

Pertanika Journal of

# SCIENCE & TECHNOLOGY

VOL. 32 (S4) 2024

A Special Issue Devoted to
Forest Industry Related Environmental Issues,
Possibilities, and Challenges

Guest Editors Zaiton Samdin, Ruzana Sanusi and Norfaryanti Kamaruddin



A scientific journal published by Universiti Putra Malaysia Press

#### Pertanika Journal of Science & Technology

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Recognized internationally as the leading peer-reviewed interdisciplinary journal devoted to the publication of original papers, it serves as a forum for practical approaches to improving quality in issues pertaining to science and engineering and its related fields.

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#### Pertanika Journal of

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(Special Issue)

**Guest Editors** 

Zaiton Samdin, Ruzana Sanusi and Norfaryanti Kamaruddin



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#### **Preface**

We are delighted to introduce the Pertanika Journal of Science and Technology Special Issue, coinciding with the 6<sup>th</sup> Wood and Biofibre International Conference 2023 (WOBIC 2023). Themed "Forest to Shelves: Roles in Climate Change and Community Entrepreneurship," this edition explores the pivotal roles and interactions between the forest industry and environmental management.

The forest industry and environmental management are deeply interconnected, necessitating careful coordination and collaboration. Proper environmental management ensures the sustainable utilisation of forest resources and is crucial in mitigating the adverse impacts on our ecosystems. Conversely, the forest industry contributes to environmental management through responsible practices, conservation efforts, and biodiversity promotion.

This Special Issue, "Forest Industry Related Environmental Issues, Possibilities, and Challenges," delves into a wide range of topics that illuminate the challenges and opportunities for advancing sustainable practices. It deepens the understanding of how the forest industry can contribute positively to environmental management, benefiting both our ecosystems and the communities that rely on them.

This compilation provides an essential platform for examining the complex dynamics between the forest industry and environmental management. It emphasises effective bioremediation techniques to address environmental challenges, reduce pollutants, restore ecological balance, optimise wood quality and landslide risk mitigation strategies and enhance the resilience of the forest industry. This issue seeks to promote a comprehensive understanding of the sector's challenges and opportunities, fostering collaboration and encouraging sustainable initiatives for ecologically harmonious coexistence by presenting a wide array of topics and viewpoints. In addition, it also facilitates a deeper understanding of managing and utilising forest resources for various industrial and community applications, contributing to healthier forest ecosystems and promoting sustainable forest resource use.

We trust that readers will find this Special Issue enlightening and inspiring. It offers valuable insights and encourages adopting sustainable practices that foster a balanced relationship between the forest industry and the environment. Through the diverse perspectives and discussions featured here, we aspire to

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spur meaningful dialogue, enhance collaboration, and inspire innovations in environmental management. May this issue catalyse positive change, contributing to a resilient and sustainable future for our forest ecosystems and their dependent communities.

#### **Guest Editors**

Zaiton Samdin (Prof. Dr.) Ruzana Sanusi (Dr.) Norfaryanti Kamaruddin (Dr.)



#### SCIENCE & TECHNOLOGY

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

Noorsyazwani Mansoor<sup>1</sup>, Adlin Sabrina Muhammad Roseley<sup>1,2\*</sup>, Seca Gandaseca<sup>3</sup>, Sabiha Salim<sup>1</sup>, Rasdianah Dahali<sup>2</sup> and Lee Seng Hua<sup>4</sup>

<sup>1</sup>Faculty of Forestry and Environment, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia <sup>2</sup>Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

<sup>3</sup>School of Biology, Faculty of Applied Science, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia <sup>4</sup>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

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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

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

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	10 x 10
		(>40% of clays)	

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.

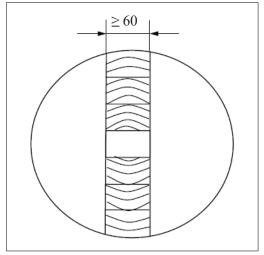


Figure 2. The general cutting pattern of a log with a diameter > 180 mm

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.

$$MOE_{dyn} = \rho AV^2 \tag{1}$$

Where MOE<sub>dyn</sub> is the dynamic MOE (Nmm<sup>-2</sup>),  $\rho$  is the wood density (kgm<sup>-3</sup>), and AV is the velocity of the stress wave (ms<sup>-1</sup>). 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:

$$Vel = \frac{S}{TOF} \tag{2}$$

Where Vel is the acoustic velocity (ms¹), 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.

#### **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:



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

$$Green \ density = \frac{Mass_g}{Volume_g} \tag{3}$$

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<sup>3</sup>, of the test piece

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

#### **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  $65 \pm 5$  % and temperature of  $20 \pm 2^{\circ}$ 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:

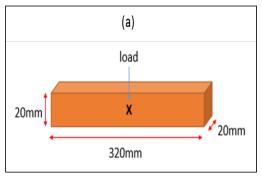


Figure 4. Dimension of sample test for bending test



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

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

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<sup>2</sup> (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,

 $\alpha$ : 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<sup>2</sup> (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<sup>2</sup> (MPa).

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

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

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<sup>2</sup> (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<sup>3</sup>, was determined. The density  $\rho_0$  was calculated in kg/m<sup>3</sup> 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<sup>3</sup> (or cm<sup>3</sup>), of the test piece in the dehydrated condition.

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

#### **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<sup>3</sup> (or cm<sup>3</sup>), of the test piece.

The results were expressed to the nearest 5 kg/m³ (0.005 g/cm³).

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

#### 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

	Basic density							Green d	lensity	
Thinning intensities	N	Mean value (kgm <sup>-3</sup> )	SD	Min	Max	N	Mean value (kgm <sup>-3</sup> )	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

<sup>\*</sup>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<sup>-3</sup>. The mean value of wood density in the variation of thinning intensities ranged from 568 kgm<sup>-3</sup> to 634 kgm<sup>-3</sup>. The wood density was higher (634 kgm<sup>-3</sup>) in thinning 1 (40%) compared to thinning 3 (60%), which is 568 kgm<sup>-3</sup>. 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).

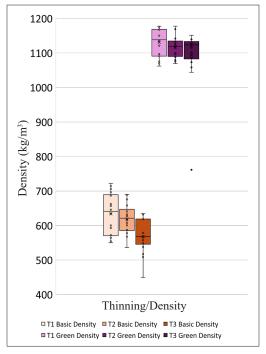


Figure 7. Boxplot of wood density of *E.pellita* under all thinning intensities

#### **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

<sup>\*</sup>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).

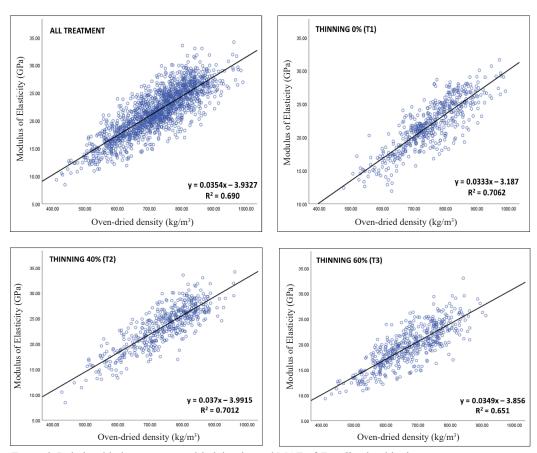
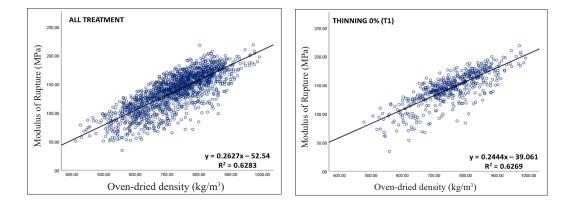
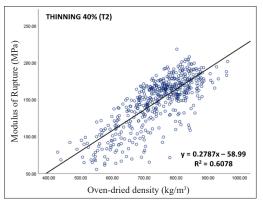


Figure 8. Relationship between oven-dried density and MOE of E. pellita by thinning





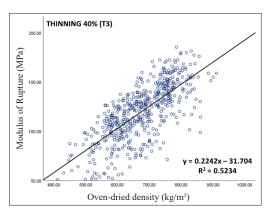


Figure 9. Relationship between oven-dried density and MOR of E. pellita by thinning

#### 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.

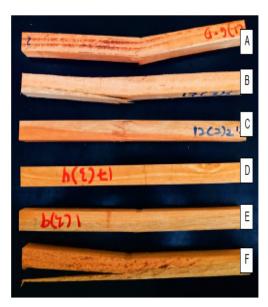


Figure 10. Types of failure mode in bending test

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.

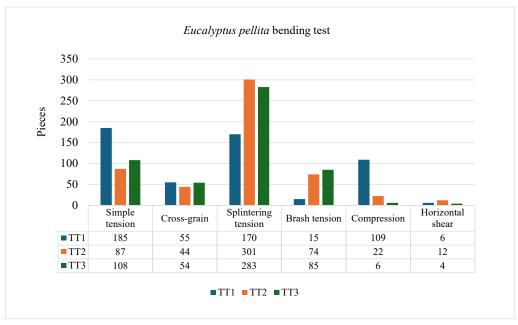


Figure 11. The failure mode for each sample from all three thinning

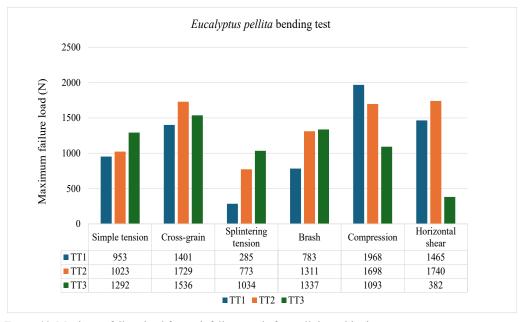


Figure 12. Maximum failure load for each failure mode from all three thinning

1		5				J			
Thinning		Tree			Billet			Wood slab	
intensities	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

Table 4

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

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).

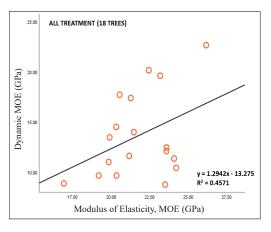
All thinning 1, 2, and 3 show a positive correlation between the dynamic MOE and static MOE of *E. pellita* obtained from billets and wood slabs, as shown in Figure 14 and Figure 15

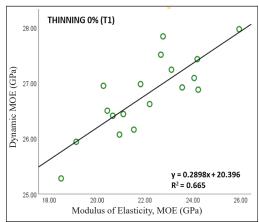
This study shows that moderate thinning treatment can enhance the elasticity properties of *E.pellita* wood, as the same results were observed in the previous study conducted by Russo et al. (2019). Furthermore, using a moderate thinning intensity can be a good choice for producing wood-based products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

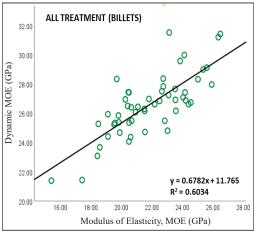
Wood conditions (density) were a few factors affecting the distribution of acoustic waves through the wood. The particles of denser wood were closely packed together, leading to more resistance to transfer the sound wave vibrations compared to less dense materials. Results from this study show as the 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).

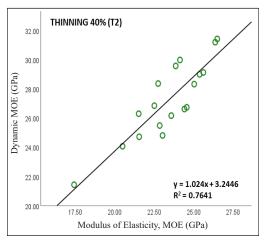
This study found a positive correlation between the dynamic MOE and static MOE on 18 trees, billets and wood slabs, as these equations can predict the static MOE based

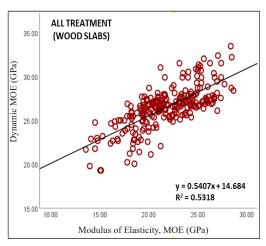
<sup>\*</sup>SD = standard deviation

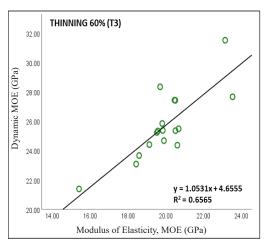






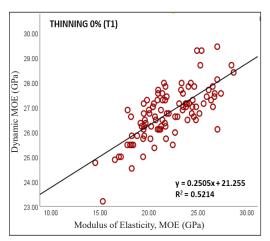


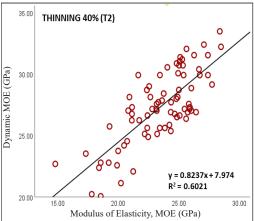




*Figure 13.* Relationship between static MOE and dynamic MOE under all thinning obtained from trees, billets, and wood slabs of *E. pellita* 

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





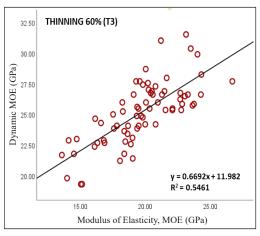


Figure 15. Relationship between static MOE and dynamic MOE obtained from wood slabs of *E. pellita* 

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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## Macronutrient Interactions and Microbial Population in Ultisols and Spodosols Affecting the Incidence of Ganoderma Disease

Cindy Diah Ayu Fitriana<sup>1,2\*</sup>, Herry Wirianata<sup>1</sup>, Yohana Maria Theresia Astuti<sup>1</sup>, Fariha Wilisiani<sup>1</sup>, Sukarman<sup>2</sup>, Septa Primananda<sup>2</sup> and Wahyuni Puji Utami<sup>1,2</sup>

#### **ABSTRACT**

The spread of Ganoderma disease in oil palm plantations is affected by several factors, one of the most significant being the soil type. Different soil types influence the availability of nutrients and moisture, which can affect the growth and spread of Ganoderma. This study investigates the impact of spodosols and ultisols on soil macronutrient dynamics and their effect on microbial populations, ultimately influencing Ganoderma distribution. Using a nested sampling design, we collected data from 120 palms across 411 hectares. We analyzed the impact of soil type (sand, ultisol) on soil pH, organic carbon, macronutrients (P-total, P-Bray, Exchangeable K, Exc-Mg, Exc-Ca), and bacterial and fungal populations at 1 m, 2 m, and 3 m distances from infected and healthy palms. Data analysis employed Two-Way ANOVA. The results reveal that soil pH and organic carbon positively influenced Ganoderma incidence in spodosol soil. At the same time, macronutrients P-total, P-Bray, and K had positive interactions with the disease in both soil types. Conversely,

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E-mail addresses:

cindy.fitriana@id.wilmar-intl.com (Cindy Diah Ayu Fitriana) her.wirianata@gmail.com (Herry Wirianata) astutimaria2000@gmail.com (Yohana Maria Theresia Astuti) farihawilis@gmail.com (Fariha Wilisiani) sukarman.ace@id.wilmar-intl.com (Sukarman) septa.primananda@id.wilmar-intl.com (Septa Primananda) utami.wahyunipuji@gmail.com (Wahyuni Puji Utami) \*Corresponding author

Exc-Mg and Exc-Ca showed positive interactions in spodosol soil but negative interactions in ultisol soil. Nitrogen had no significant impact on spodosol soil. Regarding microbial populations, ultisol soil exhibited higher bacterial populations around infected palms (23.4% at 1 m and 12.5% at 3 m). Spodosol soil showed higher bacterial populations further away (2.3% at 1 m and 41.3% at 3 m). Fungal populations were higher in ultisol soil compared to spodosol soil for infected palms (27.01 x

<sup>&</sup>lt;sup>1</sup>Program Magister Manajemen Perkebunan, Institute of Stiper, 55281 INSTIPER Maguwoharjo, Yogyakarta, Indonesia

<sup>&</sup>lt;sup>2</sup>Ecological Management Unit Research and Development Department of Wilmar International Plantation, Central Kalimantan, Indonesia

 $10^6$  cfu/g and  $26.00 \times 10^6$  cfu/g, respectively). This study highlights the complex interplay between soil type, macronutrients, microbial populations, and the spread of Ganoderma. These findings inform the development of effective disease management strategies for oil palm plantations.

