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

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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 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

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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 m^3 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 m^3 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

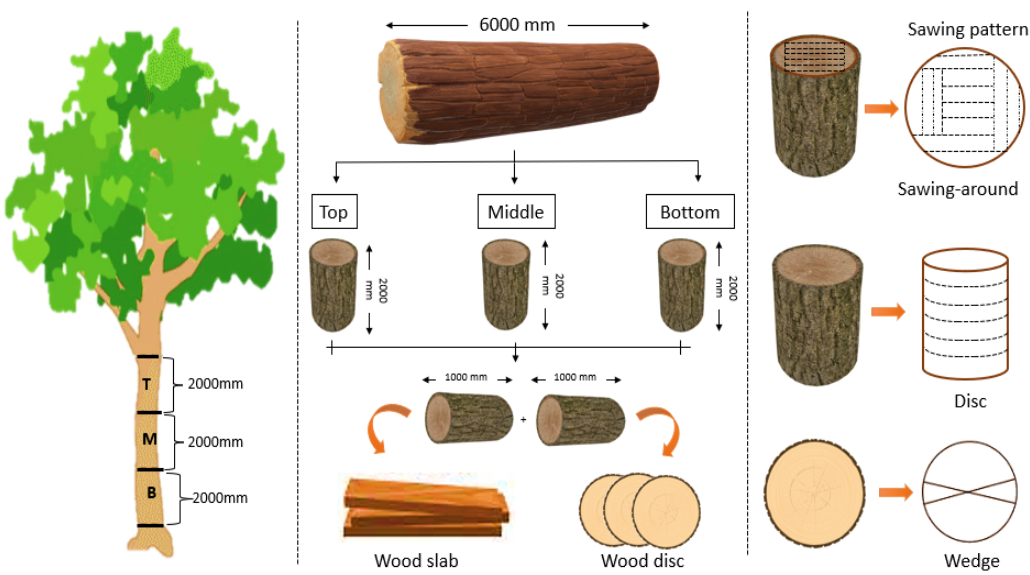

Figure 2. Summary of the harvesting process and sample processing

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

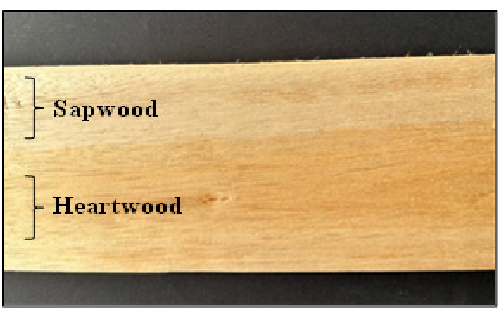

Figure 4. Differences of colour between sapwood and heartwood of *P. falcataria*

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.

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

A1 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:

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

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 ± 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:

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

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:

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

Where $Mass_{OD}$ is the mass of wood samples after oven-dried at 103 ± 2°C, and $Volume_{OD}$ is the volume of wood samples after oven-drying at 103 ± 2°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 ± 2°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^{-3} 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 ± 2°C and relative humidity of 65 ± 5°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:

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

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

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 ± 2°C and relative humidity of 65 ± 5°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:

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

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^2 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.

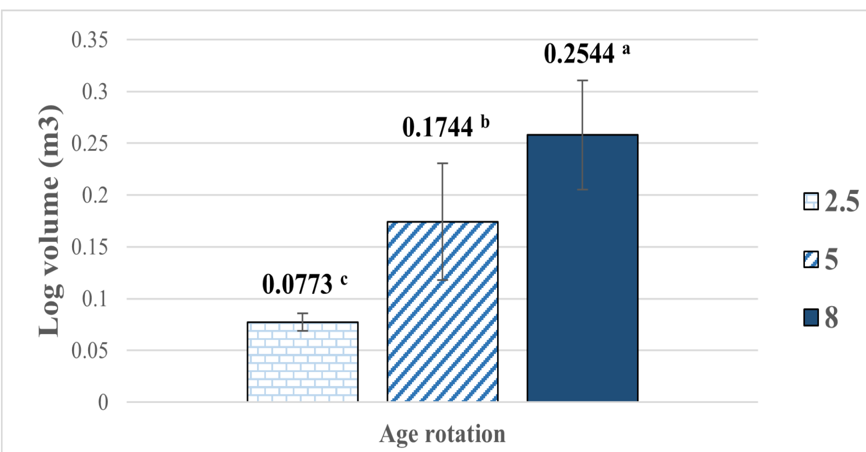

Figure 5. The log volume of *P. falcataria* wood is based on different age rotations. Note: Mean a and b showed significant differences at $p \leq 0.05$

