Biology, Faculty of Applied Science, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia*
[4]*Department of Wood Industry, Faculty of Applied Sciences, Universiti Teknologi MARA, 26400 Bandar Pusat Jengka, Pahang, Malaysia*

ABSTRACT

Acoustic velocity (AV) offers a non-destructive means of reliably measuring wood properties, presenting a valuable alternative to the traditional method known for its destructiveness, costliness, and time consumption. This technique is widely used in the timber industry to predict the bending strength of standing trees and logs. Hence, a study was conducted to assess the dynamic and static elastic properties of *Eucalyptus pellita* in various thinning intensities using the AV technique and laboratory testing. The selected 11-year-old *E. pellita* wood was obtained from thinning trials in Sabah Softwood Berhad, Brumas, Sabah. This investigation collected samples from three distinct thinning intensities (0%, 40%, and 60%). Dynamic modulus of elasticity (MOE), which relies on the time of flight (TOF) principle, was measured using an acoustic velocity approach, and physical and static testing was conducted according to standard ISO 13061. Results from this study show that thinning treatments significantly affect the physical and mechanical properties of *E.pellita*. The study also found that the static modulus of elasticity (MOE) value may be predicted using the acoustic velocity approach, with $R^2 = 0.46$, $R^2 = 0.60$, and $R^2 = 0.53$ on standing trees, billets, and wood slabs, respectively. The application of non-destructive tests in forest plantations can help the foresters assess the wood properties

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E-mail addresses:
mnoorsyazwani@gmail.com (Noorsyazwani Mansoor)
adlin@upm.edu.my (Adlin Sabrina Muhammad Roseley)
seca@uitm.edu.my (Seca Gandaseca)
sabiha@upm.edu.my (Sabiha Salim)
rasdianahdahali@gmail.com (Rasdianah Dahali)
leesenghua@uitm.edu.my (Lee Seng Hua)
*Corresponding author

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efficiently, and specific parameters can be measured on a tree stand without falling the tree. Besides, thinning at a moderate intensity also helped to enhance the mechanical properties and dynamic MOE value of the *E. pellita* wood.

Keywords: Acoustic velocity (AV), bending strength*, Eucalyptus pellita*, thinning treatments

INTRODUCTION

Eucalyptus was introduced to Malaysian Borneo in 2012 as a replacement for *A.mangium,* which suffered a loss due to *Ceratocystis manginecans* (Alwi et al., 2021; Roux & Wingfield, 2009). According to Binkley et al. (2017), eucalyptus covered 26% of the total planted area globally. Since the 1970s, this species has been widely used as a surrogate material for timber supply and has been established in forest plantations. For this reason, studies regarding the properties of eucalyptus, such as solid wood utilisation, wood density and anatomy, acoustic wave velocity assessment, and MOE, have been conducted (Barotto et al., 2017; Hii et al., 2017; Japaruddin et al., 2022; Raymond, 2002).

Besides, *E. pellita* is a forest plantation species with a high potential in structural applications due to its fast-growing characteristics. A recent study assessing the effect of thinning on wood properties through the acoustic velocity of eucalyptus wood was conducted, and the results show that the thinning intensity influenced the dynamic MOE. Besides, moderate thinning could enhance the stiffness properties of the wood (Gendvilas et al., 2021; Russo et al., 2019).

The effect of silvicultural practices from a previous study shows an inconsistent correlation (de Moraes Gonçalves et al., 2004; Nogueira et al., 2015; Prasetyo et al., 2017). Silvicultural practices are implemented to manipulate the tree growth, and the standard treatments include thinning and pruning. Silviculture treatments were developed to improve the growth rate of plantations and produce high-quality wood-based products. The effects of silviculture practice wood quality might not be determined by simple factors (Listyanto & Nichols, 2009).

It is imperative to assess the wood quality and wood properties of trees to enhance forest stands in forest plantations (Russo et al., 2019; Wang et al., 2007). Wood quality encompasses the properties of the wood, such as its density and stiffness (Marini et al., 2021). As noted in a study by Auty and Achim (2008), these properties are often influenced by the growing condition of the forest stands. Some authors have performed their studies explicitly focusing on assessing the wood properties (Antony et al., 2011; Ayanleye, 2020; Baettig et al., 2017; Balasso et al., 2021; Butler et al., 2017; Liu et al., 2007; Todaro & Macchioni, 2011). The wood properties were measured by conducting mechanical testing in the laboratory (Gao et al., 2017). This method, however, is destructive and time-consuming (Sharma et al., 2020). Thus, alternative techniques and tools that are portable and practical must be utilised for efficient wood properties evaluation.

In recent years, non-destructive testing (NDT) methods have emerged as a valuable tool in the forestry and timber industry, offering the ability to assess the wood properties of standing trees and logs without causing damage. Besides, this method has been used to evaluate wood properties in the forest industry for the last two decades (Schimleck et al., 2019). This technique is also able to effectively evaluate the wood quality while preserving samples intact. One of the NDT tools that can be used for in situ wood properties assessment is the acoustic velocity (AV) technique. This AV method has evolved from product assessment to evaluation of logs and standing trees (Carter et al., 2005; Proto et al., 2017; Wang et al., 2007). Among the key parameters assessable through this method are the elastic properties of wood, particularly the modulus of elasticity (MOE), which plays a crucial role in assessing wood properties.

The AV measurement relies on the time-of-flight (TOF) principle by generating a stress wave through the impact of striking a hammer on the transmitter probe (Chen et al., 2015; Fundova et al., 2019; Legg & Bradley, 2016). Stress wave propagation in wood is influenced and controlled by the wood's properties, including the physical and mechanical properties. Hence, the wood properties can be estimated from the fundamentals of stress wave propagation in wood (Wang et al., 2000). Based on previous and recent studies, there are correlations between the dynamic MOE of AV and the woods (Antony et al., 2012; Auty et al., 2016).

This study was conducted to investigate the relationship between the effect of thinning on the physical and mechanical properties of *E. pellita* and the use of acoustic velocity in predicting MOE. The impact of thinning on mechanical properties using the acoustic velocity approach can be determined based on a regression model by correlating two variables (static MOE and dynamic MOE).

MATERIALS AND METHOD

Study Site

E. pellita was obtained from the Sabah Softwood Berhad (SSB) plantation site in Brumas, Tawau, Sabah, Malaysia, with an elevation range between 200-600 m. Figure 1 shows the *E. pellita* plantation in Sabah Softwood Berhad (SSB).

The experimental site was established in 2019 with 3 m x 3 m spacing, and the area of the plantation planted is 1.08 hectares. Table 1 summarises the information on the tree stand.

Thinning intensity can be defined as a regulation of stand density. It also refers to how many trees will be removed from the tree stand. Thinning treatments of *E. pellita* were subjected to 3 different thinning intensities, namely thinning 1 (0%), thinning 2 (40%), and thinning 3 (60%). The percentage (%) refers to the number of trees cut from the total number of trees in the same area. Thinning 1 (0%) refers to no thinning applied, and thinning 2 (40%) and 3 (60%) refers to the stand thinning to 40% and 60% from the total

Figure 1. E. pellita plantation in Sabah Softwood Berhad (SSB)

Table 1
General characteristics of the experimental site

Site	Stand age	Soil type	Plot size (m)
SSB Plantation	11 years old	Kumansi (>40% of clays)	10 x 10

Source: Sabah Softwood Berhad (SSB) Tawau

tree stand on the plot. This study consists of three thinning treatments, each consisting of 100 individual trees (300 trees for three thinning in total). The thinning was done at the age of 2 years.