Keywords: Ganoderma spp, macronutrient, microbes, oil palm, soil type

#### INTRODUCTION

Ganoderma "spp" is a soil-borne pathogen in the Basidiomycota Fungal Family (Corley & Tinker, 2015). The fungus can infect plants through roots and airborne basidiospores, capable of degrading lignin, a key plant structural component (Paterson, 2007). Some Ganoderma species act as pathogens in oil palm plants, causing basal stem rot in both lower and upper stem regions. Oil palm plants affected by Ganoderma "spp" tend to be challenging to detect in the early stages of infection. The dispersal of Ganoderma "spp" spores during the initial infection occurs within the plant's tissues, and further attacks manifest as physiological changes (Chong et al., 2017). In the initial stages of Ganoderma infection, physiological changes in the palm are characterized by the formation of more than three spear leaves and withered fronds, and further attacks lead to the development of fruiting bodies on oil palm trees (Pilotti, 2005). The formation of fruiting bodies on oil palm trees has high potential as an active source of inoculum, dispersing spores with wind assistance in the morning and evening. Ganoderma's fruiting bodies (basidia) release spores, visually resembling mist. Spore dispersion originating from basidia formed in the trunk of oil palm trees has the potential to accelerate the spread of the disease in healthy palms (Hamzah et al., 2021). When the palm trunk becomes hollow, the plant reaches a high severity level and finds it difficult to maintain productivity. Ganoderma fungal attacks exhibit internal symptoms, such as a color change from white to brown in the cortex tissue, causing the cortex tissue to become brittle and the trunk to hollow out (Soetopo et al., 2022).

One of the factors influencing the spread of Ganoderma disease in the field is the variation in soil characteristics. The characteristics of different soil types can significantly affect the soil's physical, chemical, and nutritional properties, consequently influencing the growth and development of Ganoderma in oil palm plantations. Soil pore characteristics, such as size, shape, and availability, can impact spore migration within the soil (Aziz et al., 2019). Larger pores can facilitate spore movement, allowing them to travel faster and farther (Gałązka et al., 2017). Widiastuti et al. (2018) discovered a correlation between soil nutrient status and Ganoderma infestation, with potassium (K) and magnesium (Mg) exhibiting significant effects. Goh et al. (2020) emphasize the role of a more diverse soil microbial community (bacteria) in soils with high pH and calcium levels, which can suppress the incidence of the disease. Shariffah-Muzaimah et al. (2020) supported this by demonstrating the potential of Streptomyces sp. GanoSA1, a soil actinomycete, in reducing disease incidence. Rakib et al. (2017) highlight the importance of micronutrients,

especially copper (Cu) and zinc (Zn), in the spatial distribution of Ganoderma species, with lower concentrations of these nutrients in infected areas. Zhang et al.'s (2012) research indicates a positive correlation between the availability of organic matter in the soil and the Ganoderma population.

Several previous studies have identified an interaction between spodosol soil type, pH acidity, and a 25–35°C temperature range as optimum conditions for developing G. lucidum (Kapoor & Sharma, 2014). Rees et al. (2007) found that the disease is more severe in areas with high humidity, while growth is inhibited at high temperatures (>40°C). Soil texture can also impact nutrient availability and soil moisture, influencing spore growth and dispersion (Nazir et al., 2010). Soils with high sand content tend to have good drainage but may struggle to retain water and nutrients (Gerendas et al., 2013; Matichenkov et al., 2020). When nutrients are easily leached or dissolved from spodosol soil, pathogenic microorganisms may face limitations in the nutritional resources required for their growth and development (Matichenkov et al., 2020). However, there is no research on the differences in physical, chemical, and biological soil characteristics around Ganodermainfected and healthy plants in two different soil types (spodosol and ultisol). This study analyzes the differences in physical, chemical, and biological soil characteristics around plants infected with Ganoderma and healthy plants in two soil types, namely Spodosols and Ultisols). Therefore, this study is crucial for analyzing the interrelated factors influencing the vulnerability of oil palm plants to Ganoderma infection. This research is intended to provide recommendations regarding nutrient management for plants in Ganoderma-endemic areas and to offer a general overview of the developmental patterns of Ganoderma in two distinct soil types.

#### MATERIALS AND METHODS

The research was conducted in oil palm plantations in Wilmar International Plantation Region Central Kalimantan at four locations, each with two different soil type characteristics (Figure 1). Ultisol soil sampling was carried out at MS and KSY, while Spodosol soil sampling was conducted at MS and KKP.

#### **Materials**

The instruments utilized in this research include a thermohygrometer for measuring temperature and humidity, a lux meter for light intensity measurements, a Global Positioning System (GPS) for geographical location, a soil auger for soil sampling, and petri dishes and beaker glasses for sample preparation. A Laminar Air Flow Cabinet (LAFC), autoclave for sterilization, colony counter for bacterial enumeration, orbital shaker, and stirrer lever are employed for biochemical processes. Additional laboratory equipment includes an L-stick, forceps, and a Bunsen burner.



Figure 1. Location of research (Wilmar Plantation, 2023)

The materials comprise Nutrient Agar (NA) and Potato Dextrose Agar (PDA) for microbial growth media, King's B Medium for specific cultivation, and soil and leaf samples. Ganoderma sp. isolates are also included as primary research material.

#### Methods

The flow chart of this research is presented in the following Figure 2.

#### **Soil Sample Selection Technique**

The selection of plant samples was carried out using cluster and purposive sampling, with the details provided in Table 1.

The selection of test plant samples, palm in spodosols (PS) and palm in ultisols soils (MS), was obtained from 30 plants in different locations with similar soil characteristics and plant morphology. Diseased plants selected exhibited characteristic symptoms of Ganoderma infection (wilting fronds, spear leaves not opening, and the presence of basidiocarps). Healthy plant samples were chosen 20 meters from the infected trees at three different sampling distances (1 meter, 2 meters, and 3 meters) (Figure 3).

Soil samples taken using an auger from the same category (soil type, plant health category, and distance) were composited into 5 test samples. Each soil sample from 6 different plants with the same category was composited into 1 test sample (Figure 4).

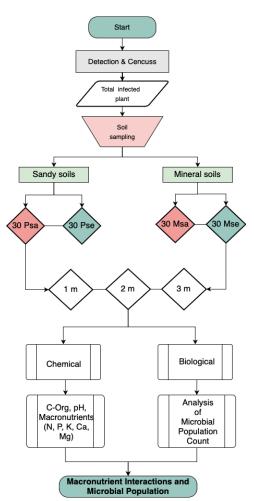


Figure 2. Flow chart macronutrient interactions and microbial population in disease plant and healthy plant

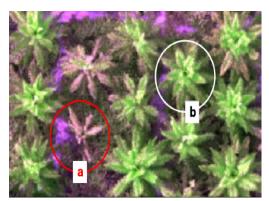


Figure 3. Illustration of sampling point for: (a) infected palms (b) healthy palms (Internal documentation of Wilmar Plantation Indonesia, 2023)





Figure 4. Illustration of soil sampling using auger (Internal documentation of Wilmar Plantation Indonesia, 2023)

Table 1
Soil sampling scheme for physical, chemical, and biological analysis

Sample Specifications	Ssa	Usa	Sse	Use
a. Sampling Location (Location)	30	30	30	30
b. Samples(Nutrient & Microbe Testing)	5	5	5	5
c. Sample Distance (1, 2 & 3) m	3	3	3	3
Total Samples	15	15	15	15

<sup>\*</sup>Ssa (Diseased palms in Spodosols), Sse (Healthy palms in Spodosols), Usa (Diseased palms in Ultisols), Use (Healthy palms in ultisols)

In this experiment, there are 90 diseased palms (Usa) and 90 healthy palms (Use) in ultisol soil, as well as 90 (Ssa) and 90 (Sse) in spodosol soil. Each soil sample was taken from different depths of 0-30, 30-60, and 60-90 cm, composited based on the sampling distance from oil palm trees, which are 1 m, 2 m, and 3 m at 4 points around the sample plant (Figure 5).

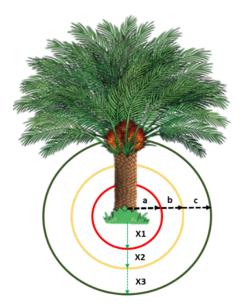


Figure 5. Scheme for soil sampling in ultisol and spodosol soils at different depths. (a: 1 meter, b: 2 meters, c: 3 meters, x1: soil depth 10–20 cm, x2: soil depth 20–40 cm, x3: soil depth 40–60 cm)

# Analysis of Soil Macronutrients and Micronutrients

The soil samples collected according to the specified categories in Figures 1 and 2 were analyzed for their macronutrients and micronutrients in the chemical laboratory of the Ecological Management Unit R&D Department at Wilmar Central Kalimantan. Nitrogen analysis in the soil was conducted using the Kjeldahl distillation method, P-bray using the Bray I method, total phosphorus (P-Total) with spectrophotometry using molybdate fanadat reagent, Exc-K, Exc-Ca, and Exc-Mg were analyzed using percolation techniques and detected using tomic Absorption Spectroscopy AAS type AAcle900F.

# **Analysis of Microbial Population Count**

Microbial Population Analysis on Soil Samples from the Root Zone of Healthy and Diseased Plants was conducted following a modified method based on Chaudhary et al. (2019). The composited soil samples were filtered using a 2-mesh sieve, and then 3 grams of soil were randomly sampled according to the treatment. The 3-gram soil samples were mixed with 300 ml of NB and PDB media in Erlenmeyer flasks and incubated in a shaker at room temperature for four days using Flask shaker orbital incubator Unimax: HEIDOLP. A 10 ml sample from the solution was taken, and serial dilution was performed using a 0.85% NaCl saline solution with incremental dilution from 10<sup>-1</sup> to 10<sup>-6</sup>. At each dilution stage, 100 μL was taken and spread-plated on KB and PDA media, followed by incubation at room temperature for four days after inoculation. Different colonies on each petri dish were counted using the following formula. Observations in this test only counted the number of bacterial and fungal populations. The fungi/bacteria analyzed resulted from spread plate

activities in dilutions from  $10^{-2}$  to  $10^{-7}$ , and the number of single colonies formed on PDA/KB/NA media in each petri dish was counted. The colony count range for each dilution was 25–250 colonies; if the count was below or above this range, calculations were not performed on the petri dish. Microbial population calculation analysis was based on the formula (Bellali et al., 2019):

$$Cf \, u/m \, l(g) = \frac{number \, of \, counted \, cells}{Concentration \, x \, Dillution \, factor}$$
[1]

## **Data Analysis**

The data analysis used in this research includes the Two-Way ANOVA test, the Mann-Whitney Test, and the Friedman Test. The data analysis from the treatments of this study was performed with the Duncan Multiple Range Test (DMRT) at a significant level of 5%.

#### RESULTS AND DISCUSSION

# Analysis of pH and Organic Carbon on the Development of Ganoderma

The soil pH and organic carbon analysis results indicate that all soil samples fall into the acidic category (Table 2). This analysis aims to understand the development of soil microorganisms in two different host plants with varying plant health categories.

Table 2 pH analysis results using the KCl method in spodosol and ultisol soil types for diseased and healthy plants

Soil Type	Plants Condition	Sig	pH-KCl
Ultisols	Diseased (Usa)	0.00	$3.680^{a}$
	Healthy (Use)	0.01	$3.210^{ab}$
Spodosols	Diseased (Ssa)	0.41	4.218 <sup>b</sup>
	Healthy (Sse)	0.00	3.783°

Note: Different letters indicate a significant difference

In general, the pH values around healthy plants in ultisol or spodosol soils tend to be more acidic compared to the soil pH around plants infected with Ganoderma. This condition aligns with the typical characteristics of acidic tropical soils, and plants like palm trees can grow well. The higher pH in soils around infected plants may be due to the specific activities of microbes or pathogens. Some microbes or pathogens can produce acids or reduce the availability of certain nutrients for plants, which generally lowers the soil pH, making it more acidic. However, there are specific conditions where microbial activity can lead to more alkaline soil pH if substances that increase pH are produced. It can occur if the decomposition processes in the soil are reduced; thus, the soil pH tends to remain higher or more alkaline (Supriyanto et al., 2020).

The analysis results indicate that the highest organic carbon (C-organic) content, 2.50%, is found in soil samples from the roots infected with Ganoderma (diseased soil). In ultisol soil types, the results differ, with higher C-organic values in the soil area that is not infected with Ganoderma (healthy plants). The lowest C-organic value is observed in the healthy spodosol soil treatment, with a value of 0.95% (Figure 6).

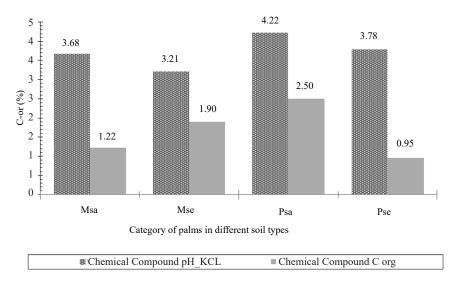


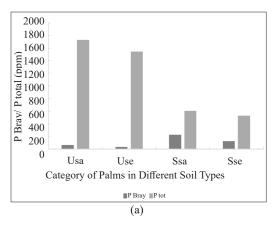
Figure 6. Comparison of pH and C organic values in spodosol soil (Usa & Use) and ultisol soil (Ssa & Sse)

The sandy soil selected as the sampling site belongs to the Spodosols order. Spodosols are characterized by a spodic layer containing a high organic matter content, typically resulting from the accumulation of organic material in the surface layer (Hartati et al., 2021; Santoso et al., 2013). On the other hand, Ultisols tend to form from parent materials that are more acidic and less leached, leading to higher levels of organic matter and lower cation exchange capacity (Fujii et al., 2009). Microorganisms in the soil produce enzymes to decompose organic matter and generate nutrients available for plants and other microbes. The activity of these enzymes is highly influenced by soil pH. Some enzymes operate most efficiently at low pH, while others function optimally at higher pH levels (Reardon et al., 2022).

#### The Role of Soil Macronutrients in the Development of Ganoderma

The soil macronutrient contents analyzed in this study include total phosphorus (P total), P-Bray, total nitrogen (N-total), Exc-K, Exc-Mg, and Exc-Ca, as presented in Figure 7.

Analysis of P-Total and P-Bray in Soil with Ganoderma-Infected Plants in Spodosol (Ssa) and Ultisol (Usa) Soils, and Ganoderma-Uninfected Plants in Spodosol (Sse) and Ultisol (Use) Soils. The P-total values were higher in Ssa and Usa than in Sse and Use.



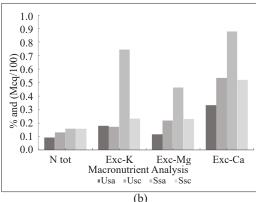


Figure 7. Soil macronutrient analysis in ultisol and spodosol soils, a) Total phosphorus (P-Total) and Bray phosphorus (P-Bray), b) Total nitrogen (N-total), Exc-K, Exc-Mg, Exc-Ca

The P-total value around Ganoderma-infected plants in Usa was 64.8% higher than in Ssa. The variance in P-total around infected plants in ultisol soil was 10.8% higher than healthy plants. Meanwhile, in infected plants in spodosol soil, it was 13.3% higher than in healthy plants. The P-Bray value in Ssa was 71.6% higher than in Usa. The variance in P-Bray around infected plants in spodosol soil was 52.6% higher than healthy plants, whereas in ultisol soil, it was 45.7%. The analysis results show that macronutrient values in spodosol soil are higher than in ultisol soil. Three macronutrient elements in ultisol soil (N-tot, Exc-Mg, and Exc-Ca) were higher in Use than in Usa. Meanwhile, the average nutrient content of Exc-K was higher by 0.1 ppm in Usa and Ssa compared to Use and Sse. Exc-K, Exc-Mg, and Ca values were higher in Ssa and Usa, while there was no difference in nutrient content values for N-total in the soil around sick or healthy plants.