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 (years)	N (per age)	Green Moisture Content (%)			
		Top	Middle	Bottom	Average
2.5	60	169.3	185.2	186.1	180.9 ± 32.2[a]
5	60	140	132.9	115	129.3 ± 19.7[c]
8	60	156.4	165.2	127.9	149.8 ± 30.2[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^{-3}. 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 (years)	N (per age)	Green Density (kgm^{-3})			
		Top	Middle	Bottom	Average
2.5	60	577.3	681	743.1	667.1 ± 107.1[a]
5	60	696.6	685.6	767.0	716.4 ± 74.4[b]
8	60	659.5	655.5	673.0	659.5 ± 72.7[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^{-3} 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 (years)	N (per age)	Basic Density (gcm^{-3})			
		Top	Middle	Bottom	Average
2.5	60	0.23	0.23	0.26	0.24 ± 0.37[a]
5	60	0.29	0.30	0.36	0.32 ± 0.48[c]
8	60	0.25	0.25	0.30	0.27 ± 0.39[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^{-3} 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).

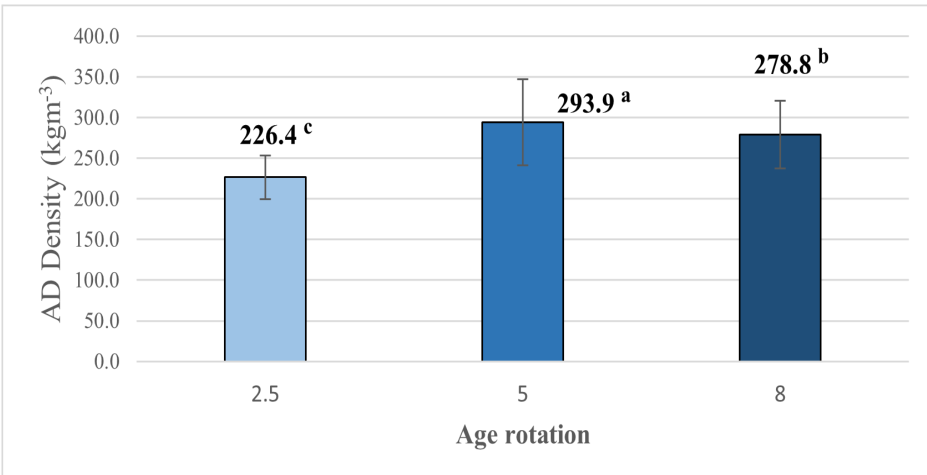

Figure 6. The air-dried density of *P. falcataria* wood based on different age rotations. Note: Mean a and b showed significant differences at $p \leq 0.05$

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^{-3}. 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^{-3} compared to 252.6 kgm^{-3}. 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.