The thinning type for this study is low thinning, also known as thinning from below. Thinning from below involves removing trees from the lower canopy, suppressed trees (trees that experienced a limited growth rate), and small-diameter trees. This thinning often results in evenly distributed tree stands and focuses on trees potentially developing into large-diameter trees.

Preparation of Sample

A total of 18 trees with similar diameters at the breast (DBH) classes were chosen to represent the population of the three thinning. The trees were chosen based on the diameter at breast height (DBH) of the populations, and six trees were selected for each thinning. Not only that but the trees were also selected based on the accessibility of the tree to be taken out from the plot, good appearances (less to no defects) and acoustic velocity value of the trees.

The acoustic velocity of all 18 trees was measured using the time-of-flight (TOF) principle and recorded using the Fakopp Microsecond Timer before the harvesting. All these 18 trees were then processed into sample dimensions according to standard ISO

3129 (ISO 3129 Wood-Sampling method and general requirements for physical and mechanical testing of small clear wood specimens, 2019). The tree is then processed into a specific cutting pattern for a log more than 180mm diameter based on standard ISO 3129, as shown in Figure 2.

The wood slabs were air-dried until the moisture content (MC) reached equilibrium before sample processing. A total of 1556 small clear specimens were prepared for mechanical testing, and these samples were used to find prediction and empirical data for the mechanical properties with the NDT method. Additionally, 1137 small clear specimens were produced to examine the density.

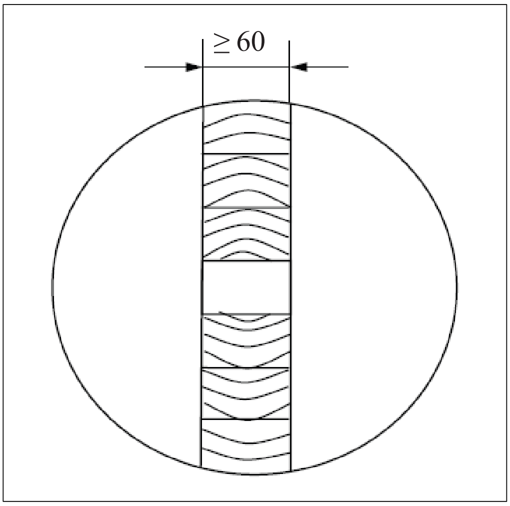


Figure 2. The general cutting pattern of a log with a diameter > 180 mm
Source: ISO 3129:2019

Assessment of Non-Destructive Testing (NDT)

For non-destructive testing (NDT), the acoustic velocity (AV) of the Fakopp Microsecond Timer was performed and measured on 18 trees, billets and wood slabs. Billets is the log of the *E.pellita* tree that was cut into 2 m lengths, which produced 54 billets for 18 trees from all thinning. The wood slabs were made from the billets processed at the sawmill, with each wood slab having a 2 m length. Equation 1 explains the relations of acoustic velocity, wood density and wood stiffness.

$$MOE_{dyn} = \rho AV^2 \quad (1)$$

Where MOE_{dyn} is the dynamic MOE (Nmm^{-2}), ρ is the wood density (kgm^{-3}), and AV is the velocity of the stress wave (ms^{-1}). The AV was assessed on 18 trees, 54 billets and 246 wood slabs derived from thinning 1 (0%), thinning 2 (40%), and thinning 3 (60%) using the acoustic wave's time-of-flight (TOF) principle. The AV was measured by measuring the vibrational speed between 2 points, using the transmit and receiver probe with 1–2 kHz frequencies (Figure 3).

The hammer striking from the transmit to the receiver probe generated the acoustic velocity. The AV on trees, billets, and wood slabs was measured by using the Fakopp Microsecond Timer that relies on the TOF principles based on Equation 2:

$$Vel = \frac{S}{TOF} \quad (2)$$

Where Vel is the acoustic velocity (ms^{-1}), S is the distance between the two probes (m), and TOF is the time of flight (s). The AV measurement on billets and wood slabs was taken before the static bending test of small clear specimens. The dynamic MOE was calculated based on the formula mentioned above, and the relationship between dynamic MOE and static MOE was established using the simple linear regression method.

Figure 3. Assessment of acoustic velocity on billets of *E.pellita*

Determination of Green Density

The green density of the wood was taken from wedge samples derived from the discs of 18 trees based on the Australian and New Zealand Standard AS/NZ 1080.3:2000. The formula for the calculation of the green density was derived in Equation 3 below:

$$Green\ density = \frac{Mass_g}{Volume_g} \quad (3)$$

Where,
$Mass_g$: mass of sample at green condition, in kg, of the test piece
$Volume_g$: volume of sample at green condition, in m^3, of the test piece

The results were expressed to the nearest 5 kg/m^3 (0.005 g/cm^3).

Test Method

The physical and static mechanical properties of *E.pellita* wood were performed based on standard ISO 13061. The bending test followed the ISO 13061-3:2014 Determination of Ultimate Strength in Static Bending and ISO 13061-4:2014 Determination of Modulus of Elasticity in Static Bending. The density of *E.pellita* wood was determined according to standard ISO 13061-2:2014 Determination of Density for Physical and Mechanical Test. Before the test, the green MC was defined by ISO 13061-1:2014 Determination of Moisture Content for Physical and Mechanical Test.

Preparation of Samples and Procedure for Bending Test

Figure 4 shows how the samples and dimensions for the bending test were cut and prepared according to standard ISO 13061.

The samples were conditioned to a constant mass under a relative humidity of 65 ± 5 % and temperature of 20 ± 2°C before testing. A total of 1556 samples for all thinning treatments were tested for mechanical testing at the Material Testing Lab, Faculty of Forestry and Environment, UPM. The three-point flexure bending test was conducted using a 10kN Instron Universal Testing Machine. During the test, the sample test was positioned horizontally on top of two points, with the load applied at the centre load of the material, with the tangential surface facing the load (Figure 5).

Each sample's depth and width (mm) were measured using vernier callipers before the test. The MOE and modulus of rupture (MOR) were calculated based on the given Equation 4:

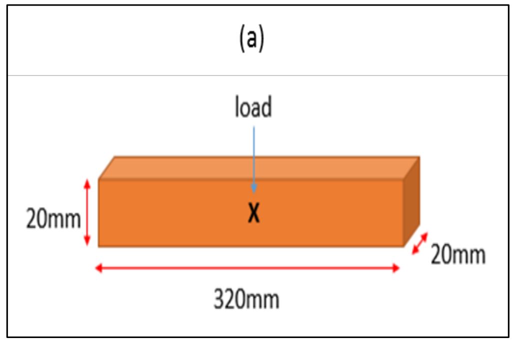


Figure 4. Dimension of sample test for bending test

Figure 5. Set up for the 3-point flexure bending test

$$E_w = \frac{Pl^3}{4bh^3 f} \tag{4}$$

Where,

P : load equal to the difference between the upper and lower limits of loading in N

l : span distance, in mm

b : width of the test piece, in mm

h : height of the test piece, in mm

The results were expressed to an accuracy of 1 N/mm^2 (MPa).