Sandy soil has better drainage than other ultisol soils due to its coarse texture, reducing the risk of waterlogging that can lead to oxidation and phosphorus loss in easily soluble forms (Brown et al., 2017; Byrne et al., 2022). The total phosphorus content in sandy soil potentially tends to be lower than in other ultisol soils; however, phosphorus in sandy soil is more easily accessed by plants and is more available for root absorption (Mayakaduwa et al., 2023). Some plants facing stress or specific pathogen infections can increase the secretion of organic acids or enzymes that alter nutrient availability around the root zone (Castro-moretti et al., 2020). This response can affect the total phosphorus and P-Bray levels in the soil. Phosphorus is one of the essential nutrients Ganoderma requires for growth, cell division, and reproduction (Li et al., 2016). The availability of phosphorus in the soil can also influence the interaction between Ganoderma and its host plants (Hou, 2009). The total nitrogen (N-total) in sandy soil is usually lower than in ultisol soil.

The high N-total content in spodosol soil is presumed to be due to the spodic layer in spodosols, which has a high organic matter content. The difference in N-total between

spodosol and ultisol soils is typically influenced by several factors, including organic matter content, the speed of organic matter decomposition, nitrogen leaching rate, and microorganism activity in the soil (Burgos et al., 2006). Higher N-total levels allow for additional nutrient presence in spodosol soil areas for pathogen development (Tong et al., 2020). Soilborne pathogens can positively respond to increased nitrogen availability in the soil (Shen et al., 2022). High magnesium levels can disrupt calcium absorption, leading to an increased incidence of diseases in plants (Huber & Jones, 2013). Elevated Mg levels in sick oil palm plants in sandy soil can negatively impact calcium absorption by plants. Impaired calcium absorption makes plants susceptible to pathogen attacks and diseases (Gupta et al., 2022).

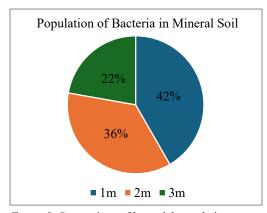
# Role of Soil Biology in the Spread of Ganoderma Enumeration of Bacterial Populations in the Rhizosphere of Oil Palm Trees

The highest bacterial population enumeration was found in the ultisol soil around healthy plants (Use), reaching 294.05 x 10<sup>8</sup> cfu/g of soil (Table 3).

Table 3
Comparison of bacterial populations in the roots of infected and healthy plants (cfu/g)

Code		]	Bacteria		
		1	2	3	(cfu/g)
Usa	Ultisol soils around infected palm	20.60 x 10 <sup>8</sup>	26.37 x 10 <sup>8</sup>	48.39 x 10 <sup>8</sup>	95.36 x 10 <sup>8</sup>
Use	Ultisol soils around non-infected palms	161.74 x 10 <sup>8</sup>	131.97 x 10 <sup>8</sup>	$0.34 \times 10^8$	294.05 x 10 <sup>8</sup>
Ssa	Spodosol soils around infected palms	8.98 x 10 <sup>8</sup>	126.87 x 10 <sup>8</sup>	97.56 x 10 <sup>8</sup>	233.41 x 10 <sup>8</sup>
Sse	Spodosol soils around non-infected palms	2.05 x 10 <sup>8</sup>	4.02 x 10 <sup>8</sup>	2.41 x 10 <sup>8</sup>	8.48 x 10 <sup>8</sup>

In ultisol soil, the highest bacterial population is found at 1 meter (23.4% of the total population), and the lowest is at 3 meters (12.5% of the total population) (Figure 8). Meanwhile, in spodosol soil, the lowest bacterial population is at 1 meter (2.3% of the total population), and the highest is at 3 meters from the plant (4.3%). Thus, it can be concluded that the bacterial population from the exploration results in ultisol soil at distances of 1, 2, and 3 meters is inversely proportional to spodosol soil.



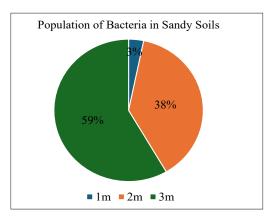


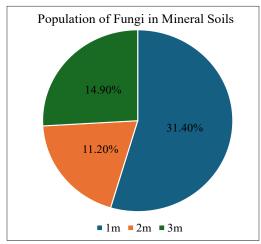
Figure 8. Comparison of bacterial population percentages in spodosol soil (Ssa & Sse) and ultisol soil (Usa & Use) around healthy (Se) and Ganoderma-infected (Sa) plants

The results are presented in Table 4 based on the analysis data of fungal populations in each soil sample. The highest fungal population is around diseased plants in spodosol and ultisol soils. The fungal population is quite high in ultisol soil around diseased plants, reaching 27,012 cfu/g. Meanwhile, in spodosol soil, the fungal population around diseased plants reaches 26,009 cfu/g.

Table 4
Fungal population in spodosol soil (Ssa & Sse) and ultisol soil (Usa & Use) around healthy plants (Se) and Ganoderma-infected plants (Sa)

Code		I	E		
		1	2	3	Fungi (cfu/g)
Usa	Ultisol soils around infected Palm	16.30 x 10 <sup>6</sup>	67.9 x 10 <sup>5</sup>	3.92 x 10 <sup>6</sup>	27.01 x 10 <sup>6</sup>
Use	Ultisol soils around non-infected palms	$2.78 \times 10^6$	0.06 x 10 <sup>5</sup>	0.61x 10 <sup>6</sup>	$3.40 \times 10^6$
Ssa	Spodosol soils around infected palms	15.54 x 10 <sup>6</sup>	$0.97 \times 10^{5}$	10.37x 10 <sup>6</sup>	26.00 x 10 <sup>6</sup>
Sse	Spodosol soils around non-infected palms.	$3.12 \times 10^6$	95.29 x 10 <sup>5</sup>	6.44 x 10 <sup>6</sup>	19.08 x 10 <sup>6</sup>

Considering the proportion of fungal populations at each sampling distance, differences in the distribution patterns of fungi in the two analyzed soil types were observed (Figure 9). In ultisol soil, the highest proportion of fungal population is found at 1 meter from the planting point (31.4%), while the lowest is at 2 meters. It contrasts with spodosol soil, where the highest fungal population is 3 meters from the planting point, while the lowest population is at the same distance as in ultisol soil, which is 2 meters.



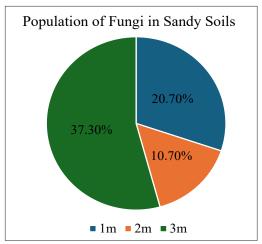


Figure 9. Distribution of fungal populations in spodosol soil (Ssa & Sse) and ultisol soil (Usa & Use) around healthy plants (Se) and Ganoderma-infected plants (Sa)

Source: Author

The higher bacterial population in ultisol soil near the roots of healthy plants at 2-3 meters may be attributed to several factors related to plant root activity and environmental conditions around the roots (Cheng et al., 2022; Jin et al., 2022; Liu et al., 2022). The fungal population in diseased oil palm plants infected with Ganoderma tends to be higher than in healthy plants due to the influence of Ganoderma on soil structure, which can inhibit the growth and activity of microbes in the rhizosphere (Anandyawati et al., 2017).

#### **CONCLUSION**

This study demonstrates the significant influence of soil type on macronutrients, microbial communities, and the distribution of Ganoderma in oil palm plantations. In spodosol soil, pH, organic carbon, P-total, and P-Bray positively impacted Ganoderma occurrence, while exchangeable Mg and Ca showed mixed interactions. Notably, bacterial populations around infected palms were higher at 2–3m in ultisol soil than in spodosol soil. These findings highlight the complexity of soil-disease interactions and emphasize the need for soil-specific management strategies. Optimizing nutrient management based on soil type can enhance plant resistance to Ganoderma. Further research should explore the microbiome differences between healthy and infected areas to understand the broader ecological impact of this disease. By elucidating the intricate relationships between soil properties, microbial dynamics, and the spread of Ganoderma, it can develop more effective and sustainable disease management strategies for diverse oil palm plantation environments.

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# **SCIENCE & TECHNOLOGY**

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# Physico-Mechanical Properties of *Paraserianthes falcataria* (Batai) in Relation to Age and Position Variation

Sarah-Nur Hanis Roslan<sup>1</sup>, Sabiha Salim<sup>1,2</sup>, Adlin Sabrina Muhammad Roseley<sup>1,2\*</sup> and Wan Nur Shasha Najiha Zainal Abidin<sup>2</sup>

<sup>1</sup>Faculty of Forestry and Environment, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia <sup>2</sup>Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

#### **ABSTRACT**

Paraserianthes falcataria, locally known as Batai, is a non-native, fast-growing species selected by Malaysia's forest plantation programme. Limited empirical studies have been conducted regarding this species, specifically the one planted domestically. A comprehensive understanding of its wood properties is essential to effectively introduce and utilise this species commercially. Thus, a study was conducted to evaluate the physico-mechanical properties of Batai and their correlation with age and position variation. In this study, P. falcataria was harvested from a forest plantation in Kuala Krai, Kelantan, Malaysia, encompassing three different age variations: 2.5, 5 and 8 years. Five replicates were felled for each age, and the logs were segmented into three 2 m portions representing variations along the vertical axis: top, middle and bottom. Additionally, radial variation was examined by distinguishing between heartwood and sapwood. Subsequently, samples were tested with static bending and compression tests following standard protocols (ISO 13061-3: 2014, ISO 13061-4, and ISO 13061-17: 2017). The results revealed statistically significant physico-mechanical properties among different ages and within-tree sections. This study

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E-mail addresses:

sarahnurhanisroslan@gmail.com (Sarah-Nur Hanis Roslan) sabiha@upm.edu.my (Sabiha Salim) adlin@upm.edu.my (Adlin Sabrina Muhammad Roseley) wanshasha18@gmail.com (Wan Nur Shasha Najiha Zainal Abidin) \*Corresponding author provides valuable documentation on *P. falcataria* wood properties, contributing to the field's knowledge. Moreover, it exposes the harvesting determinants towards the planters and wood industry, facilitating better utilisation of *P. falcataria* wood across various applications.

*Keywords:* Age, heartwood, *Paraserianthes falcataria*, physical and mechanical properties, position, sapwood

#### INTRODUCTION

In the past, the natural forest served as the primary source of wood supplies. However, with the ongoing decline in wood resources, alternative solutions are being explored and proposed. Rather than sourcing directly from natural forests, the emphasis has shifted towards forest plantation as the central strategy for sustaining the wood industry's supply and demand. Over time, this global initiative has gained momentum, with a critical focus on fast-growing tree species. Among these is Paraserianthes falcataria, a tree categorised as a light hardwood with exceptional quality of rapid growth. Due to this factor, it is listed under the forest plantation programme in Indonesia, Malaysia and the Philippines. P. falcataria is a pioneer species from the Leguminosae family. It originated in Indonesia, primarily from Molucca Island, previously Falcataria moluccana. A few synonyms or aliases are comprised of Albizia moluccana Miq. (1855), Albizia falcata (L.) Backer (1908), Albizia falcataria (L.) Fosberg (1965), Paraserianthes falcataria (L.) I. C. Nielsen (1983), with the latest being Falcataria falcata (L.) (Arche et al, 1998; Govaerts et al., 2021; Rojo, 1997; Soerianegara & Lemmens, 1993). In Malaysia, it is known as Batai by the locals (Malaysian Timber Industry Board [MTIB], 2019), which differs from Indonesia and is called Sengon.

*P. falcataria* forest plantations can be found in a few countries such as Indonesia, Philippines and Malaysia. As in Indonesia, this species has been the accolade of forest plantation and the epitome of commercial wood in the country. In Malaysia, *P. falcataria* species started to gain its limelight after implementing the large-scale commercial Forest Plantation Programme (FPP) by the MTIB in 2006. The vision of the programme was to achieve 375,000 ha of forest plantation with targeted annual planting of 25,000 ha per year within the duration period of 15 years (2006–2020). The total planted areas of *P. falcataria* species in Sabah and Sarawak were 64,500 ha and 14,200 ha, respectively (Ratnasingam et al., 2020). This species is also planted in Peninsular Malaysia, although the data regarding the plantations are still unavailable.

Batai's Mean Annual Increment (MAI) differs based on the grown area due to its surrounding or ecological factors. Even the differences in age and silviculture significantly affect the MAI of this species. According to studies conducted in Indonesia of smallholder plantations in Pati district, Central Java, the average MAI of *P. falcataria* trees ranging from 5 to 6 years old is 19 to 21 m³ ha⁻¹ year⁻¹ (Rohadi et al., 2018). *P. falcataria* trees of a 6-year rotation period that have undergone thinning treatment showed a slight increase in the MAI with a value of 22.5 m³ ha⁻¹ year⁻¹ (Stewart et al., 2021).

Different age rotations also affect the wood properties and qualities, including vertical and radial variations. The usual norm was that the tree's age affected the wood performance as it is related to the ratio of juvenile and mature wood, where the younger age will be more dominated by the former than the latter (Fajriani et al., 2013). Previous studies on

wood with different age rotations reported variation in the specific gravity between the tree of age 5, 7 and 9 years of *P. falcataria*, which seemed to be the transition line between the mature and juvenile parts. Furthermore, the age rotations showed variations in density and mechanical properties (Listyanto, 2018). Juvenile wood has lower quality than mature wood (Dinwoodie, 2000; Shmulsky & Jones, 2019). Thus, it is essential to investigate the effect of different age rotations relating to the suitability of harvesting age, which leads to the quality of timber production.

The position of the wood based on tree height or vertical variation also affects the wood quality. The lateral growth or radial variation significantly affects wood properties due to heartwood and sapwood, including mature wood and core or juvenile. Based on the vertical variation, it was stated that timber density decreases moving up the tree stem, with the bottom part being the densest (Kiaei, 2016). It was proven by the previous study on *P. falcataria* by Akhir and Kasim (2011), which found that the density increases from the top downward towards the bottom. Meanwhile, for radial variation, it was stated that heartwood has better quality and performance than sapwood (Dinwoodie, 2000; Shmulsky & Jones, 2019). However, this is not the case with fast-growing species, such as *E. grandis*, *D. costulata*, and *P. falcataria*, as the sapwood showed superior results in density, whilst density plays a massive role in mechanical strength. It clarifies that more studies need to be conducted on vertical and radial variations of wood to understand the stated topics better.

Alas, the data on the wood properties of this species planted in Malaysia is scarce, thus leading to less local marketability due to quality uncertainty. To overcome the issue, the investigation into *P. falcataria* wood characteristics are required, focusing on local conditions and analysing various age rotations to find the ideal harvesting age and vertical and radial variation for effective resource management. The specific objective of this study is to evaluate the wood physico-mechanical properties of different age rotations of Batai wood, which comprises 2.5, 5 and 8 years, and its correlation with the vertical and radial variation of the tree. Furthermore, the second objective is to analyse the correlation between *P. falcataria* wood density and its mechanical properties. The data obtained in this study can be used further for application purposes and other quality enhancement measures. This paper is targeted to be the guideline for *P. falcataria* wood properties planted in forest plantations, specifically in Kelantan, Malaysia.

#### MATERIALS AND METHODS

#### **Selection of Tree Samples and Harvesting**

The *P. falcataria* trees were carefully selected based on their targeted age variations of 2.5, 5 and 8 years. They were harvested from a plantation located in Kuala Krai, Kelantan, situated on the west coast of Peninsular Malaysia (Figure 1). The planting distance was recorded as 5 x 5 m with silviculture treatment of weeding and a single dosage of slow-release fertilising

treatment. Other treatments, such as vine cutting and pruning, were also practised at the plantation. Five replicates of trees at each age were felled to a standardised 6 m log height. The logs were then divided into three 2 m billets with vertical variations at the top, middle and bottom (Figure 2). The 2 m logs were subsequently processed into wood discs (Figure 3) and wood slabs at a nearby sawmill, with thicknesses of 50 mm and 30 mm, respectively. After processing, the materials were transported from Kelantan to Univesiti Putra Malaysia, Serdang, Selangor and left to dry until the MC reached 12-15% using the air-dried method.