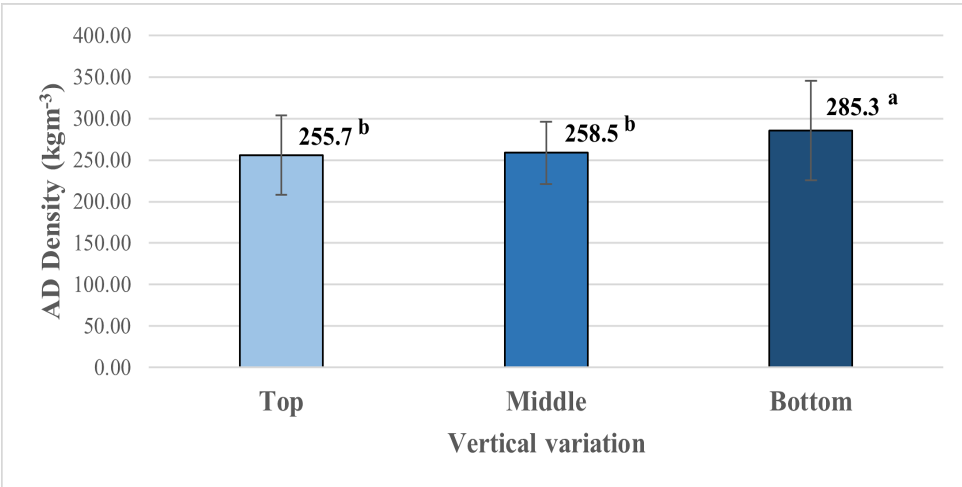

Figure 7. The air-dried density of *P. falcataria* wood based on vertical variation. Note: Mean a and b showed significant differences at $p \leq 0.05$

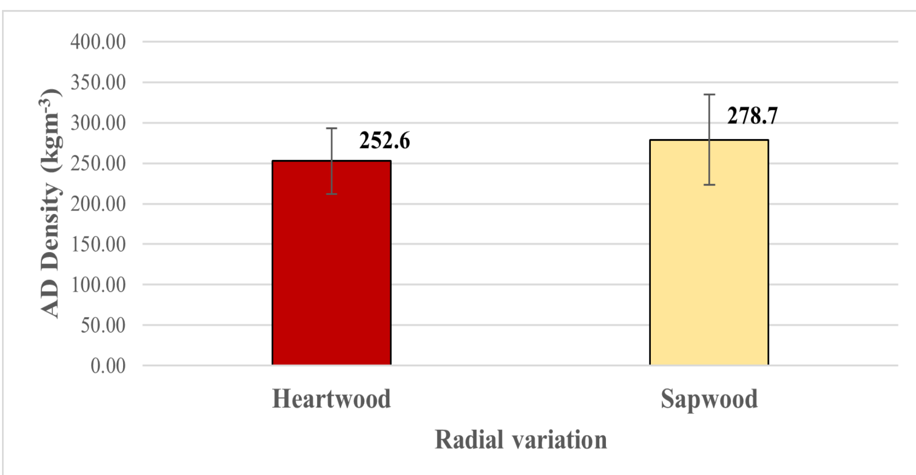

Figure 8. The air-dried density of *P. falcataria* wood based on the radial variation

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.

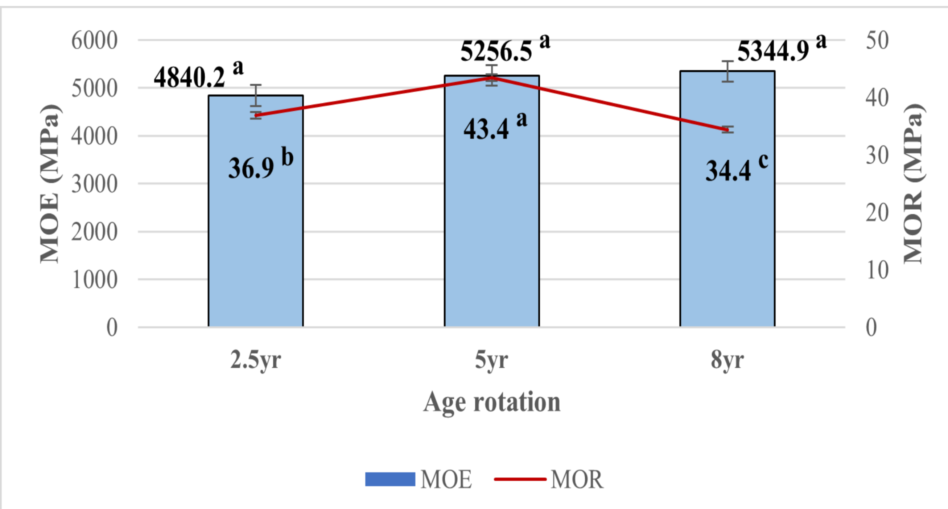

Figure 9. The MOE and MOR of *P. falcataria* wood based on different age rotations. Note: Mean a and b showed significant differences at $p \leq 0.05$

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.