An adjustment of the MOE to 12% moisture content was done using the following Equation 5:

$$E_{12} = \frac{E_w}{1 - \alpha\,(W - 12)} \tag{5}$$

Where,
α : correction factor for the moisture content, 0.02
W : moisture content of the wood based on standard ISO 13061-1

The mean and the standard deviation of the results obtained for the individual sample were calculated to a precision of 1 N/mm^2 (MPa).

For the calculation of the modulus of elasticity (MOR) value, the formula was derived in Equation 6:

$$\sigma_{b,W} = \frac{3P_{max}l}{2bh^2} \tag{6}$$

Where,
P_{max} : maximum load, in N
l : the span distance, in mm
b : width of the test piece, in mm
h : height of the test piece, in mm

The results were expressed to a precision of 1 N/mm^2 (MPa).

An appropriate adjustment of the ultimate bending strength to 12% moisture content was made using the formula (Equation 7):

$$\sigma_{b,12} = \sigma_{b,W}\,[1+\alpha\,(W - 12)] \tag{7}$$

Where,
α : correction factor for the moisture content, 0.04
W : moisture content of the wood based on standard ISO 13061-1.

The mean and the standard deviation of the results obtained for the individual sample were calculated to a precision of 1 N/mm^2 (MPa).

Preparation of Samples and Procedure for Wood Density

The sample dimension for the oven-dry density was prepared based on standard ISO 13061. Figure 6 shows the dimension of the sample test for the oven-dry density of *E. pellita* wood.

Determination of Oven-dry Density

The samples were uniformly dried in the oven. The samples were cooled in a desiccator, and their weight and dimensions were immediately taken. Using the given equation, the density of the sample in its oven-dry state, kg/m^3, was determined. The density ρ_0 was calculated in kg/m^3 using the formula given (Equation 8):

$$\rho_0 = \frac{m_0}{a_0 \times b_0 \times l_0} = \frac{m_0}{V_{max}} \tag{8}$$

Where,

m_0 : mass, in kg (or g), of the test piece in the dehydrated condition.

a_0, b_0, and l_0 : dimensions, in m (or cm), of the test piece in the dehydrated condition.

V_0 : volume, in m^3 (or cm^3), of the test piece in the dehydrated condition.

The results were expressed to the nearest 5 kg/m^3 (0.005 g/cm^3).

Determination of Basic Density

The basic density for the samples was prepared based on wedge samples and calculated according to Australian and New Zealand Standard AS/NZ 1080.3:2000 and standard ISO 13061-2:2014 Determination of Density for Physical and Mechanical Test. The formula for the calculation of the basic density was derived in Equation 9:

$$\rho_y = \frac{m_0}{a_{max} \times b_{max} \times l_{max}} = \frac{m_0}{V_{max}} \tag{9}$$

Where,

a_{max}, b_{max}, and l_{max} : dimensions, in m (or cm), of the test piece at a content greater than equal to the fibre saturation point before any shrinkage occurs due to drying.

V_{max} : green volume, in m^3 (or cm^3), of the test piece.

The results were expressed to the nearest 5 kg/m^3 (0.005 g/cm^3).

The mean and standard deviation of the sample results were calculated to an accuracy of 10 kg/m^3 (or 0.01 g/cm^3).

Data Analysis

Statistical analysis was performed using one-way analysis variance (ANOVA) with three dependent variables: thinning under three intensities (0%, 40% and 60%). ANOVA analysis will determine the significance level of thinning intensity towards eucalyptus wood's mechanical and physical properties. The physical and mechanical testing data for *E. pellita* were analysed through SPSS, which produced a 95% confidence level or *p*-value of less than 0.05.

Besides that, descriptive analysis was also used to calculate dynamic and static MOE. A two-tailed linear correlation and regression analysis was performed between the static and dynamic MOE on trees, billets, and wood slabs of *E. pellita*. This analysis is crucial to determine whether the non-destructive analysis is related to the static MOE in the small clear specimens.

RESULTS AND DISCUSSION

Physical Properties

The average and standard deviation of the wood density of *E.pellita* under all thinning intensities are summarised in Table 2.

Table 2
Descriptive analysis of the density of E. pellita *wood*

Thinning intensities	Basic density					Green density				
	N	Mean value (kgm^{-3})	SD	Min	Max	N	Mean value (kgm^{-3})	SD	Min	Max
1 (0%)	18	634	58.04	550.00	721.76	18	1130	33.60	1061.69	1175.46
2 (40%)	18	619	42.81	536.00	689.27	18	1117	32.77	1069.10	1177.38
3 (60%)	18	568	47.96	448.83	633.99	18	1094	88.19	761.17	1150.96
Total	54	607	56.57	448.83	721.76	54	1113	58.58	761.17	1177.38

*SD= standard deviation

For the physical properties, the density was determined using the wedge samples, which were obtained from discs derived from 18 trees of the thinning. The average mean value of basic density under all thinning intensities is 607 kgm^{-3}. The mean value of wood density in the variation of thinning intensities ranged from 568 kgm^{-3} to 634 kgm^{-3}. The wood density was higher (634 kgm^{-3}) in thinning 1 (40%) compared to thinning 3 (60%), which is 568 kgm^{-3}. The observed reductions in wood density due to thinning ranged from 2.3% to 8.2% from thinning 1 (0%) to 3 (60%). Figure 7 shows the boxplot of wood density under all thinning intensities. The statistical analysis showed a significant difference at $p < 0.05$ in the wood density for all thinning intensities.

Based on the results above, thinning does affect wood density. The increasing volume of the trees causes a decrease in wood density due to the thinning applied to them (Bhandari et al., 2021; Bhandari et al., 2022).

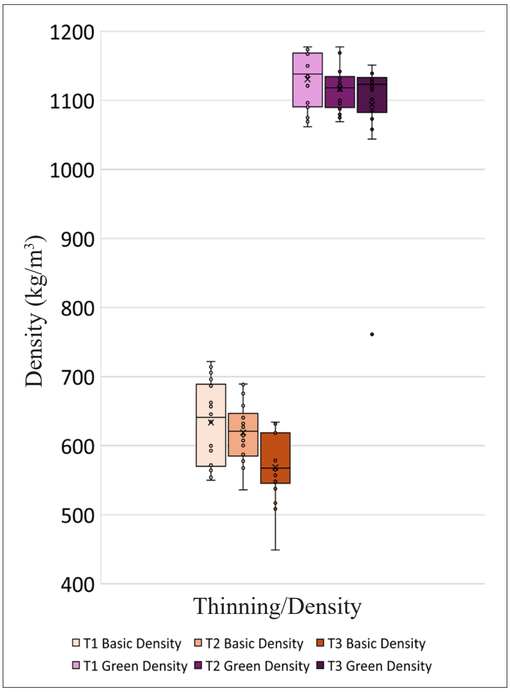


Figure 7. Boxplot of wood density of *E.pellita* under all thinning intensities

Mechanical Properties

Descriptive statistics under all thinning intensities are presented in Table 3.

Based on the data presented, the mean value of the static mechanical properties of *E.pellita* wood is 21.68 GPa and 137.29 MPa for MOE and MOR, respectively. The statistical analysis shows significant differences between the thinning and the mechanical properties of *E.pellita* wood with a p-value <0.05.