Figure 1. P. falcataria forest plantation in Kelantan

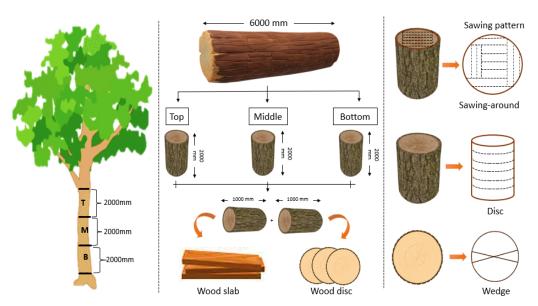


Figure 2. Summary of the harvesting process and sample processing

# **Sample Processing**

Once the sample reached the specified MC of 12–15%, it underwent further processing into a test specimen, varying in size according to the dimensions required by the testing standards. At this stage, the distinction between the sample's heartwood and sapwood was

visually made based on colour differences, as depicted in Figure 4, for the radial variation study.



Figure 3. The differences in wood disc diameter are based on age rotation, where A, B and C represent 2.5, 5 and 8 years, respectively



Figure 4. Differences of colour between sapwood and heartwood of *P. falcataria* 

#### **Log Volume Estimation**

For each tree of all parameters, the diameter of logs, both small end and large end, was measured. The cross-sectional area was first calculated, followed by the log volume calculation. Log volume was estimated using Smalian's formula for straight logs, as in Equation 1, and the volume was expressed in cubic meters.

Volume 
$$(m^3) = \frac{A_1(m) + A_2(m)}{2} x L(m)$$
 (1)

AI is the cross-sectional area of a small end log, A2 is the cross-sectional area of a large end log, and L is the log length.

#### **Wood Properties Evaluation**

## Determination of Green Moisture Content (MC)

The green MC of *P. falcataria* trees was measured using a wood disc cut into a wedge shape consisting of heartwood and sapwood. The evaluation was conducted with two replicates of wedges for each tree of varying ages. The wedges were weighed and placed directly in the oven until a constant mass was achieved. The Green MC was calculated using the following Equation 2:

$$MC_G\% = \frac{Mass_G(g) - Mass_{OD}(g)}{Mass_{OD}(g)} \times 100$$
 (2)

Where  $Mass_G$  is the mass of wood samples in green condition, and  $Mass_{OD}$  is the mass of wood samples after oven-drying at  $103 \pm 2$ °C.

# **Determination of Green Density**

Green density was also evaluated using the same wedge samples obtained from the wood discs, following the same procedure as the Green MC method. The mass of the wedges was measured before oven-drying, and their volume was determined using the water displacement method. Subsequently, the green density was calculated using the following Equation 3:

$$Density_G(kgm^{-3}) = \frac{Mass_G(kg)}{Volume_G(m^3)}$$
(3)

Where  $Mass_G$  is the mass of wood samples in green condition, and  $Volume_G$  is the volume of wood samples in green condition.

# **Basic Density**

The basic density of *P. falcataria* wood was determined by Australian and New Zealand standard (2020), AS/NZ 1080-3 Timber-Method for Density. Basic density was also evaluated from the same wood wedge sample as in the previous green MC and density determination. The basic density was then calculated using the following Equation 4:

Basic density 
$$(kgm^{-3}) = \frac{Mass_{OD}(kg)}{Volume_G(m^3)}$$
 (4)

Where  $Mass_{OD}$  is the mass of wood samples after oven-dried at  $103 \pm 2^{\circ}\text{C}$ , and  $Volume_{OD}$  is the volume of wood samples after oven-drying at  $103 \pm 2^{\circ}\text{C}$ .

## Air-Dried Density and MC

Samples of air-dried density and MC evaluation were a 20 mm x 20 mm x 20 mm cube. The air-dried density and MC evaluation were done according to standard ISO 13061-2:2014, Determination of density for physical and mechanical tests, and ISO 13061-1:2014, Determination of moisture content for physical and mechanical tests, respectively. Samples were weighed, and the sample volume was taken before oven-drying at  $103 \pm 2^{\circ}$ C until constant weight was reached. The constant weight of the sample was then obtained, and air-dried density, including the MC, was calculated and expressed in kgm<sup>-3</sup> and per cent,

respectively. The MC obtained was used to calculate MOE and MOR value adjusted to 12% MC.

#### Static Bending

The static bending test was performed using a Universal Testing Machine INSTRON 5582 (100 kN, INSTRON, Norwood, MA, USA) to determine the modulus of elasticity (MOE) and modulus of rupture (MOR) of *P. falcataria* wood. The test was carried out with 450 replicates per age, with 150 samples each representing the top, middle and bottom for vertical variation. The test pieces were sized at 320 mm x 20 mm x 20 mm and conditioned at the temperature of  $20 \pm 2^{\circ}$ C and relative humidity of  $65 \pm 5^{\circ}$ C before the point load test. The test was carried out using standard ISO 13061-3:2014, Determination of ultimate strength in static bending, and ISO 13061-4:2014, Determination of modulus of elasticity in static bending, for MOR and MOE, respectively. The load was applied at the sample's centre point at a 10 mm/min loading rate. The MOE and MOR were calculated by using the following Equation 5 and 6, which was then adjusted to 12% MC:

Modulus of elasticity (MOE) = 
$$\frac{Pl^3}{4b(h^3)f}$$
 (5)

Modulus of rupture (MOR) = 
$$\frac{3(P_{max})l}{2b(h^2)}$$
 (6)

Where P is the load equal to the difference between the upper and lower limits of loading (N),  $P_{max}$  is the maximum load (N), l is the span (mm), b is the breadth of test piece (mm), h is the height of test piece (mm), and f is the deflection equal to the difference between deflection at upper and lower limits of loading (mm).

#### **Compressive Strength**

The compressive strength of *P. falcataria* wood was assessed through a compression test by the standard ISO 13061-17:2017: Determination of ultimate stress in compression parallel to the grain. The number of replicates matched the samples tested in the bending test. Each sample was processed into a test piece with dimensions of 60 mm x 20 mm x 20 mm. Before testing, the samples were conditioned at a temperature of  $20 \pm 2^{\circ}$ C and relative humidity of  $65 \pm 5^{\circ}$ C. During the test, a load was applied at 1 mm/min. The compressive strength of the sample was calculated using Equation 7 below and later was adjusted to 12% MC:

Compressive strength parallel to grain = 
$$\frac{F_{max}}{a \times b}$$
 (7)

Where  $F_{max}$  is is the maximum load (N), a and b are the cross-sectional dimensions of the test piece (mm), and the compressive strength is expressed in the MPa unit.

#### **Statistical Analysis**

Statistical Package for the Social Sciences (SPSS) software was used to statistically analyse all the data collected during the test to evaluate the physical and mechanical qualities. The General Linear Model Univariate analysis and One-way ANOVA were selected as the analytical approach, and Tukey's HSD test was used to analyse the results further. The Linear Regression Model also examined the relationship between density and mechanical properties. The correlation of density with mechanical properties of the sample for each parameter comprised of different age rotation, vertical and radial variation were studied, where a scatter plot graph of density against mechanical properties was plotted, and the R<sup>2</sup> value of each plot was analysed.

#### RESULTS AND DISCUSSION

#### **Log Volume Estimation**

The volume of logs is essential to determine the best harvesting age, which indirectly leads to better output for planters and the industry. Based on the log volume calculation using Smalian's formula (Şahin & Comak, 2023), the value increases significantly between the age rotation of 2.5 years to 5 years, with a solid increase of 125.7%. In contrast, from 5 years to 8 years, it increases by 45.9%. The log volume based on the different age rotations can be seen in Figure 5.

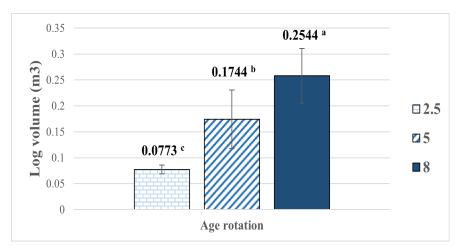


Figure 5. The log volume of *P. falcataria* wood is based on different age rotations. Note: Mean a and b showed significant differences at  $p \le 0.05$ 

# **Physical Properties**

The physical properties of *P. falcataria* were evaluated, including during its green condition and air drying, to gain a deeper understanding and manage data regarding this species.

#### Green MC

The green MC was determined for each age rotation and top, middle and bottom position. As for age rotation of 2.5, 5 and 8 years of *falcataria* tree, the green MC was between 115.0% and 186.1%. In comparison, green MC for top, middle and bottom positions was between 140.0-169.3%, 132.9-185.2%, and 115.0-186.1%, respectively. Based on the result obtained, the age rotation of 2.5 years sample showed the highest green moisture content compared to the other two age rotations, 5 and 8 years. Green MC values are on par but slightly on the higher side with the value of green MC of P. falcataria planted in Indonesia (Listyanto, 2018), but lower when compared to falcataria planted in the Philippines and other parts of Peninsular Malaysia (Akhir & Kasim, 2011; Marasigan et al., 2022). The green MC is also considered high compared to other species (Listyanto, 2018), such as Tectona grandis planted in Java with green MC of 106.2–107.9% (Seta et al., 2023). Thus, proper drying and handling are needed to prevent the strength of the wood from being compromised. Moisture content has a significant effect on wood strength and properties. Rapid or unequal drying can lead to wood defects such as splitting, warping and others, which directly decreases the value of the wood in the market. The green MC values of *P. falcataria* are shown in Table 1.

Table 1

The green moisture content of P. falcataria based on age and vertical variation

Age rotation	N	Green Moisture Content (%)			
(years)	(per age)	Top	Middle	Bottom	Average
2.5	60	169.3	185.2	186.1	$180.9 \pm 32.2^{a}$
5	60	140	132.9	115	$129.3\pm19.7^{c}$
8	60	156.4	165.2	127.9	$149.8\pm30.2^{\text{b}}$

### **Green Density**

The green density of *P. falcataria* for 2.5, 5, and 8-year age rotations was between 577.3 and 767 kgm<sup>-3</sup>. Based on the data, all three age rotations showed the highest green density value at the bottom, as shown in Table 2. Green density evaluation is considered necessary for logistic purposes. Information on green density is needed for logistical purposes when transporting timber logs from the harvesting site to the sawmill and factory.

Table 2
The green density of P. falcataria based on age and vertical variation

Age rotation	N	Green Density (kgm <sup>-3</sup> )			
(years)	(per age)	Top	Middle	Bottom	Average
2.5	60	577.3	681	743.1	$667.1 \pm 107.1^{a}$
5	60	696.6	685.6	767.0	$716.4\pm74.4^{b}$
8	60	659.5	655.5	673.0	$659.5 \pm 72.7^{\rm a}$

# **Basic Density**

The basic density of *P. falcataria* is summarised in Table 3. The basic density differs based on age and position, with an average basic density of 2.5 to 8-years age rotation in the 0.24–0.32 gcm<sup>-3</sup> range. Regarding vertical variation, the bottom position showed the highest value of basic density for all age rotations. The value descended from bottom to middle but slightly increased from middle to top. The differences in basic density value between the age rotations were probably due to the ratio of juvenile to matured wood, where 2.5 and 5 years are more dominant with juvenile wood than eight years (Listyanto, 2018; Rahayu et al., 2014). This high percentage of juvenile timber leads to lower density in the younger age of *P. falcataria* wood (Fajriani et al., 2013). Despite that, it can be seen from Table 3 that 5-year-old *P. falcataria* has higher basic density compared to 8-year-olds. It is contrary to the theory that the density is related to the ratio of juvenile wood. A previous study conducted stated that lateral growth, including radial growth, was affected by a few factors such as xylem density, microfibril angle as well as fibre length (Kojima et al., 2009a), which in turn contributed to the reason for density being in such way as seen between P. falcataria of 5 and 8 years old. Moreover, it was also stated that P. falcataria trees are subjected to xylem maturation after reaching a specific diameter instead of depending on cambium age (Kojima et al., 2009b). Thus, 5-year-old P. falcataria has a higher basic density than the 8-year-old due to the mentioned factors, which require further investigation.

Table 3

The basic density of P. falcataria based on age and vertical variation

Age rotation	N	Basic Density (gcm <sup>-3</sup> )			
(years)	(per age)	Top	Middle	Bottom	Average
2.5	60	0.23	0.23	0.26	$0.24\pm0.37^{a}$
5	60	0.29	0.30	0.36	$0.32\pm0.48^{c}$
8	60	0.25	0.25	0.30	$0.27\pm0.39^{b}$

#### **Air-Dried Density**

The air-dried density of *P. falcataria* varies with age rotation, as shown in Figure 6, in ranges of 226.4, 293.9 and 278.8 kgm<sup>-3</sup> for 2.5, 5 and 8 years old, respectively. The result

showed a significant difference between the air-dried density of all age rotations. It can be seen that 2.5 years has significantly lower air-dried density compared to the other two age rotations. The reason for such data is juvenile wood, as previously stated. In contrast, the ratio between juvenile and mature wood decreases as the age increases, directly leading to increased density (Fajriani et al., 2013).

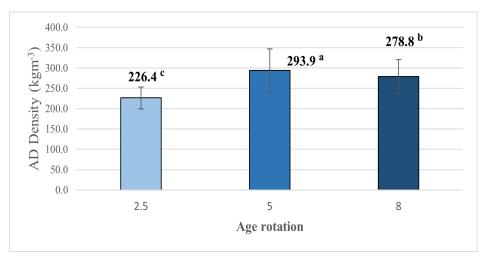


Figure 6. The air-dried density of *P. falcataria* wood based on different age rotations. Note: Mean a and b showed significant differences at  $p \le 0.05$ 

The air-dried density was further examined based on the vertical variation of the billet's top, middle and bottom positions. Statistical analysis revealed no significant difference between the top and middle AD density, except the bottom. As illustrated in Figure 7, the bottom exhibited the highest value of AD density, measuring 285.3 kgm<sup>-3</sup>. This observation showed that the density decreases from the bottom base to the top, similar to other research and theory, where the density will decrease from the base upward along the stem (Kiaei, 2016). A former study on *P. falcataria* planted in Malaysia also corroborated this pattern, demonstrating increasing density from the top downward (Akhir & Kasim, 2011).

The AD density according to radial variation is presented in Figure 8. The data revealed a significant difference between the AD density of heartwood and sapwood, with the latter exhibiting a significantly higher value than the former, with 278.7 kgm<sup>-3</sup> compared to 252.6 kgm<sup>-3</sup>. This finding contradicts the usual theory of heartwood having a higher density value than sapwood (Dinwoodie, 2000). However, this result is aligned with previous research on *Eucalyptus grandis*, where sapwood is denser than heartwood (Bal & Bektas, 2012). Moreover, other studies show that the density of *P. falcataria* species increases from the pith to the bark (Akhir & Kasim, 2011; Ishiguri et al., 2007), thus supporting the result of

sapwood being denser than heartwood. The reason for this is related to the high presence of juvenile wood, which leads to less dense heartwood.