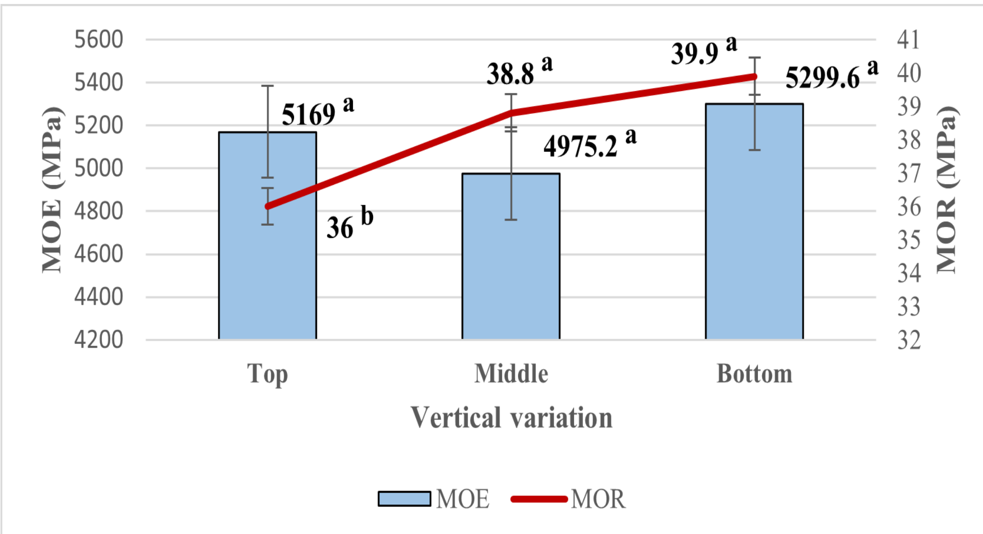

Figure 10. The MOE and MOR of *P. falcataria* wood based on vertical variation. Note: Mean a and b showed significant differences at $p \leq 0.05$

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.