Table 3 shows that the mean value for the mechanical properties of all thinning decreases when intensive thinning is applied. The diameter increment has caused the wood to become less stiff, as this is caused by thinning to obtain a high diameter and volume of wood (Candel-Pérez et al., 2018). However, moderate thinning increased the wood stiffness, as the value increased by 7.1% from 21.92 GPa to 23.47 GPa and 2% from 144.96 MPa to 147.74 MPa for both MOE and MOR values. Hence, moderate thinning positively affects the wood stiffness (Coletta et al., 2016).

Table 3
Descriptive statistic of the mechanical properties of E. pellita *wood*

Thinning intensities	MOE			MOR		
	N	Mean value (GPa)	SD	N	Mean value (MPa)	SD
1 (0%)	525	21.92	3.67	525	144.96	28.53
2 (40%)	509	23.47	4.17	509	147.74	33.73
3 (60%)	522	19.68	3.96	522	119.38	28.37
Total	1556	21.68	4.23	1556	137.29	32.82

*SD = standard deviation

Correlation Between MOE and MOR with Oven-Dried Density

Figures 8 and 9 show the relationship between density and *E. pellita* wood's mechanical properties. The figure shows a positive correlation between the oven-dried density and the mechanical properties of *E. pellita* wood, with $R^2 = 0.69$ and $R^2 = 0.63$ for MOE and MOR under all thinning, respectively. The correlation between these variables shows that low MC may improve the wood stiffness and strength properties (Lahr et al., 2017).

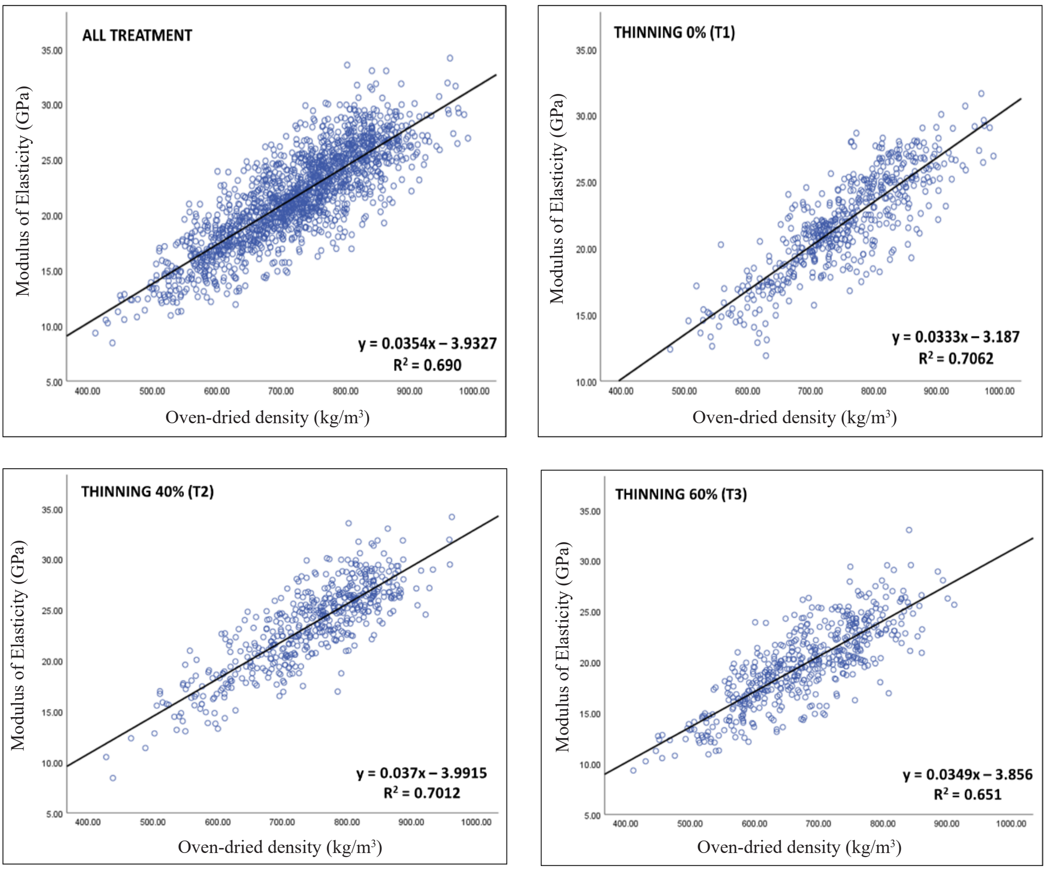
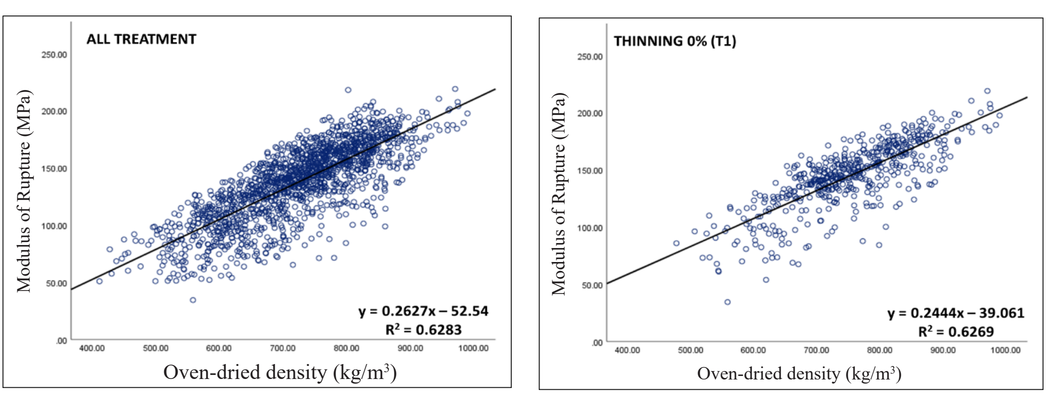


Figure 8. Relationship between oven-dried density and MOE of *E. pellita* by thinning



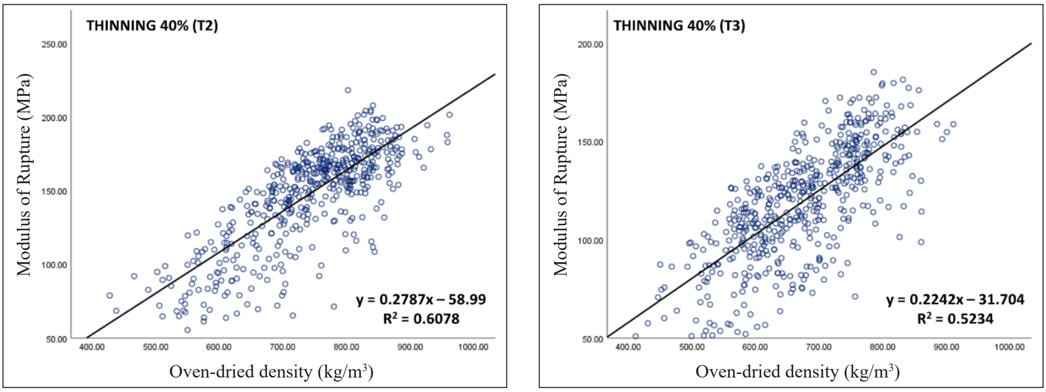


Figure 9. Relationship between oven-dried density and MOR of *E. pellita* by thinning

Failure Mode

The failure mode for each sample was determined based on the standard ASTM D143 Static Bending Test. According to the standard, there are six types of failure modes: simple tension (a), cross-grain tension (b), splintering tension (c), brash tension (d), compression (e), and horizontal shear (f), as shown in Figure 10.