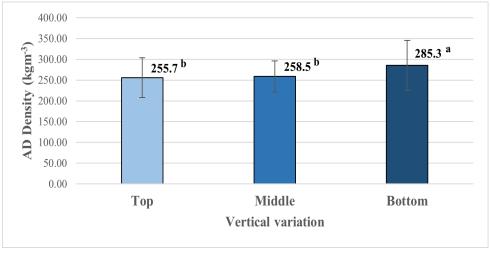


Figure 7. The air-dried density of *P. falcataria* wood based on vertical variation. Note: Mean a and b showed significant differences at  $p \le 0.05$ 

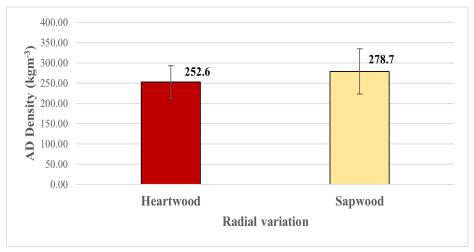


Figure 8. The air-dried density of P. falcataria wood based on the radial variation

## **Mechanical Properties**

## Static Bending

A static bending test evaluated the sample's Modulus of Rupture (MOR) and Modulus of Elasticity (MOE). The 5-year age rotation showed the highest MOR value of 43.4 MPa,

followed by 2.5 and 8 years with 36.9 MPa and 34.4 MPa, respectively. However, the case was otherwise with MOE, where there was no significant difference between all three ages, but the average value increases with age. Although the MOR value increases from 2.5 to 5 years, it decreases afterwards. The latter has the highest MOR value with 43.4 MPa, and the 8-years has the lowest MOR value with 34.4 MPa. The reason for the 8-year-old low MOR value is due to lower wood density compared to those of a 5-year-old. The MOR value might be influenced by geographical or another anatomically or physiological phenomenon, such as the formation of larger vessels causing a less dense wood (Hamdan et al., 2020). Nevertheless, the result showed that *P. falcataria* could already be harvested at a 5-year age rotation. The MOE and MOR value of *P. falcataria* is presented in Figure 9.

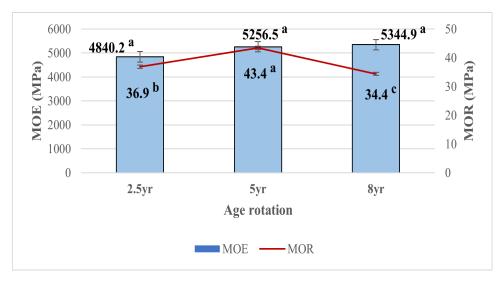


Figure 9. The MOE and MOR of *P. falcataria* wood based on different age rotations. Note: Mean a and b showed significant differences at  $p \le 0.05$ 

The MOE and MOR were also assessed based on vertical variation. The MOE and MOR value of *P. falcataria* is shown in Figure 10. MOE values of the top, middle and bottom were not significantly different, ranging from 4975.2 to 5299.6 MPa. Despite that, the MOR value increases from the top position downward, with the top having the lowest MOR value of 36 MPa, followed ascendingly by the middle and bottom, with 38.8 and 39.9 MPa, respectively. The result is inclined toward the theory that the mechanical strength of wood increases from the bottom upward and is accompanied by a factor of density (Marasigan et al., 2022). However, an earlier study stated that there was no consistent pattern in mechanical strength along the vertical variation, as it depends on the species

itself (Mohd-Jamil & Khairul, 2017). The bottom and middle positions showed the best MOR and MOE values compared to the top.

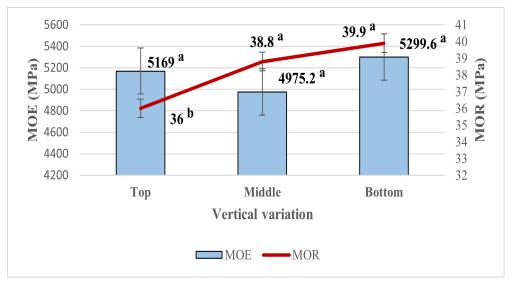


Figure 10. The MOE and MOR of P. falcataria wood based on vertical variation. Note: Mean a and b showed significant differences at  $p \le 0.05$ 

In terms of radial variation, sapwood exhibited superior values in both MOE and MOR, measuring 5538.3 MPa and 38.9 MPa, respectively. The values for both MOE and MOR significantly rise from heartwood to sapwood. This finding is consistent with earlier research mentioning that the mechanical strength of *P. falcataria* increases from pith to bark (Ishiguri et al., 2007). Furthermore, similar trends have been observed in other fast-growing species, such as Eucalyptus and Jelutong, where sapwood demonstrated a higher mechanical strength compared to its heartwood (Bektaş et al., 2020; Mohd-Jamil & Khairul, 2017). Density influences the mechanical strength, as previously stated, where the sapwood of *P. falcataria* wood is denser than its heartwood. The average value of MOE and MOR based on radial variation is presented in Figure 11.

#### **Compressive Strength**

Figure 12 shows the compressive strength of *P. falcataria* based on three different age rotations. Statistical analysis showed that the compressive strength between 2.5 and 8 years old significantly differed. The highest compressive strength value is 19.4 MPa, followed by 8 and 5 years old, with 17.5 and 12 MPa, respectively.

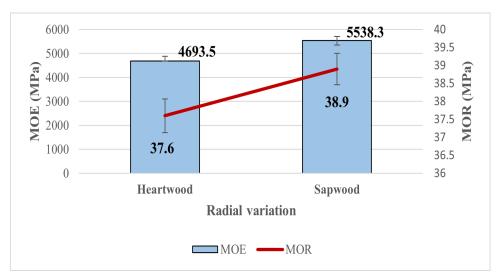


Figure 11. The MOE and MOR of P. falcataria wood based on radial variation

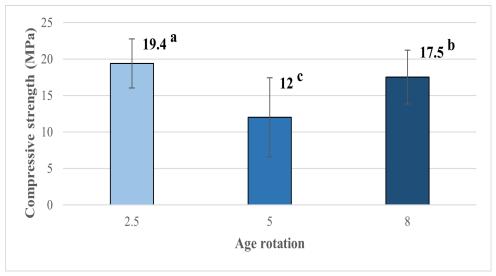


Figure 12. The compressive strength of *P. falcataria* wood based on different age rotations. Note: Mean a and b showed significant differences at  $p \le 0.05$ 

In terms of vertical variation, the bottom section exhibited the highest compressive strength of 17.7 MPa compared to the top and middle sections, as presented in Figure 13. There was no significant difference between the top and middle sections, with both having similar average compressive strength values of 15.6 MPa. The result is consistent with other studies indicating that the mechanical strength of wood decreases from the base upward

along the tree stem, which is also accompanied by density factor (Marasigan et al., 2022), where the bottom was denser compared to the top and middle, as shown in Figure 7.

Compressive strength between heartwood and sapwood showed that the latter has a higher average value of 16.8 MPa, compared to the former with 15.8 MPa, as seen in Figure 14. The sapwood density of *P. falcataria* was denser than heartwood, thus leading to higher compressive strength. The result also showed similarity with other fast-growing species, such as Eucalyptus (Bal & Bektas, 2012).

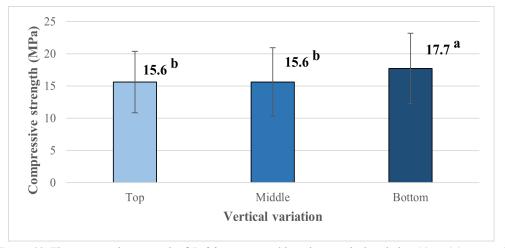


Figure 13. The compressive strength of *P. falcataria* wood based on vertical variation. Note: Mean a and b showed significant differences at  $p \le 0.05$ 

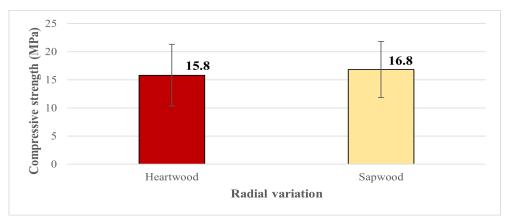


Figure 14. The compressive strength of P. falcataria wood based on radial variation

## Analysis of the Relationship Between Density and Mechanical Properties

Density can predict wood strength through mechanical properties such as static bending and compression. A linear regression model was constructed based on the stated properties,

comparing different age rotations and the vertical variation of wood to investigate the degree of relation between density and mechanical properties. The correlation and coefficient of determination (R<sup>2</sup>) were determined and further analysed.

# Relationship Between Density and Static Bending based on Different Age Rotation and Vertical Variation

#### Correlation Analysis Between Density and Modulus of Elasticity (MOE)

The correlation between density and MOE of each age rotation was analysed and compared, where Figures 15, 16 and 17 represent the correlation for 2.5, 5- and 8-year samples, respectively. All three graph models showed an increasing trend, resulting in a positive correlation, with the R<sup>2</sup> value range of 0.5125 to 0.6708, indicating that density can be a good predictor of MOE. The observation of the R<sup>2</sup> pattern revealed that the correlation of MOE with density increases with age. It must have been accompanied by the fact that the ratio of juvenile wood to mature wood began to decrease with the increase in age and wood diameter growth (Fajriani et al., 2013; Kojima et al., 2009b; Listyanto, 2018; Rahayu et al., 2014). It specifies that MOE is dependent on density.

On the other hand, the relationship of density with MOE of each age rotation based on vertical variation was also examined to understand the topic further. As stated previously, Figures 15, 16 and 17 also portrayed the correlation of the density with MOE based on vertical variation with top, middle and bottom, being B, C and D, respectively. As the graph shows, all three age rotations showed a positive correlation, with the R<sup>2</sup> value between 0.3161 and 0.6718. Density can be a good predictor based on the value, but the high range of values might mean that the MOE is much better predicted by other factors, such as the wood microfibril angle (MFA). Previous studies on *P. falcataria* showed that its MOE was significantly influenced by fibre length, cell wall thickness, and vessel diameter (Hamdan et al., 2020).

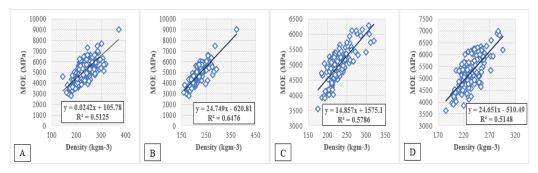


Figure 15. Relationship between Density and MOE based on age and vertical variation. Notes: A: 2.5 years, B: Top, C: Middle, D:Bottom

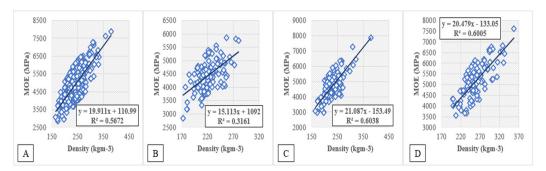


Figure 16. Relationship between Density and MOE based on age and vertical variation. Notes: A: 5 years, B: Top, C: Middle, D: Bottom

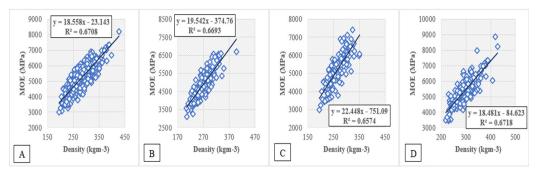


Figure 17. Relationship between Density and MOE based on age and vertical variation. Notes: A: 8 years, B: Top, C: Middle, D: Bottom

## Correlation Analysis Between Density and Modulus of Rupture (MOR)

Figures 18, 19, and 20 displayed the relationship analysis between density and MOR of 2.5, 5- and 8-year age rotation. The graph showed that all three age rotations positively correlate density and MOR with R<sup>2</sup> of 0.4468 to 0.5615, revealing that almost half of the data fit into the model. In contrast with MOE, it was observed that the coefficient of determination of density and MOR decreases with the increase of age rotation. It might be attributed to other factors that affected the result considering all aspects of macroscopic, microscopic, and sub-microscopic (Tabet & Aziz, 2013). Even so, the correlation of density and MOR for all age rotations portrayed the same positive correlation pattern.

Likewise, there was a specific correlation trend with density and MOR being positively correlated based on the vertical variation for 2.5, 5- and 8-year Batai wood samples. Only the R<sup>2</sup> value for 2.5 years showed an increasing trend from top to bottom position, with the latter being the highest value. Unfortunately, the pattern was not consistent with the other two age rotations. Overall, density can be the predictor of MOR, but the value was not as high, which may be due to the fact that other factors influenced the MOR, such as

fibre length, cell wall thickness, and vessel diameter (Hamdan et al., 2020). Still, density is a regularly used wood-strength predictor (Kiae, 2016).

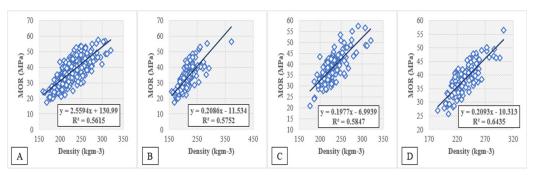


Figure 18. The relationship between density and MOR is based on age and vertical variation. Notes: A: 2.5 years, B: Top, C: Middle, D: Bottom

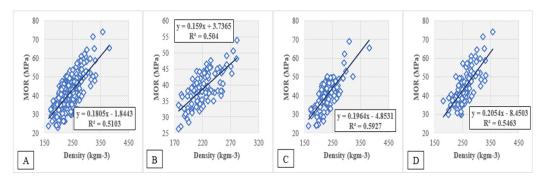


Figure 19. Relationship between Density and MOR based on age and vertical variation. Notes: A: 5 years, B: Top, C: Middle, D: Bottom

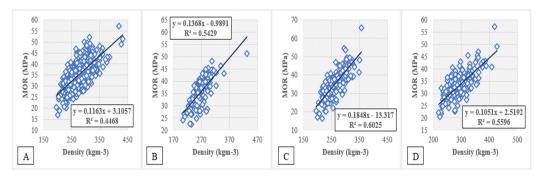


Figure 20. Relationship between Density and MOR based on age and vertical variation. Notes: A: 8 years, B: Top, C: Middle, D: Bottom

## Relationship Between Density and Compressive Strength based on Different Age Rotation and Vertical Variation

The relationship between density and compressive strength of Batai wood in correlation and coefficient of determination were examined and shown in Figures 21, 22 and 23 for age rotation of 2.5, 5- and eight years, respectively. The R<sup>2</sup> value ranged from 0.2115 to 0.4902, indicating that density can partially predict the compressive strength of wood. A specific positive correlation trend can be observed for the correlation strength throughout the different age rotations. The low R<sup>2</sup> values may be due to different factors, as mentioned by other studies where the compressive strength of *P. falcataria* wood was influenced considerably by microscopic factors consisting of fibre length, fibre lumen diameter, and cell wall thickness (Hamdan et al., 2020).

The correlation analysis between density and compressive strength according to top, middle, and bottom positions showed a similar pattern among the different age rotations, all positively correlated. The R<sup>2</sup> value linearly increased from the top position downward towards the bottom, except for eight years Batai, as the value decreased from the middle to the bottom. Five years Batai depicted the R<sup>2</sup> for compressive strength with a range of 0.2561 to 0.5022 (Figure 22). Once again, this showed that density could predict the compressive strength but differed in accordance with the position of the wood and that the strength might be contributed more by other factors.

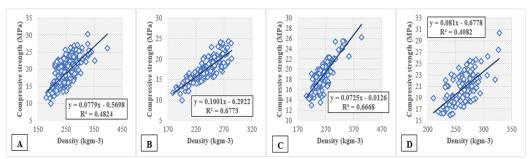


Figure 21. Relationship between Density and Compressive strength based on age and vertical variation. Notes: A: 2.5 years, B: Top, C: Middle, D: Bottom

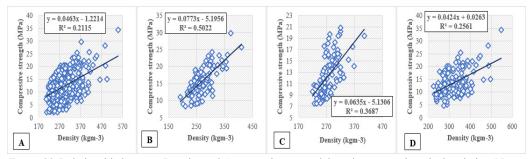


Figure 22. Relationship between Density and Compressive strength based on age and vertical variation. Notes: A: 5 years, B: Top, C: Middle, D: Bottom

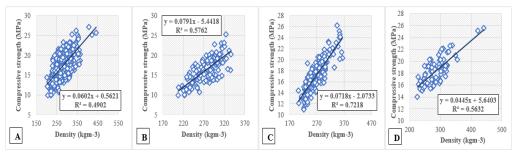


Figure 23. Relationship between Density and Compressive strength based on age and vertical variation. Notes: A: years, B: Top, C: Middle, D: Bottom

#### CONCLUSION

P. falcataria wood sourced from a forest plantation displays diverse mechanical strengths influenced by age rotation, vertical and radial variation, and wood density. The physicomechanical data categorise P. falcataria as SG7 according to MS 544-2 standards. The mechanical strength differed based on vertical variation but with no specific pattern between different age rotations. Notably, sapwood demonstrated superior physico-mechanical properties than heartwood, diverging from trends observed in other species but aligning with characteristics seen in fast-growing species such as eucalyptus. Furthermore, our findings emphasise the significant influences of wood density on the mechanical strength of falcataria wood. Additionally, the volume of logs increased progressively from 2.5 to 8 years. This research provides essential insights into the mechanical properties of P. falcataria wood, shedding light on its classification and variations in mechanical strength under different parameters. These findings offer valuable contributions to the field, enabling better utilisation and understanding of this wood species for various applications.