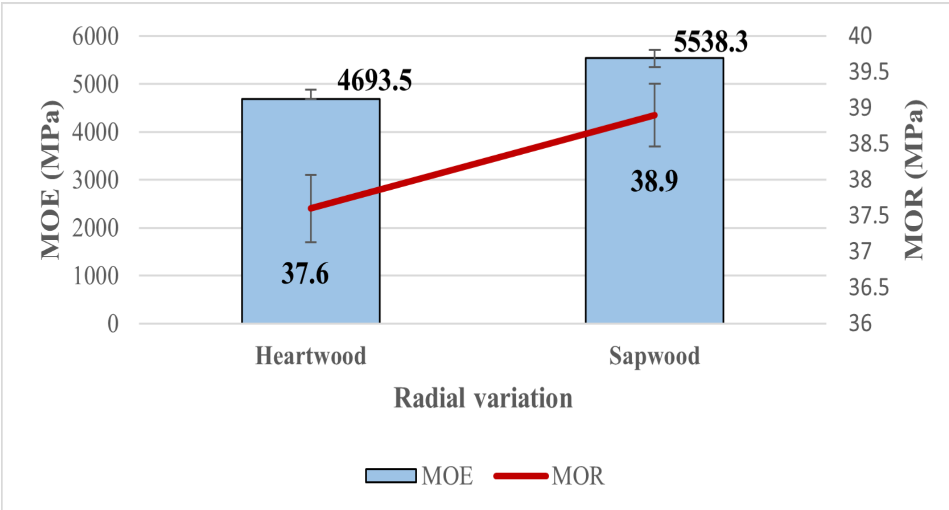

Figure 11. The MOE and MOR of *P. falcataria* wood based on radial variation

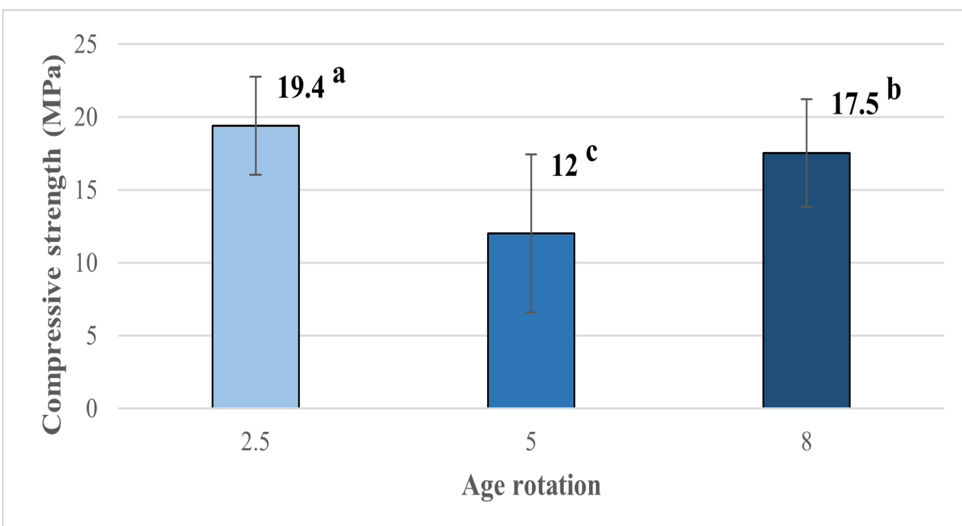

Figure 12. The compressive strength of *P. falcataria* wood based on different age rotations. Note: Mean a and b showed significant differences at $p \leq 0.05$

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 & Bektaş, 2012).

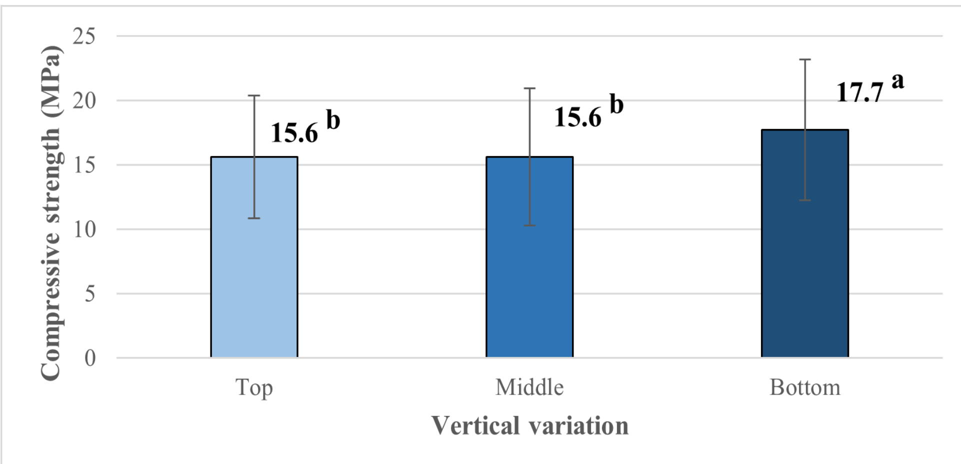

Figure 13. The compressive strength of *P. falcataria* wood based on vertical variation. Note: Mean a and b showed significant differences at $p \leq 0.05$

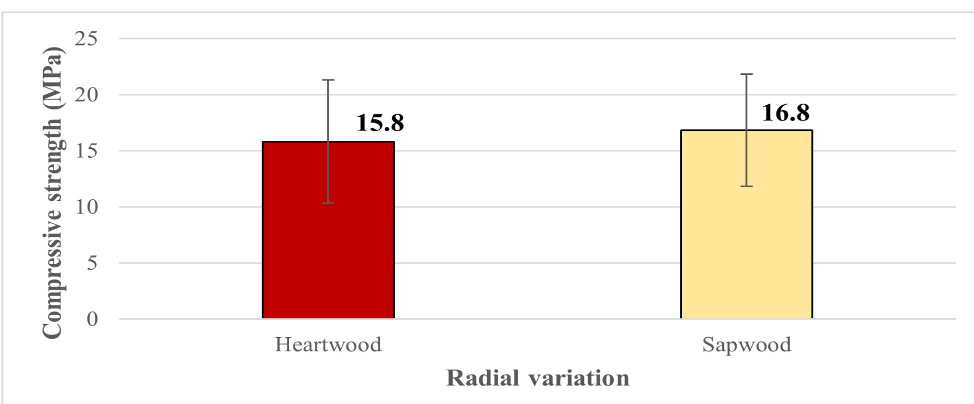

Figure 14. The compressive strength of *P. falcataria* wood based on radial variation

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^2) 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^2 value range of 0.5125 to 0.6708, indicating that density can be a good predictor of MOE. The observation of the R^2 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^2 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).