Figure 10. Types of failure mode in bending test

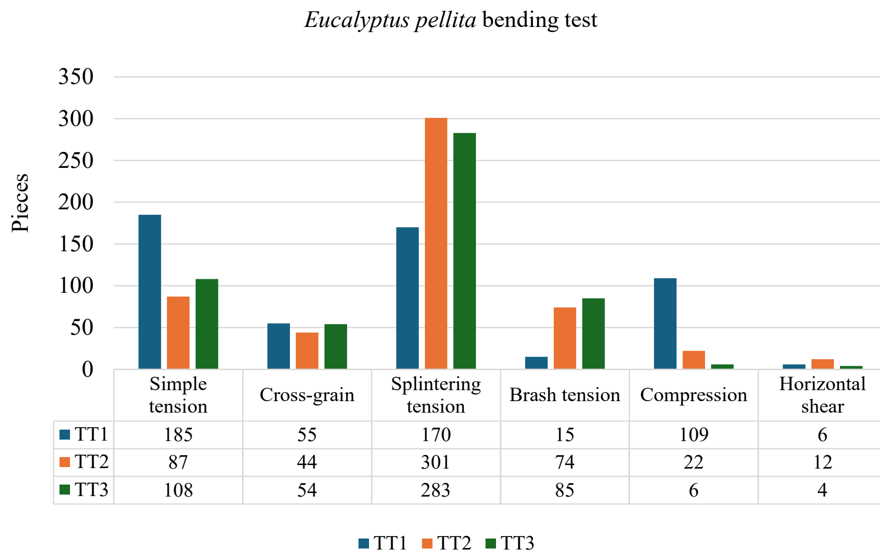
The bar chart in Figures 11 and 12 shows the frequencies of failure mode recorded on each sample test and the maximum failure load for each failure mode for all thinning.

Simple tension and splintering are the most common failure modes in the samples. A study by Derikvand et al. (2019) also shows the same failure mode observed from the *E. nitens* samples.

Meanwhile, the maximum failure load based on thinning has indicated a value of 1968 N for thinning 1 (compression failure), 1740 N for thinning 2 (horizontal shear) and 1536 N for thinning 3 (cross grain).

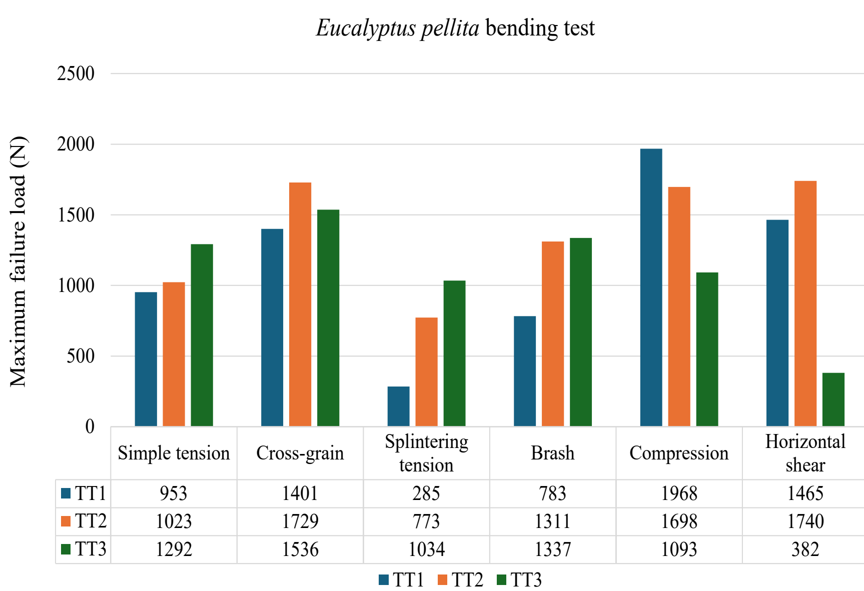
Acoustic Velocity (AV)

The descriptive statistics for dynamic MOE in trees, billets and wood slabs are shown in Table 4.



	Simple tension	Cross-grain	Splintering tension	Brash tension	Compression	Horizontal shear
TT1	185	55	170	15	109	6
TT2	87	44	301	74	22	12
TT3	108	54	283	85	6	4

Figure 11. The failure mode for each sample from all three thinning



	Simple tension	Cross-grain	Splintering tension	Brash	Compression	Horizontal shear
TT1	953	1401	285	783	1968	1465
TT2	1023	1729	773	1311	1698	1740
TT3	1292	1536	1034	1337	1093	382

Figure 12. Maximum failure load for each failure mode from all three thinning

Table 4
Descriptive statistics of the dynamic MOE on trees, billets and wood slabs of E. pellita

Thinning intensities	Tree			Billet			Wood slab		
	N	Mean (GPa)	SD	N	Mean (GPa)	SD	N	Mean (GPa)	SD
1 (0%)	6	14.42	4.13	18	26.80	0.70	98	26.77	1.05
2 (40%)	6	14.72	5.12	18	27.24	2.63	77	27.29	2.96
3 (60%)	6	11.79	3.21	17	25.69	2.31	71	25.17	2.54
Total	18	13.64	4.20	53	26.59	2.12	94	26.47	2.40

*SD = standard deviation

The average value of the dynamic MOE for trees, billets and wood slabs were 13.64 GPa, 26.59 GPa and 26.47 GPa, respectively, for all three thinning. The value of dynamic MOE in wood slabs increased by 2% from 26.77 GPa to 27.29 GPa as moderate thinning was applied. However, as the thinning intensity increased, the value of dynamic MOE decreased by 8% from 27.29 GPa for thinning 2 (40%) to 25.17 GPa for thinning 3 (60%). For statistical analysis, there is a significant difference between the dynamic MOE and all three thinning, with a $p < 0.05$ for wood slabs. Meanwhile, no significant difference was found between the dynamic MOE with all three thinning trees and billets of *E.pellita*.

The dynamic MOE on the trees, billets and wood slabs positively correlates with the static MOE under all thinning, with $R^2 = 0.46$, $R^2 = 0.60$, and $R^2 = 0.53$, respectively (Figure 13).

All thinning 1, 2, and 3 show a positive correlation between the dynamic MOE and static MOE of *E. pellita* obtained from billets and wood slabs, as shown in Figure 14 and Figure 15

This study shows that moderate thinning treatment can enhance the elasticity properties of *E.pellita* wood, as the same results were observed in the previous study conducted by Russo et al. (2019). Furthermore, using a moderate thinning intensity can be a good choice for producing wood-based products with good wood quality and properties.

Wood conditions (density) were a few factors affecting the distribution of acoustic waves through the wood. The particles of denser wood were closely packed together, leading to more resistance to transfer the sound wave vibrations compared to less dense materials. Results from this study show as the thinning intensity increased, the density decreased. Hence, the dynamic MOE was also reduced as high thinning intensity results in lower-dense wood. Besides, the increase in juvenile wood content is also one of the elements contributing to the rise, but it only slows the wave propagation through the wood (Liu et al., 2021).