Based on these findings, it can be concluded that it is ideal to start harvesting *P. falcataria* planted in Kelantan at the age of 5 years. The wood density and mechanical properties showed better performance with a good log volume for timber production. 2.5 years, they scored lower in wood density and log volume, leading to minor harvesting favours even with on-par mechanical properties in certain parts. Nevertheless, it is worth considering harvesting *P. falcataria* at an 8-year age rotation for a better log volume with better recovery, targeting higher timber production for market supply.

#### **ACKNOWLEDGEMENT**

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Review Article

# A Review of Landslide Conditioning Factors in the Tropical Forests

Ahmad Syakir Jasni<sup>1</sup>, Bate Saverinus<sup>1</sup>, Zulfa Abdul Wahab<sup>1</sup>, Law Tze Ding<sup>1</sup>, Rhyma Purnamasayangsukasih Parman<sup>1</sup>, Sheriza Mohd Razali<sup>2</sup>, Jamhuri Jamaluddin<sup>1</sup>, Siti Nurhidayu Abu Bakar<sup>1</sup>, Hazandy Abdul Hamid<sup>1,2</sup> and Norizah Kamarudin<sup>1,2</sup>\*

### ABSTRACT

A variety of natural and human-induced factors can trigger landslides. A combination of these factors, with several key factor characteristics, may increase the risk of landslides. This paper reviews the comprehensive conditioning factors that contribute to landslide occurrence. Landslide occurrence varied with the conditioning factors and has been documented in response to the need to understand and mitigate the risks associated with these natural events. Twenty-six conditioning factors were identified in landslide occurrences from 16 articles reviewed using a systematic literature review with PRISMA guidelines. All 16 articles study landslides: Malaysia (66% of the article), Indonesia (13% of the article), Vietnam, Philippines and Brazil (7% of the article for each country) mostly applied the conditioning factors for landslides susceptibility map modeling. The discussion

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E-mail addresses:

leosyakir21@gmail.com (Ahmad Syakir Jasni)

205324@student.upm.edu.my (Bate Saverinus)

zulfa.abdwahab@gmail.com (Zulfa Abdul Wahab)

208026@student.upm.edu.my (Law Tze Ding)

rhyma@upm.edu.my (Rhyma Purnamasayangsukasih Parman)

sherizasmr@gmail.com (Sheriza Mohd Razali)

jamhuri@upm.edu.my (Jamhuri Jamaluddin)

sitinurhidayu@upm.edu.my (Siti Nurhidayu Abu Bakar)

hazandy@upm.edu.my (Hazandy Abdul Hamid)

norizah\_k@upm.edu.my (Norizah Kamarudin)

\*Corresponding author

of this work focuses on the conditioning factor of landslides in tropical forests. This study is crucial in improving risk assessment and developing effective mitigation and management strategies. In addition, the information from this study can be used in future studies to develop and validate models that simulate landslide processes under different conditions and are essential for predicting potential landslide events and their impacts.

*Keywords*: Conditioning factor, landslide, risk, tropical forests, predisposing factor

<sup>&</sup>lt;sup>1</sup>Department of Forestry Science and Biodiversity, Faculty of Forestry and Environment, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

<sup>&</sup>lt;sup>2</sup>Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

### INTRODUCTION

A landslide is a geological occurrence involving soil movement in any downslope due to gravity force. Various landslides occur in terms of size and speed and can happen in various landscapes (Medwedeff et al., 2020). Landslides are a reoccurring problem, often involving natural and human-induced factors (Sezer et al., 2011). Justifying and comprehending the factors behind landslide occurrence is essential for risk assessment, public safety, environmental protection, infrastructure resilience, and informed decision-making at various levels. It enables a proactive approach to reducing landslide risks and enhancing disaster preparedness and response.

To date, distinctive disciplines of geotechnical engineering and earth sciences have been developed to investigate landslides' mechanics systematically and causes integrated with various machine learning algorithms (Reichenbach et al., 2018). The findings may provide insights into the development of more efficient and accurate landslide-predictive models that decision-makers and land-use managers can use to mitigate landslide hazards. They can also be instrumental in policy and decision-making regarding natural risk management.

Therefore, this review discusses the substantial steps in understanding the causes of landslides by systematically reviewing the conditioning factor contributing to landslides in tropical forests.

## **Concepts of Landslides and Conditioning Factors**

Some key factors generally contributing to landslides are topography, hydrology, geology, soil and vegetation. Shirvani (2020) describes areas characterized by the factors mentioned above, also known as predisposing factors, as more susceptible to landslides. These factors set the stage for landslides by creating an elevated risk of slope failure. Predisposing factors often interact with triggering factors that can be (1) natural triggering factors such as heavy rainfall, earthquakes, and flood frequency or (2) anthropogenic factors such as forest fragmentation, forest loss, logging, and mining (Peduzzi, 2010; Shirvani, 2020). In tropical countries, where heavy rainfall and steep terrain are common (Forbes et al., 2012), several conditioning factors contribute to landslide occurrence, for example, rainfall intensity, topography, geological conditions, soil characteristics, land use, land cover change and forestry (LULUCF) and previous landslide history. Medwedeff et al. (2020) suggested that the contributing factors of landslides, i.e., topography, hydrology, geology, soil, and vegetation, require site-specific management for further investigate the physical controls on landslide size, thus dictating the degree to which landslides contribute to secondary hazards such as flooding and debris flows. Flood and debris flow following landslides may result from the intense and prolonged rainfall that saturated the soil, reducing its stability and triggering landslides (Canavesi et al., 2020; Diara et al., 2022; Lee, 2019; Soma & Kubota, 2018). The hilly terrain is prone to landslides and debris flows, mainly when

rainwater infiltrates the soil (Li et al., 2016; Roback et al., 2018). In addition, in some areas, experiencing LULUCF will make the hillslope more susceptible to landslides since the stabilizing effect of the slope characterized by vegetation roots is removed (Diara et al., 2022; Soma & Kubota, 2018). The predisposing and triggering factors of landslides vary according to landscape.

Landslides are often called major wasting events because they involve the rapid movement and displacement of significant amounts of Earth materials down a slope, such as rock, soil, and debris, especially in areas prone to landslides. These events result in the "wasting" or loss of material from the original location, and the substantial impact varies according to the landscape, environment, and human activities (Canavesi et al., 2020; Ibrahim et al., 2021; Nhu et al., 2020). The magnitude of the Landslide is the crucial factor in the wasting events. Medwedeff et al. (2020) highlight that cohesive strength and hillslope relief are correlated to landslide size and averaged to the distribution of hillslope in a landscape. The triggering factors in the landscape heightened the probability of landslide occurrence.

Recent advances in observation technology of remotely sensed imagery integrated with problem-solving algorithms and machine learning have facilitated landslide modeling and zonation susceptibility for hazard prediction and mitigation measures (Lee, 2019; Nsengiyumva & Valentino, 2020; Shirvani, 2020; Wang et al., 2021). In this work, however, we focus on identifying conditioning factors for landslide occurrence, and the application of modeling and algorithm-based assessment and monitoring for landslides is not included. The significance of this work is to provide decision-makers and land use managers with an understanding of the predisposing and triggering factors in areas prone to landslides and initial planning action for them to take action before modeling and algorithm can be made. Peduzzi (2010) discussed that decision-makers need to be convinced of the best management of natural resources in forest areas to protect human lives and their welfare from hazards. Thus, the lack of spatial vector and raster data due to high cost and availability and the lack of landslide-related experts in forestry-related agencies is one of the most significant aspects of this review work, which discusses the conditioning factors of landslides in forest areas where landslides are common (Hashim et al., 2017). Observing the conditioning factors without applying technology, modeling, and algorithms can further help related agencies take early preventive action by simply observing the surrounding conditions of the related factors.

### MATERIALS AND METHODS

An illustrated four-fold framework for the SLR (Mohamed Shaffril et al., 2021) in Figure 1 is proposed for this review of conditioning factors for landslide occurrence. Keyword search is the first step in SLR in constructing a literature database. The search was conducted on

the selected database in the Web of Science, Scopus, Science Direct, Google Scholars, and Google engine search using keywords and Boolean search criteria applied to the "title," "abstract," and "keywords" of the publications. The search content focuses on 'landslide,' 'conditioning factors,' 'tropical,' 'landslide mitigation,' and 'landslide susceptibility.' From the preliminary search of the title and the abstract, there is no limitation on literature and information type as long as the content is related to landslides. Since the study on landslides has systematically documented from 1900 with more than 30,000 results using the keywords mentioned above, this study has set the custom range search from 2010 to the present.

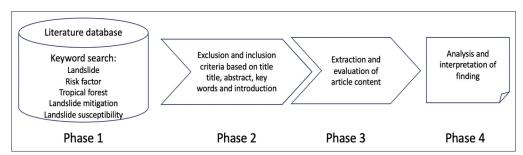


Figure 1. The Methodology for systematic literature review (SLR) search

A preferred reporting item for systematic reviews and meta-analyses (PRISMA) template (Page et al., 2021) is illustrated in Figure 2, which shows the 222 articles found from the identification using keyword search and excluded 196 articles since the articles not related to tropical forests. Next, all 24 remaining articles were screened based on indicators or criteria that lead to a landslide occurrence, which later excluded five articles. The remaining 19 articles were extracted by reading the eligibility of the articles that discussed the indicator or criteria of landslide occurrence. After the extraction, three articles were removed due to ineligibility. Finally, six articles from the analysis and interpretation of the findings are included as a literature database. A total of 26 factors are listed in Table 1 following the PRISMA guideline for identifying the conditioning factors, and these are the factors discussed in this review.

### **Conditioning Factor for Landslide Occurrence in Tropical Forests**

The literature database following PRISMA guidelines has reviewed 16 articles on landslide occurrence in tropical forests from the last 13 years. Twenty-six conditioning factors for landslide occurrence have been identified. The adaptation of these 26 factors varies since different landscapes have different conditioning factors, and the priority of the factors also varies (Ibrahim et al., 2021). The investigated articles covered five countries with tropics characterization: Malaysia (66% of the article), Indonesia (13% of the article), Vietnam, Philippines, and Brazil (7% of the article for each country). All the discussed

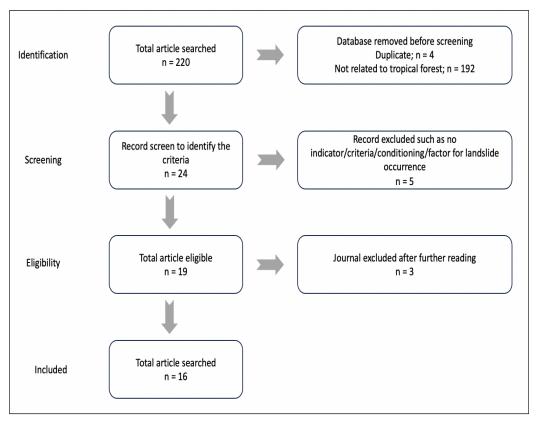


Figure 2. The literature database was developed based on PRISMA guidelines

Table 1
List of conditioning factors for landslide occurrence (Source: Author)

N -	Conditioning	Conditioning Review from previous work*															
No.	factor	A	В	С	D	Е	Н	I	J	K	L	M	N	0	P	Q	R
1	Rainfall						<b>√</b>	√		√	<b>V</b>	√	√	<b>√</b>		√	√
2	Slope	$\sqrt{}$	$\sqrt{}$		$\sqrt{}$	$\sqrt{}$	$\sqrt{}$	$\sqrt{}$	$\sqrt{}$	$\sqrt{}$	$\sqrt{}$	$\sqrt{}$	$\sqrt{}$	$\sqrt{}$	$\sqrt{}$	$\sqrt{}$	$\checkmark$
3	LULC	$\sqrt{}$	$\sqrt{}$				$\sqrt{}$	$\sqrt{}$	$\sqrt{}$		$\sqrt{}$	$\sqrt{}$		$\sqrt{}$	$\sqrt{}$	$\sqrt{}$	$\sqrt{}$
4	TWI	$\sqrt{}$							$\sqrt{}$				$\sqrt{}$			$\sqrt{}$	
5	Lithology	$\sqrt{}$	$\sqrt{}$			$\sqrt{}$			$\sqrt{}$	$\sqrt{}$	$\sqrt{}$	$\checkmark$	$\sqrt{}$			$\sqrt{}$	$\checkmark$
6	Distance to stream	$\sqrt{}$	$\sqrt{}$				$\checkmark$				$\sqrt{}$	$\checkmark$	$\sqrt{}$		$\sqrt{}$	$\sqrt{}$	$\checkmark$
7	Total Curvature	$\sqrt{}$				$\checkmark$	$\checkmark$				$\sqrt{}$		$\checkmark$			$\sqrt{}$	
8	Elevation	$\sqrt{}$	$\sqrt{}$	$\sqrt{}$		$\sqrt{}$			$\sqrt{}$	$\sqrt{}$	$\sqrt{}$		$\sqrt{}$			$\sqrt{}$	
9	SPI	$\sqrt{}$							$\sqrt{}$	$\sqrt{}$						$\sqrt{}$	
10	Soil		$\sqrt{}$	$\sqrt{}$		$\sqrt{}$			$\sqrt{}$	$\sqrt{}$		$\checkmark$		$\sqrt{}$	$\sqrt{}$	$\sqrt{}$	$\checkmark$
11	Aspect	$\sqrt{}$	$\sqrt{}$		$\sqrt{}$	$\sqrt{}$	$\sqrt{}$			$\sqrt{}$	$\sqrt{}$	$\checkmark$	$\sqrt{}$				$\sqrt{}$
12	NDVI		$\sqrt{}$	$\sqrt{}$	$\sqrt{}$	$\sqrt{}$	$\sqrt{}$					$\sqrt{}$			$\sqrt{}$	$\sqrt{}$	$\sqrt{}$

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Table 1 (Continue)

NI-	Conditioning	ing						Review from previous work*									
No.	factor	A	В	С	D	Е	Н	I	J	K	L	M	N	О	P	Q	R
13	Distance to road	<b>√</b>	<b>V</b>			<b>V</b>	<b>√</b>				√	$\checkmark$	√		$\sqrt{}$	√	<b>√</b>
14	TRI	$\sqrt{}$															
15	Forest status													$\sqrt{}$			
16	Road density															$\sqrt{}$	
17	River density										$\sqrt{}$					$\checkmark$	
18	Profile Curvature	$\sqrt{}$	$\sqrt{}$						$\sqrt{}$	$\sqrt{}$						$\sqrt{}$	
19	Plan Curvature			$\sqrt{}$	$\checkmark$				$\sqrt{}$	$\sqrt{}$					$\sqrt{}$		
20	Distance to fault	$\checkmark$	$\sqrt{}$	$\checkmark$			$\sqrt{}$					$\checkmark$			$\sqrt{}$	$\sqrt{}$	$\sqrt{}$
21	Fault density				$\sqrt{}$						$\sqrt{}$						
22	Sediment transport index (STI)									$\sqrt{}$							
23	Landform						$\sqrt{}$	$\sqrt{}$									
24	Slope gradient								$\sqrt{}$								
25	Slope curvature								$\sqrt{}$								
26	Flow accumulation								√								

\*A: Al-Najjar et al. (2019); B: Javier and Kumar (2019); C: Sezer et al. (2011); D: Pradhan et al. (2010); E: Pradhan and Lee (2010); F: Althuwaynee et al. (2012); G: Diara et al. (2022); H: Canavesi et al. (2020); I: Ibrahim et al. (2021); J: Soma and Kubota (2018); K: Hashim et al. (2017); L: Selamat et al. (2022); M: Arfadly et al. (2023); N: Pradhan (2011); O: Nhu et al. (2020); P: Shahabi and Hashim (2015)

articles adopt the conditioning factors to model the landslide occurrence with a landslide susceptibility map (LSM). The conditioning factors reported in this review can also be found in all areas of the globe and may not represent tropical areas because tropical regions vary widely in topography. Factors such as altitude, proximity to the equator, prevailing winds, and geological history all influence the landscape of a particular tropical area. The conditioning factors reviewed and reported in this work can accurately predict the occurrence of landslides when the areas share the same characteristics as those reported in the 26 reviewed works (Gonzalez et al., 2024).