This study found a positive correlation between the dynamic MOE and static MOE on 18 trees, billets and wood slabs, as these equations can predict the static MOE based

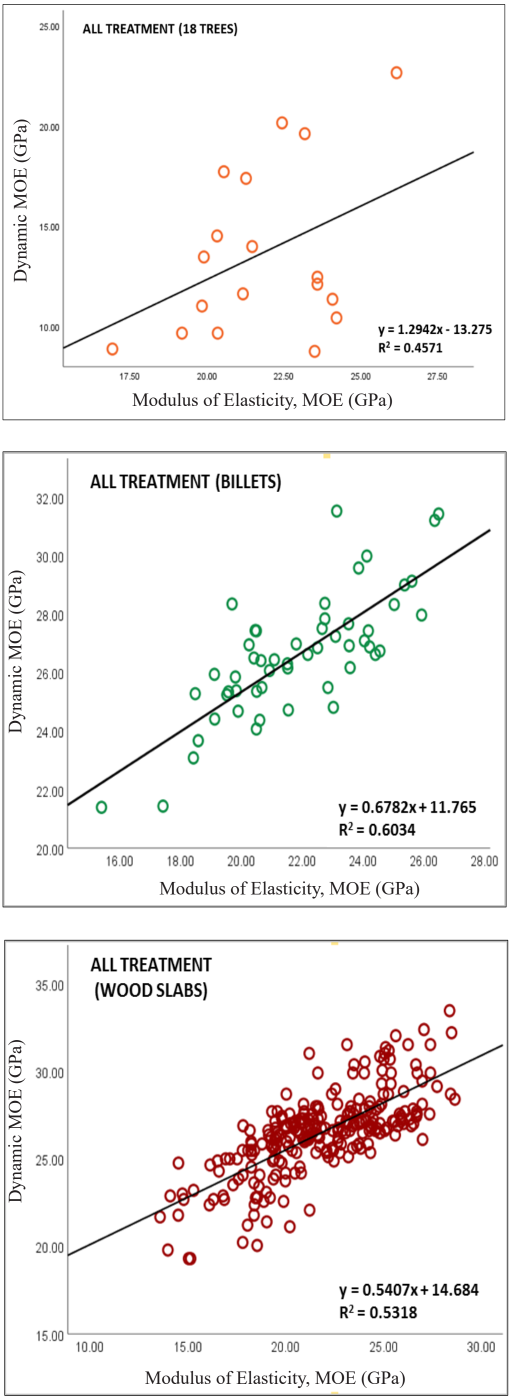


Figure 13. Relationship between static MOE and dynamic MOE under all thinning obtained from trees, billets, and wood slabs of *E. pellita*

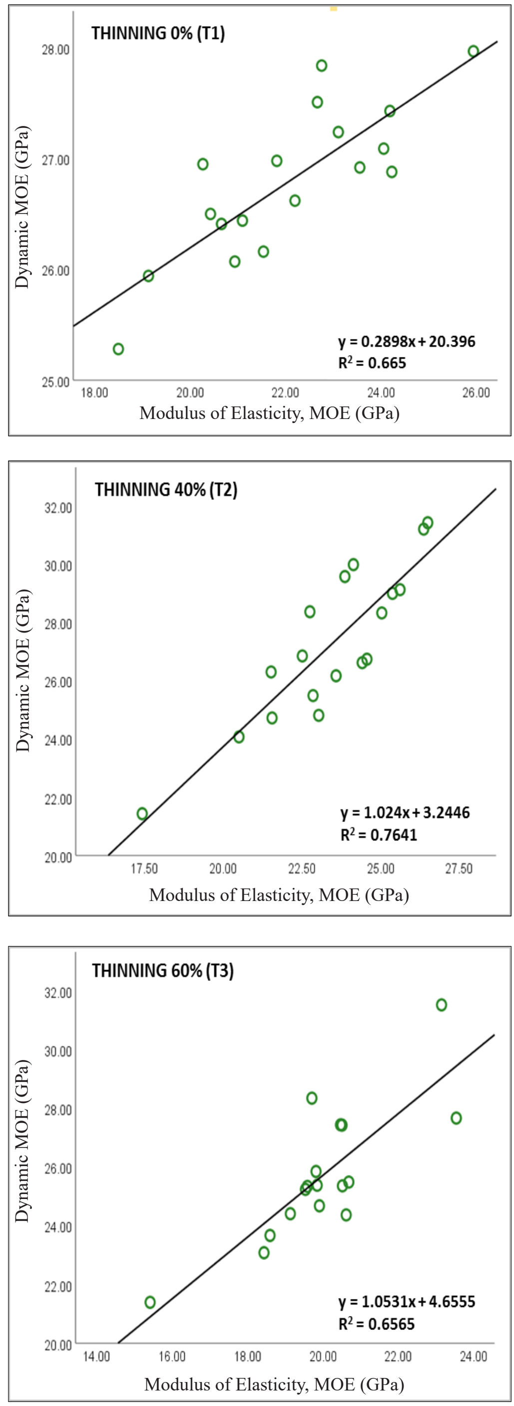


Figure 14. Relationship between static MOE and dynamic MOE obtained from billets of *E. pellita*

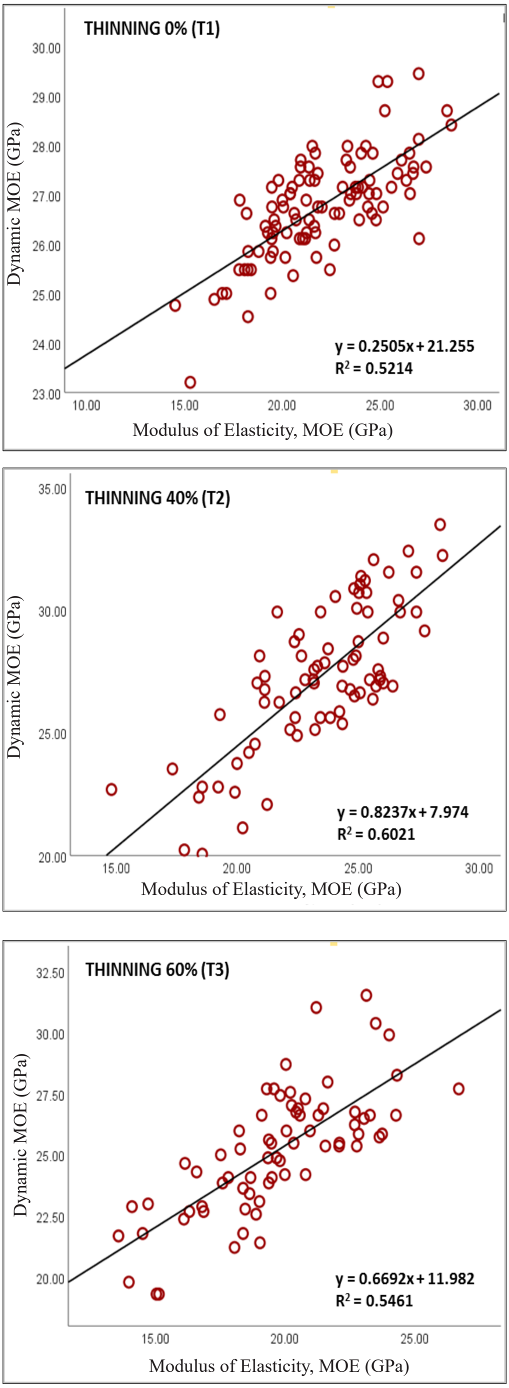


Figure 15. Relationship between static MOE and dynamic MOE obtained from wood slabs of *E. pellita*

on the dynamic MOE values. The result is consistent with research by Papandrea et al. (2022) and Van and Schimleck (2022), demonstrating a strong relationship between the dynamic MOE and static MOE of standing trees and logs from poplar and eucalyptus clones. The study also shows that the wood density influences dynamic MOE in hardwood species. This result indicates that the AV that relies on the TOF principle gives an excellent predictive value of static MOE properties tested on the small clear samples of *E. pellita* wood.

CONCLUSION

Thinning treatment does affect the physical and mechanical properties of *E. pellita* wood. We also concluded that thinning treatment at a moderate thinning intensity (40%) could enhance the rigidity and strength properties of *E.pellita* wood. This study also revealed that the acoustic velocity method could predict static MOE by positively correlating dynamic MOE with $R^2 = 0.46$, $R^2 = 0.60$, and $R^2 = 0.53$ on standing trees, billets, and wood slabs.

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REFERENCES

Alwi, A., Meder, R., Japarudin, Y., Hamid, H. A., Sanusi, R., & Yusoff, K. H. M. (2021). Near-infrared spectroscopy of Eucalyptus pellita for foliar nutrients and the potential for real-time monitoring of trees in fertiliser trial plots. *Journal of Near Infrared Spectroscopy*, *29*(3), 158-167. https://doi.org/10.1177/09670335211007971

American Society for Testing and Materials. (2023). D143. Standard Test Methods for Small Clear Specimens of Timber. ASTM International. https://www.astm.org/d0143-22.html

Antony, F., Schimleck, L. R., Jordan, L., Daniels, R. F., & Clark, A. (2012). Modeling the effect of initial planting density on a within-tree variation of stiffness in loblolly pine. *Annals of Forest Science*, *69*(5), 641-650. https://doi.org/10.1007/s13595-011-0180-1

Auty, D., Achim, A., Macdonald, E., Cameron, A. D., & Gardiner, B. A. (2016). Models for predicting clear wood mechanical properties of Scots pine. *Forest Science*, *62*(4), 403-413. https://doi.org/10.5849/forsci.15-092

Auty, D., & Achim, A. (2008). The relationship between standing tree acoustic assessment and timber quality in Scots pine and the practical implications for assessing timber quality from naturally regenerated stands. *Forestry*, *81*(4), 475-487. https://doi.org/10.1093/forestry/cpn015

Ayanleye, S. (2020). *Assessment of some wood properties by near infrared spectroscopy* [Doctoral dissertation, University of British Columbia].

Baettig, R., Cornejo, J., & Guajardo, J. (2017). Evaluation of intra-ring wood density profiles using NIRS: comparison with the X-ray method. *Annals of Forest Science*, *74*(1), 1-8. https://doi.org/10.1007/s13595-016-0597-7

Balasso, M., Hunt, M., Jacobs, A., & O'Reilly-Wapstra, J. (2021). Characterisation of wood quality of *Eucalyptus nitens* plantations and predictive models of density and stiffness with site and tree characteristics. *Forest Ecology and Management*, *491*, 118992. https://doi.org/10.1016/j.foreco.2021.118992

Barotto, A. J., Monteoliva, S., Gyenge, J. E., Martinez Meier, A., Moreno, K., Tesón, N., & Fernández, M. E. (2017). Wood density and anatomy of three *Eucalyptus* species: Implications for hydraulic conductivity. *Forest Systems, 26*(1), e010. https://doi.org/10.5424/fs/2017261-10446

Bhandari, S. K., Veneklaas, E. J., McCaw, L., Mazanec, R., & Renton, M. (2022). Effect of thinning on growth and allometry of *Eucalyptus* diversicolor. *Southern Forests: A Journal of Forest Science*, *84*(4), 298-310. https://doi.org/10.2989/20702620.2022.2155090

Bhandari, S. K., Veneklaas, E. J., McCaw, L., Mazanec, R., Whitford, K., & Renton, M. (2021). Effect of thinning and fertiliser on growth and allometry of *Eucalyptus marginata*. *Forest Ecology and Management*, *479*, 118594. https://doi.org/10.1016/j.foreco.2020.118594

Binkley, D., Campoe, O. C., Alvares, C., Carneiro, R. L., Cegatta, Í., & Stape, J. L. (2017). The interactions of climate, spacing, and genetics on clonal *Eucalyptus* plantations across Brazil and Uruguay. *Forest Ecology and Management*, *405*, 271-283. https://doi.org/10.1016/j.foreco.2017.09.050

Butler, M. A., Dahlen, J., Eberhardt, T. L., Montes, C., Antony, F., & Daniels, R. F. (2017). Acoustic evaluation of loblolly pine tree and lumber-length logs allows for segregation of lumber modulus of elasticity, not for modulus of rupture. *Annals of Forest Science*, *74*(1), 1-15. https://doi.org/10.1007/s13595-016-0615-9

Candel-Pérez, D., Lo, Y. H., Blanco, J. A., Chiu, C. M., Camarero, J. J., González de Andrés, E., Imbert, J. B., & Castillo, F. J. (2018). Drought-induced changes in wood density are not prevented by thinning in Scots pine stands. *Forests*, *9*(1), 4. https://doi.org/10.3390/f9010004

Carter, P., Briggs, D., Ross, R. J., & Wang, X. (2005). Acoustic testing to enhance western forest values and meet customer wood quality needs. In C. A. Harrington, & S. H. Schoenholtz (Eds.)., *Productivity of western forests: A forest products focus* (pp. 121-129). United States Department of Agriculture, Forest Service, Pacific Northwest Research StationGeneral Technical Report PNW; GTR-642.

Chen, Z. Q., Karlsson, B., Lundqvist, S. O., García Gil, M. R., Olsson, L., & Wu, H. X. (2015). Estimating solid wood properties using Pilodyn and acoustic velocity on standing trees of Norway spruce. *Annals of Forest Science, 72*(4), 499-508. https://doi.org/10.1007/s13595-015-0458-9

Coletta, V., Menguzzato, G., Pellicone, G., Veltri, A., & Marziliano, P. A. (2016). Effect of thinning on above-ground biomass accumulation in a Douglas-fir plantation in southern Italy. *Journal of Forestry Research*, *27*, 1313-1320. https://doi.org/10.1007/s11676-016-0247-9

Derikvand, M., Kotlarewski, N., Lee, M., Jiao, H., & Nolan, G. (2019). Characterisation of physical and mechanical properties of unthinned and unpruned plantation-grown *Eucalyptus nitens* H. Deane & Maiden lumber. *Forests*, *10*(2), 194. https://doi.org/10.3390/f10020194

de Moraes Gonçalves, J. L., Stape, J. L., Laclau, J. P., Smethurst, P., & Gava, J. L. (2004). Silvicultural effects on the productivity and wood quality of eucalypt plantations. *Forest Ecology and Management*, *193*(1-2), 45-61. https://doi.org/10.1016/j.foreco.2004.01.022

Fundova, I., Funda, T., & Wu, H. X. (2019). Non-destructive assessment of wood stiffness in Scots pine (*Pinus sylvestris* L.) and its use in forest tree improvement. *Forests*, *10*(6), 491. https://doi.org/10.3390/f10060491