The most common conditioning factor for landslide occurrence is slope (100%), followed by land use and land cover (LULC) and soil (94%) and lithology (88%). The other factors that can be related to landslide occurrence are distance to stream (75%), aspect (69%), distance to road and distance to fault (63%), elevation, rainfall and normalised different vegetation index (NDVI) (56%). These 11 conditioning factors are prevalent in tropical forests as predisposing factors, and two of them, LULC (94%) and rainfall

(56%), are the triggering factors. Literature also records total curvature, stream power index (SPI), plan curvature, profile curvature, terrain wetness index (TWI), altitude, river density, fault density, landform, terrain ruggedness index (TRI), forest status, road density, sediment transport index (STI), slope gradient, slope curvature and flow accumulation as conditioning factors of landslides in tropical forests. Even though these 16 factors are not the common conditioning factors of landslides as used by selected researchers cited in Table 1, the availability of this information will help the decision-makers increase the accuracy of landslides prediction.

LULC, distance to stream, elevation, distance to river, distance to fault, and rainfall are straightforward conditioning factors that decision-makers or the public can observe to determine the occurrence of potential landslides. However, soil, lithology, aspect, and NDVI require experts to initially analyze the characteristics that contribute to landslides. Suppose the decision makers or the public are well-known in the areas. In that case, the information on soil and lithology can be understood through information usually available from geological agencies (Pradhan et al., 2010; Sezer et al., 2011). Meanwhile, for aspect and NDVI, the data can be obtained from satellite imagery and require image processing. The primary purpose of this NDVI is to differentiate vegetation density (Sezer et al., 2011; Nhu et al., 2020). If aspects and NDVI are unavailable, changes or unusual events identified from the triggering factor of rainfall will help decision-makers or the public predict the potential of landslide occurrence when those six conditioning factors (slope, LULC, distance to stream, elevation, distance to river, and distance to fault) exist in those particular areas.

Malaysia has experienced heavy and continuous rainfall that leads to floods and landslides (Pradhan et al., 2010a) with debris flow. In extreme rainfall conditions, the soil layers become oversaturated, and steep slopes lose stability and collapse almost simultaneously, as Komoo (2022) stressed following debris flow landslides that happened at the end of 2021 in Malaysia. He added that additional factors include geological factors (soil and rock type, basin shape and rock structure) and non-geological factors (forest clearance in steep areas; slope cuts to build infrastructure, including roads; and land clearing for agriculture). Soma and Kubota (2018) and Javier and Kumar (2019) also found that areas covered with sparse vegetation have a higher probability of landslide occurrence, affecting slope stability. Gonzalez et al. (2024) highlighted that when rainwater reaches the soil surface and is absorbed into the soil, soil moisture increases, triggering landslides in tropical areas (Aristizabal et al., 2017; Lee et al., 2014; Mansor et al., 2018; Maturidi et al., 2021; Saadatkhah et al., 2016).

Each conditioning factor the researchers selected has varied justification depending on their landscape characteristics. Slope directly influences the soil strength and Landslide (Park & Kim, 2019). Aspects related to meteorological and morphological characteristics

represent the horizontal direction of mountain/hill slope faces (Youssef et al., 2015). Lithology can be indicative of soil characteristics. These characteristics can be diverse and may influence erosion, ground stability and slide occurrence (Kalantar et al., 2018; Mancini et al., 2010). Elevation can influence landslide predictions; an area with high elevation has a higher probability of elevation when other conditioning factors and triggering factors exist (Kalantar et al., 2018; Sezer et al., 2011). Plan and profile curvatures are the descending flow acceleration (erosion/deposition rate) and the flow velocity variation of a slope, respectively (Kalantar et al., 2018). Additional information on cross-sectional curvature helps assess the curvature across a slope, identifying concave features like channels by intersecting with the slope's normal plan and being perpendicular to its aspect direction.

In contrast, longitudinal curvature calculates curvature along the slope's downward direction by intersecting with the average slope plan and aspect direction (Alkhasawneh et al., 2013; Ehsani & Malekian, 2012). The distance to the fault is considered because landslides are more likely to occur near faults and rivers due to factors like erosion and unstable ground, including distance to streams and roads (Jebur et al., 2015; Kalantar et al., 2018). LULUCF can have different events of landslides. Forest areas cleared, for example, harvesting activity coupled with heavy rainfall can cause large landslides (Hashim et al., 2018) and forests characterized by high slopes are evidenced to have widespread landslides due to unstable landforms (Canvensi et al., 2020). Areas with sparse vegetation may reduce the soil strength since fewer trees absorb the soil moisture, and soil strength is reduced due to fewer roots holding the soil, thus increasing the potential of soil erosion and landslides (Nhu et al., 2020). NDVI information used as the conditioning factor can also help predict landslide occurrence, as NDVI provides information on vegetation densities (Soma & Kubota, 2018).

Identifying the conditioning factors for landslide susceptibility modeling is beneficial because it allows for a more accurate and effective landslide risk assessment. The precision of the prediction model of landslides, for example, LSM, needs prioritizing the conditioning factors (Hashim et al., 2018; Norizah, 2022), which may lead to better predictions and more targeted mitigation efforts. This prioritization helps allocate resources efficiently, enhances hazard mapping, and ultimately aids in reducing the impact of landslides on communities and the environment.

### CONCLUSION

In conclusion, conditioning factors play an important role in determining the susceptibility of tropical forests to landslides. These factors encompass a wide range of geological, topographical, climatic, and environmental characteristics that collectively influence the likelihood of landslides occurring in these regions. Understanding these conditioning factors is vital before landslide susceptibility modeling and predictions can be made. Although

this SLR focuses on tropical forests, the accuracy of landslide susceptibility modeling that will be developed using conditioning factors reviewed in this work will depend on the similarity of area characteristics. The relationship of how each conditioning factor influences one another is also crucial in ensuring the accuracy of landslide susceptibility modeling. For example, rainfall patterns can affect soil saturation, influencing slope stability. In addition, prioritizing which conditioning factors influence landslide occurrence most is very important to accurately develop the landslide susceptibility models, and this involves decision-making on multiple conditioning factors. Understanding the Methodology or algorithms for multi-criteria decision-making analysis (MCDA) can create robust landslide susceptibility models that provide valuable insights into areas at high risk of landslides. Therefore, understanding the conditioning factors allows for implementing targeted mitigation efforts. It enables authorities and stakeholders to focus their resources and interventions on areas with the highest landslide susceptibility, reducing the potential for disaster and safeguarding human communities and the natural environment. In addition, this, in turn, aids in land-use planning, infrastructure development, and disaster preparedness.

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Review Article

# A Review of the Potential Socioeconomic Impacts of Bamboo Plantation on Local Community

Zaiton Samdin<sup>1,2\*</sup>, Nurul Izzati Abdullah Zawawi<sup>1</sup>, Norzanalia Saadun<sup>1,3</sup> and Norfaryanti Kamaruddin<sup>1</sup>

<sup>1</sup>Laboratory of Sustainable Bioresource Management, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

### **ABSTRACT**

Bamboo is a versatile and essential resource that thrives in tropical climates, providing shelter, tools, and even a staple vegetable in Asia, Africa, and South America. This paper reviews the potential socioeconomic impact of bamboo plantations on local communities, emphasizing the relevance of bamboo cultivation across different cultural and environmental contexts. It delves into the multifaceted potential of bamboo, moving beyond its historical significance, and describes the plant's adaptability, showcasing its transformative application in construction, medicine, energy, and beyond. The goal is to synthesize existing knowledge and insights on the subject, providing a valuable resource for policymakers, researchers, and industry stakeholders. By consolidating existing knowledge globally, it offers an understanding of the potential benefits, challenges, and strategies associated with bamboo plantations. It is hoped that this review can serve as a foundational resource for

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E-mail addresses:
zaisa@upm.edu.my (Zaiton Samdin)
izzatiaz97@gmail.com (Nurul Izzati Abdullah Zawawi)
norzanalia@upm.edu.my (Norzanalia Saadun)
norfaryanti@upm.edu.my (Norfaryanti Kamaruddin)
\*Corresponding author

those seeking to promote the growth of the bamboo industry while enhancing the wellbeing of local communities. It is intended for publication in a scholarly journal to disseminate this knowledge globally, fostering informed decision-making and sustainable practices in agroforestry and bamboo cultivation across diverse regions.

Keywords: Bamboo, impact, plantations, socioeconomic

<sup>&</sup>lt;sup>2</sup>School of Business and Economics, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia <sup>3</sup>Faculty of Forestry and Environment, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

### INTRODUCTION

Wood is a fundamental material that has transitioned from natural forests to plantation forests as the primary source of timber (De Araujo, 2023). Plantation forests are favored for providing small-diameter trees with short-cutting cycles, typically between five and eight years. The development of forest plantations dates back to the early 1900s, with French colonialists initiating small-scale rubber (*Hevea brasiliensis*) and teak (*Tectona grandis*) plantations in Laos (Van Der Meer Simo, 2021). The subsequent introduction of Eucalypt species in the late 1960s expanded the landscape, primarily on state-owned land (Pichler et al., 2021). These efforts, supported by the Australian government in the 1970s, aimed to identify suitable species, sources, and establishment techniques, including *Eucalyptus tereticornis* and *Eucalyptus camaldulensis*.

The socioeconomic implications of industrial forest plantations are widely documented, notably by Hofflinger et al. (2021). In East Africa, where rural households depend on land and natural resources such as water, firewood, and non-wood forest products (NWFPs), the impact of industrial forest plantations raises a significant concern (Derebe & Alemu, 2023). Extensive land requirements for industrial plantations often result in reduced agricultural land availability, causing adverse environmental and socioeconomic effects. However, it is imperative to acknowledge that large-scale forestry investments can bring economic development and alternative income sources, including formal employment and infrastructure improvements (Cheng et al., 2023; Isworo, 2023).

Recent research on large-scale plantation projects highlights the importance of selecting suitable tree species and understanding their varied uses, including fuelwood, pulpwood, and sawn timber. This knowledge has expanded significantly, especially concerning species like Eucalyptus, Acacia, Pinus, and Tectona, which are often adopted outside their native regions in Africa, Asia, and Latin America (Rajeev et al., 2023). However, in a properly planned plantation, the selection of species might encompass Napier grass, known for its rapid growth and suitability as livestock feed, vetiver grass, valued for its erosion prevention qualities, a range of bamboo species chosen for their versatile uses, guinea grass, serving as additional animal fodder, and switchgrass, utilized for biomass creation and energy production (Pandey et al., 2023). It emphasizes the importance of not only the species but also the specific source or variety within that species, ensuring its compatibility with the intended purpose and local conditions, thereby contributing to the success of any plantation project.

Bamboo offers distinctive advantages, particularly in cost-effective production, processing, drying, and curing. Moreover, bamboo serves as an environmentally friendly substitute for wood, contributing to the mitigation of deforestation, pollution and the preservation of natural ecosystems (Lau et al., 2023). Bamboo's widespread availability

and rapid growth rates make it pivotal in both direct domestic and commercial applications (Hailemariam et al., 2022).

With forest resources depleting, there is a rising demand for non-timber materials like bamboo in structural and non-structural applications traditionally dominated by wood. Bamboo's adaptability and value in applications such as furniture, interior paneling, flooring, and parquet demonstrate its potential as a sustainable and cost-effective resource across various industries and settings (Guadie et al., 2019). Comprehensive insights gleaned from prior studies will greatly assist researchers in exploring the potential socio-economic impacts of bamboo plantations on local communities.

This review highlights the potential of bamboo as a champion for social and economic growth. It creates jobs and training opportunities at every stage, from growing the bamboo to processing and building it. This income boost empowers people and communities, and the money that flows back in can be used for further development projects. But bamboo's benefits go beyond the economy. It contributes to a stable food supply, provides materials for medicine, and can even be a source of energy. As a sustainable and adaptable building material, bamboo offers a promising path for the future.

### METHODOLOGY

The methodology for this review entails several crucial steps to ensure comprehensiveness and rigor. Firstly, a meticulous search strategy will be established. This strategy will involve a resource to identify relevant reviews and analyses. Specific searches on bamboo plantations and socioeconomic impacts will be utilized, potentially supplemented by consulting reference lists of existing reviews to uncover further relevant studies.

Subsequently, clear inclusion and exclusion criteria will be set for the collected reviews. These criteria will ensure that the chosen reviews directly address the research question—the socioeconomic impacts of bamboo plantations. For instance, inclusion criteria may specify reviews published within a certain timeframe and focus on specific socioeconomic aspects such as employment, income, access to food and medicine, and bamboo's role as a source of energy and construction material.

Following the selection process, a meticulous assessment of the quality and methodology of each included review will be conducted. This step is essential for determining the reliability and validity of the synthesized evidence.

Finally, the findings from the various reviews will be synthesized. By integrating insights from different research methods and studies, the review aims to provide a comprehensive understanding of the socioeconomic effects of bamboo plantations. This synthesis process will facilitate the identification of areas of consensus among the existing literature, as well as any conflicting evidence, thereby offering valuable insights for further research and policy development in this field.

# The Socioeconomic Impact of Bamboo Plantation on Local Communities Across Different Cultural and Environmental Contexts

The establishment of bamboo plantations has become a prominent subject of interest, holding the potential to promote sustainable ecological practices and bring about significant socioeconomic impacts on local communities (Akoto Sarfo, 2021). Bamboo, known for its rapid growth, versatility, and eco-friendly attributes, presents various applications that could drive economic growth, create employment opportunities, and contribute to environmental conservation at the community level. This review explores the diverse influence of bamboo plantations on local communities, with a primary focus on their socioeconomic aspects. By conducting a thorough analysis of the social and economic effects of bamboo cultivation, this review aims to shed light on the potential benefits and challenges associated with integrating bamboo into community development strategies, including its impacts on employment opportunities, income generation, access to food and medicine, as well as its role as a sustainable source of energy and construction material. In the subsequent discussions, the intricate relationships between bamboo plantations and local socioeconomic dynamics are examined, with the overarching goal of providing insights for policies and initiatives that harness bamboo's transformative potential for improving local communities.

## **Employment**

Bamboo cultivation has emerged as a dynamic sector with diverse economic impacts on local communities (Akinlabi et al., 2017). The socioeconomic implications of bamboo plantation activities are varied, presenting both positive and negative outcomes. One notable advantage of bamboo cultivation is the creation of income opportunities for rural communities (Akoto et al., 2020). Bamboo-related activities span various stages, from planting and managing bamboo plantations to processing bamboo into various products. These activities generate jobs, supporting livelihoods in regions with limited alternative employment opportunities. Residents often secure employment in bamboo plantation management, participating in planting, nurturing, and harvesting the bamboo. Additionally, processing bamboo into diverse products, from construction materials to artisanal crafts, opens up further employment prospects (Luo et al., 2020). These opportunities significantly enhance rural communities' economic well-being by providing a source of income for local residents.