Gao, S., Wang, X., Wiemann, M. C., Brashaw, B. K., Ross, R. J., & Wang, L. (2017). A critical analysis of methods for rapid and non-destructive determination of wood density in standing trees. *Annals of Forest Science*, *74*(2), 1-13. https://doi.org/10.1007/s13595-017-0623-4

Gendvilas, V., Downes, G. M., Neyland, M., Hunt, M., Harrison, P. A., Jacobs, A., Williams, D. & O'Reilly-Wapstra, J. (2021). Thinning influences wood properties of plantation-grown *Eucalyptus nitens* at three sites in Tasmania. Forests, 12(10), 1304. https://doi.org/10.3390/f12101304

Hii, S. Y., Ha, K. S., Ngui, M. L., Ak Penguang, S., Duju, A., Teng, X. Y., & Meder, R. (2017). Assessment of plantation-grown *Eucalyptus pellita* in Borneo, Malaysia, for solid wood utilisation. *Australian Forestry*, *80*(1), 26-33. https://doi.org/10.1080/00049158.2016.1272526

International Organization for Standardization. (2019). ISO 3129:2019. *Wood – Sampling methods and general requirements for physical and mechanical testing of small clear wood specimens.* https://www.iso.org/standard/74839.html

International Organization for Standardization. (2014). ISO 13061:2014. *Physical and mechanical properties of wood – Test methods for small clear wood specimens* (ISO 1306:2014). https://www.iso.org/standard/60063.html

Japarudin, Y., Meder, R., Lapammu, M., Alwi, A., & Brown, M. (2022). Non-destructive evaluation of strength and stiffness of *Eucalyptus pellita*. A comparison of near-infrared spectroscopy and acoustic wave velocity assessment. *Journal of Near Infrared Spectroscopy*, *30*(5), 270-278. https://doi.org/10.1177/09670335221117301

Lahr, F. A., Nogueira, M. C., Araujo, V. A. D., Vasconcelos, J. S., & Christoforo, A. L. (2017). Physical-mechanical characterisation of *Eucalyptus urophylla* wood. *Engenharia Agrícola*, *37*, 900-906. http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v37n5p900-906/2017

Legg, M., & Bradley, S. (2016). Measurement of stiffness of standing trees and felled logs using acoustics: A review. *The Journal of the Acoustical Society of America*, *139*(2), 588-604. https://doi.org/10.1121/1.4940210

Listyanto, T., & Nichols, J. D. (2009). A review of relationships between wood quality and silvicultural practices. *Jurnal Ilmu Kehutanan*, *3*(2), 116-126. https://doi.org/10.22146/jik.1513

Liu, F., Zhang, H., Wang, X., Jiang, F., Yu, W., & Ross, R. J. (2021). Acoustic wave propagation in Standing Trees-Part II. Effects of tree diameter and juvenile wood. *Wood and Fiber Science*, *53*(2), 95-108. https://doi.org/10.22382/wfs-2021-12

Liu, C., Zhang, S. Y., Cloutier, A., & Rycabel, T. (2007). Modelling lumber bending stiffness and strength in natural black spruce stands using stand and tree characteristics. *Forest Ecology and Management*, *242*(2-3), 648-655. https://doi.org/10.1016/j.foreco.2007.01.077

Marini, F., Manetti, M. C., Corona, P., Portoghesi, L., Vinciguerra, V., Tamantini, S., Kuzminsky, E., Zikeli, F., & Romagnoli, M. (2021). Influence of forest stand characteristics on physical, mechanical properties and chemistry of chestnut wood. *Scientific Reports*, *11*(1), 1-10. https://doi.org/10.1038/s41598-020-80558-w

Nogueira, G. S., Marshall, P. L., Leite, H. G., & Campos, J. C. C. (2015). Thinning intensity and pruning impacts on Eucalyptus plantations in Brazil. *International Journal of Forestry Research*, *2015*(1), 168390. https://doi.org/10.1155/2015/168390

Papandrea, S. F., Cataldo, M. F., Bernardi, B., Zimbalatti, G., & Proto, A. R. (2022). The predictive accuracy of Modulus of Elasticity (MOE) in the wood of standing trees and logs. *Forests*, *13*(8), 1273. https://doi.org/10.3390/f13081273

Prasetyo, A., Aiso, H., Ishiguri, F., Wahyudi, I., Wijaya, I. P. G., Ohshima, J., & Yokota, S. (2017). Variations on growth characteristics and wood properties of three *Eucalyptus* species planted for pulpwood in Indonesia. *Tropics*, *26*(2), 59-69. https://doi.org/10.3759/tropics.ms16-15

Proto, A. R., Macrì, G., Bernardini, V., Russo, D., & Zimbalatti, G. (2017). Acoustic evaluation of wood quality with a non-destructive method in standing trees: The first survey in Italy. *iForest-Biogeosciences and Forestry*, *10*(4), 700. https://doi.org/10.3832/ifor2065-010

Raymond, C. A. (2002). Genetics of *Eucalyptus* wood properties. *Annals of Forest Science*, *59*(5-6), 525-531. https://doi.org/10.1051/forest:2002037

Roux, J., & Wingfield, M. J. (2009). Ceratocystis species: Emerging pathogens of non-native plantation *Eucalyptus* and *Acacia* species. *Southern Forests: A Journal of Forest Science*, *71*(2), 115-120. https://doi.org/10.2989/sf.2009.71.2.5.820

Russo, D., Marziliano, P. A., Macri, G., Proto, A. R., Zimbalatti, G., & Lombardi, F. (2019). Does thinning intensity affect wood quality? An analysis of Calabrian Pine in Southern Italy using a non-destructive acoustic method. *Forests*, *10*(4), 303. https://doi.org/10.3390/f10040303

Schimleck, L., Dahlen, J., Apiolaza, L. A., Downes, G., Emms, G., Evans, R., Moore, J., Paques, L., Van den Bulke, J., & Wang, X. (2019). Non-destructive evaluation techniques and what they tell us about wood property variation. *Forests*, *10*(9), 728. https://doi.org/10.3390/f10090728

Sharma, V., Yadav, J., Kumar, R., Tesarova, D., Ekielski, A., & Mishra, P. K. (2020). On the rapid and non-destructive approach for wood identification using ATR-FTIR spectroscopy and chemometric methods. *Vibrational Spectroscopy*, *110*, 103097. https://doi.org/10.1016/j.vibspec.2020.103097

Todaro, L., & Macchioni, N. (2011). Wood properties of young Douglas-fir in Southern Italy: Results over a 12-year post-thinning period. *European Journal of Forest Research*, *130*(2), 251-261. https://doi.org/10.1007/s10342-010-0425-9

Van Duong, D., & Schimleck, L. (2022). Prediction of static bending properties of *Eucalyptus* clones using stress wave measurements on standing trees, logs, and small clear specimens. *Forests*, *13*(10), 1728. https://doi.org/10.3390/f13101728

Wang, X., Carter, P., Ross, R. J., & Brashaw, B. K. (2007). Acoustic assessment of wood quality of raw forest materials-a path to increased profitability. *Forest Products Journal*, *57*(5), 6.

Wang, X., Ross, R. J., McClellan, M., Barbour, R. J., Erickson, J. R., Forsman, J. W., & McGinnis, G. D. (2000). *Strength and stiffness assessment of standing trees using a non-destructive stress wave technique*. United States, Department of Agriculture, Forest Service, Forest Products Laboratory.