Large-scale bamboo plantations, managed by private entities or as part of community-based initiatives, necessitate a workforce for various tasks. It includes plantation maintenance, bamboo harvesting, and processing. The demand for labor in the bamboo industry has the potential to reduce unemployment and underemployment in rural areas, especially in regions with suitable climatic conditions for bamboo growth (Gupta, 2020).

Local workers' involvement in commercial bamboo farming offers income and equips them with valuable skills related to bamboo cultivation and processing.

Crucially, the positive economic impact of bamboo cultivation extends beyond direct employment (Wanniarachchi et al., 2020). Revenue generated from bamboo-related activities can be reinvested in community development projects. Rural communities can utilize the income from bamboo farming to enhance local infrastructure, such as roads, schools, and healthcare facilities (Singh et al., 2021). Social projects aimed at improving residents' well-being, such as clean water initiatives or skill development programs, can be funded through income generated from bamboo. These investments contribute to an overall improvement in the quality of life and socio-economic development in rural areas.

As of 2005, the total area of bamboo plantations worldwide was 31.07 million hectares (Food and Agriculture Organization of the United Nations, 2009). Asia-Pacific accounts for 99% of global bamboo plantations, with China alone accounting for 57% (Bamboo Research and Development Institute, 2018). Africa, Latin America, and North America have a much smaller share of global bamboo plantations, at 0.6%, 0.3%, and 0.1%, respectively. The global bamboo market is expected to grow at a CAGR of 4.5% from 2021 to 2030, reaching a size of USD 59.30 billion by 2030 (MarketsandMarkets, 2021). The top bamboo-producing countries are China, India, Bangladesh, Indonesia, and Myanmar. Bamboo is used for a wide variety of products, including food, paper, construction materials, and textiles. It is also an important source of income for millions of people worldwide. The bamboo sector employs over 35 million people in China alone (State Forestry and Grassland Administration of China, 2020), and global trade in bamboo and rattan is estimated to be worth US\$14 billion annually (International Bamboo and Rattan Organization, 2020).

However, it is crucial to recognize that the economic impact of bamboo cultivation is context-dependent and comes with challenges. These challenges may include market fluctuations, environmental considerations, and issues related to land tenure (Duyen et al., 2022). Therefore, sustainable bamboo resource management is essential to maximize positive economic effects while mitigating potential negative consequences. Sustainable practices ensure that bamboo cultivation remains a viable and beneficial source of income and employment for local communities in the long term (Lee et al., 2021).

### Income

Bamboo is a significant catalyst for income generation for individuals and communities, particularly in regions where it thrives. In China, its economic contributions extend to poverty alleviation, rural development, and the promotion of local employment, highlighting the multifaceted nature of bamboo's income-generating potential (Fei, 2021). Bamboo is pivotal in enhancing financial well-being at individual and community levels, offering alternative income streams for rural areas.

The entire value chain of bamboo, from cultivation and harvesting to processing and product manufacturing, contributes to local job creation and strengthens the bamboo industry (Shukla & Joshi, 2020). As in India, economic benefits go beyond cultivation, emphasizing the potential for growth and development within the bamboo industry. The commercial potential of bamboo is significant, with increasing prices in local markets indicating its growing importance (Borowski, 2021). Although India faces challenges related to susceptibility to damage and technological limitations, the rising market demand is driving the commercialization of bamboo. Its popularity is rising due to its multifunctional nature, rapid growth, and diverse applications, from construction to crafts, making it a preferred choice for growers and communities. This versatility extends to furniture, flooring, and various products, further solidifying bamboo's economic relevance.

Bamboo's impact is felt in rural and urban settings. Rural communities benefit from farming and processing, while urban areas access cost-effective bamboo-based construction materials (Sahoo et al., 2021). This interconnected relationship supports income generation and social development. Experts advocate for a value-chain approach to bamboo by establishing links across production, management, processing, manufacturing, distribution, and utilization. This strategy enhances production efficiency, value addition at each stage, and overall competitiveness in price and quality, contributing to the economic well-being of marginalized groups and industrial sector development.

The socio-economic significance of bamboo goes beyond mere material use. It helps reduce deforestation, curb poverty, and urban migration (Baffour-Awuah, 2020). In Ghana, promoting locally available bamboo-based housing hones skills supports local income generation, and reduces the need for people to relocate. Bamboo's adaptability for construction makes it accessible to individuals with basic skills or none, fostering community involvement. Bamboo's economic role is linked to its environmental and economic sustainability (Ekwe et al., 2023). As a rapidly renewable resource, bamboo aligns with sustainable development and conservation principles. The combination of environmental, economic, and social aspects reinforces its overall sustainability as a resource for income generation.

Bamboo's capacity to generate income is versatile and transformative, with profound implications for individuals, communities, and regions. It is pivotal in improving livelihoods, rural development, and poverty reduction. Furthermore, bamboo's eco-friendly attributes and sustainability make it an ideal choice to address economic, environmental, and social challenges. The broad spectrum of bamboo applications and their significance in the value chain hold tremendous potential for economic empowerment, underscoring its role in fostering economic and social progress.

#### Source of Food

Historically, bamboo has been an integral part of human diets in the Indian Himalayan regions, with some of the notable species of edible bamboo including *Bambusa bambos*, *Bambusa vulgaris*, *Dendrocalamus hamiltonii*, *Dendrocalamus strictus*, *Dendrocalamus falcatum*, and *Phyllostachys bambusoides* (Bhardwaj et al., 2019). Particularly in the western Himalayas, tender shoots from these bamboo species are widely used in diverse culinary preparations such as curries, soups, and pickles (Acharya et al., 2023). These bamboo shoots are nutritionally rich, providing proteins, carbohydrates, vitamins, dietary fibers, minerals, and essential nutrients like thiamine, niacin, vitamin A, vitamin B6, and vitamin E, with low-fat content (Nongdam & Tikendra, 2014).

Bamboo shoots, the young sprouts of bamboo plants, have a long culinary history and are esteemed for their health benefits, including cholesterol reduction and improved digestion (Sisaye, 2013). The seeds from various bamboo species, such as *Bambusa bambos*, *Dendrocalamus strictus*, and *Phyllostachys aurea*, are commonly pickled and consumed, and they can be prepared similarly to rice or other grains, even used in brewing beer. These diverse culinary applications of bamboo have been practiced for centuries, contributing to communities' dietary diversity and health, especially in regions like the western Himalayas.

Bamboo leaves also play a valuable role as animal fodder, particularly for ruminants and larger animals like elephants, especially in areas facing a shortage of pasture fodder (Owen et al., 2012). They are believed to positively impact milk production and ghee (clarified butter) content, particularly in newborn calves (Singhal et al., 2013). In regions where green and dry fodder is limited, such as the western Himalayas, bamboo leaves are a supplementary livestock nutrition source. Bamboo leaves are considered to have higher concentrations of essential nutrients like non-structural carbohydrates, protein, phosphorus, and potassium compared to other parts of the bamboo plant, making them crucial during periods when alternative food sources are scarce, especially in winter (Halvorson et al., 2010).

The multifaceted role of bamboo in providing food resources for both humans and animals underscores its significance in supporting dietary diversity, nutrition, and the well-being of local communities, particularly in regions abundant with bamboo. These traditional uses of bamboo as a food source have played a vital role in sustaining communities and preserving local culinary and nutritional traditions.

### Medicine

The medicinal potential of bamboo is a captivating area of study, encompassing a wealth of therapeutic properties acknowledged and utilized by various traditional systems (Dongre et al., 2022). The subsequent discussion delves into the diverse medicinal applications and compounds derived from bamboo, shedding light on its role in traditional medicine.

Tabasheer, A Medicinal Gem: Tabasheer is traditionally associated with Asian regions, particularly countries like India, where bamboo grows abundantly. Tabasheer or Banslochan, extracted from the nodal joints of specific bamboo species, stands out as one of the most renowned medicinal products derived from bamboo (Patel & Mehta, 2021). Historically valued as a stimulant, febrifuge, cooling tonic, aphrodisiac, and remedy for conditions like asthma, cough, and paralytic complaints, Tabasheer showcases bamboo's potential to yield therapeutic substances with high medicinal value.

Pharmacological and Ethnomedical Applications: Bamboo's medicinal significance extends to various pharmacological and ethnomedical applications (Benjamin et al., 2023). Bamboo extracts are identified for their rich content of bioactive compounds, offering antioxidant, anticancer, anti-inflammatory, antimicrobial, antidiabetic, and antiulcer effects. These compounds position bamboo as a promising source for drug development and herbal remedies, addressing a spectrum of health issues in Southeast Asia.

Phytochemical Diversity: Bamboo's phytochemical composition, encompassing phenolic compounds, coumarins, alkaloids, triterpenes, and steroidal glycosides, plays a crucial role in addressing gynecologic problems, menopausal symptoms, and other health concerns (Anadon et al., 2016). This unique chemical makeup positions bamboo as a resource for holistic well-being that is mostly used in Spain.

Nutritional and Therapeutic Values: Bamboo extracts serve nutritional and therapeutic purposes, providing essential amino acids, selenium, potassium, and proteins (Das, 2019). Traditional practices have led to the development of pharmaceutical preparations like bamboo salt, bamboo vinegar, and bamboo extracts for managing diabetes and regulating cholesterol levels (Gagliano et al., 2022). Additionally, bamboo shoots, used in traditional Chinese medicine, contribute to nutrition and aid in labor and postpartum recovery.

Healing Applications and Digestive Aid: Bamboo shoots are used in healing poultices for wound care and infection management, showcasing their versatility (Kalyan et al., 2023). The juice of pressed bamboo shoots, often practiced in India, contains protease enzymes and aids in protein digestion, making it a valuable addition to dietary practices that support digestive health.

Bamboo-based Cosmetics: Bamboo's medicinal properties extend beyond internal health, with products like bamboo salt tablets addressing internal maladies in Korea (Chongtham & Bisht, 2020). Bamboo-derived cosmetics, including bath salts and cleansing agents, underline bamboo's versatility in personal care and well-being.

Bamboo's role in traditional medicine highlights its multifaceted benefits, surpassing its applications in food and construction. Its therapeutic properties, recognized by traditional healing systems, contribute to the overall well-being of communities, especially in bamboo-abundant regions. These practices affirm bamboo's enduring value in supporting the health and vitality of local populations, with significant potential as a source of medicinal

compounds and applications for holistic health and well-being. Continued research may further establish bamboo as a valuable resource in traditional and modern medicine.

### Source of Energy

In countries like China, Wang et al. (2021) highlight the association between the increasing demand for energy and economic growth and the resulting energy shortages faced by many nations. Addressing these challenges requires the development of new energy industries, offering dual benefits of enhancing personal incomes and mitigating national resource scarcities (Sabir et al., 2017). Biomass energy emerges as a promising prospect in this evolving energy landscape, with bamboo prominently featured as a vital contributor. Research supports bamboo's effectiveness as a fuel source, citing its exceptional combustion characteristics, high calorific value, and minimal environmental impact as factors that make it a viable solution for alleviating energy shortages (Borowski, 2020).

The conversion of bamboo waste and waste engine oil into fuel demonstrates bamboo biomass as an alternative to conventional fossil fuels. Bamboo biomass, sourced from various parts of the plant, can be converted into energy products such as syngas, biofuels, or charcoal through different processes, including biochemical or thermal conversion. However, bamboo biomass alone may not be sufficient to meet global energy needs, and integration with other energy sources is essential to ensure a sustainable energy supply (Li et al., 2020).

This review emphasizes the increasing energy demands associated with economic expansion, as well as the resulting energy shortages faced by nations. Exploration of new energy industries, notably biomass energy with bamboo, presents a great opportunity to address these challenges. Bamboo's outstanding qualities as a fuel source, coupled with its minimal environmental impact, position it as a valuable resource for mitigating energy shortages (Chin et al., 2017). While acknowledging that bamboo biomass alone may not fully meet global energy requirements, integrating bamboo with other energy sources offers a pathway toward more secure, sustainable, and eco-friendly energy systems. It aligns with the broader objectives of ensuring energy security and environmental responsibility. These insights contribute to the ongoing discourse on meeting the world's escalating energy demands while safeguarding the environment and fostering economic growth.

### Construction

Bamboo garners widespread acclaim as an exceptional building material owing to its remarkable strength and flexibility. The distinctive qualities that set bamboo apart as a construction material are attributable to its microfiber structures containing lignin and hemicellulose, which contribute to an impressive strength-to-weight ratio, surpassing even conventional construction materials like concrete and steel (Canavan et al., 2017).

A standout characteristic of bamboo is its tensile strength, surpassing that of mild steel, which renders bamboo highly resilient against stretching forces, a crucial attribute in construction applications. Bamboo also demonstrates remarkable compressive strength, capable of withstanding forces twice as effectively as concrete (Shu et al., 2020). These exceptional mechanical properties position bamboo as an ideal choice for a diverse range of construction purposes.

Bamboo possesses exceptional properties, making it an ideal choice for construction materials, providing cost-effectiveness, durability, and versatility (Yadav & Mathur, 2021). It is evident in its diverse applications, ranging from road construction (a testament to its strength and affordability) to drainage pipes, housing, and wind turbine construction (highlighting its adaptability). Traditional bamboo houses, prevalent in countries such as China, India, and the Philippines, exemplify its suitability for construction. Besides structural elements, bamboo also serves various roles, from decorative components to essential structural parts such as poles, trusses, flooring, and scaffolding (Chattopadhyay & White, 2019). These diverse applications position bamboo as a highly eco-friendly and readily available resource, meeting a range of construction needs while promoting sustainability (Yu et al., 2011). This versatility establishes bamboo as a key player in addressing contemporary construction challenges, where the balance between structural integrity and environmental sustainability is increasingly vital.

Bamboo's exceptional strength, rooted in its microfiber structures and unique chemical composition, establishes it as an outstanding building material (Sun et al., 2022). Its impressive strength-to-weight ratio, tensile strength surpassing mild steel, and exceptional compressive strength equip bamboo to tackle various construction challenges (Javadian, 2017). It finds application in a myriad of construction tasks, from traditional housing to infrastructure development. Its versatility spans decorative uses to structural components, portraying bamboo as an eco-friendly and sustainable solution aligning with contemporary construction needs and promoting environmental responsibility. These properties underscore the significance of bamboo in meeting the demands of the modern construction industry.

### CONCLUSION

Bamboo plantations have emerged as a promising strategy for promoting sustainable development and alleviating poverty in diverse regions worldwide. This review illustrates bamboo's intrinsic versatility and essentiality, which serve as a valuable global knowledge repository and offer essential guidance for policymakers, researchers, and industry stakeholders. The study's overarching goals encompass a comprehensive examination of the socioeconomic impact of bamboo plantations, with a particular emphasis on the broader implications for global decision-makers and investors. By consolidating diverse insights, the paper achieves a nuanced understanding of bamboo cultivation's myriad benefits,

challenges, and strategic considerations. A noteworthy aspect of the study lies in its explicit emphasis on the socioeconomic repercussions for local communities, accentuating the contextual relevance of bamboo within various cultural and environmental settings. This review, functioning as a foundational resource, not only advances the understanding of the socioeconomic dynamics of bamboo plantations but also passionately advocates for the industry's expansion while concurrently championing the well-being of local communities. With an intended publication in a scholarly journal, this study substantially contributes to the broader discourse surrounding sustainable agroforestry and bamboo cultivation practices. It underscores the imperative for a holistic, culturally sensitive approach, catering to the diverse needs and contexts across varied regions, promoting a more equitable and sustainable future for bamboo cultivation worldwide.

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