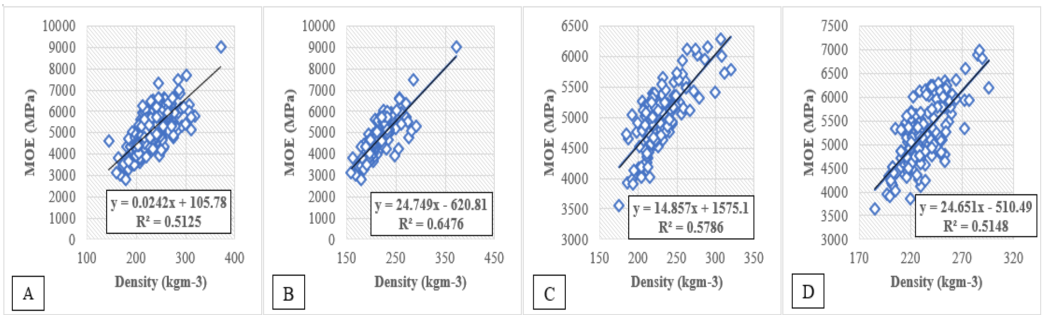

Figure 15. Relationship between Density and MOE based on age and vertical variation. Notes: A: 2.5 years, B: Top, C: Middle, D:Bottom

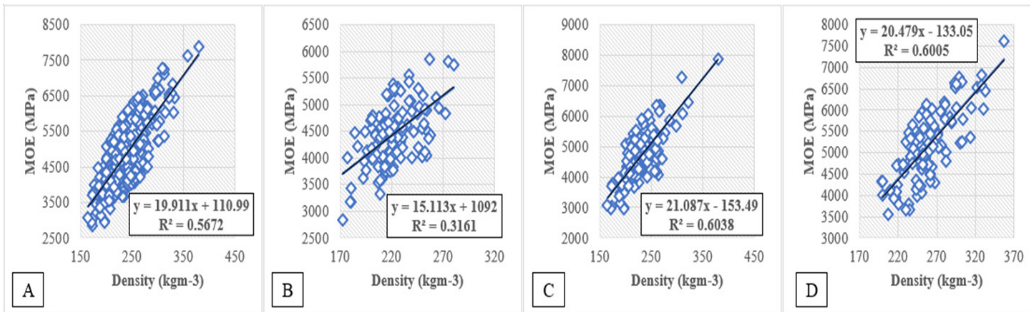

Figure 16. Relationship between Density and MOE based on age and vertical variation. Notes: A: 5 years, B: Top, C: Middle, D: Bottom

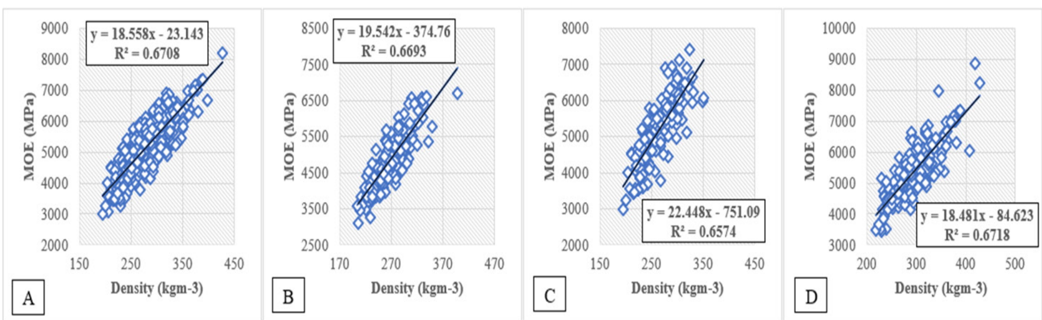

Figure 17. Relationship between Density and MOE based on age and vertical variation. Notes: A: 8 years, B: Top, C: Middle, D: Bottom

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^2 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^2 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).

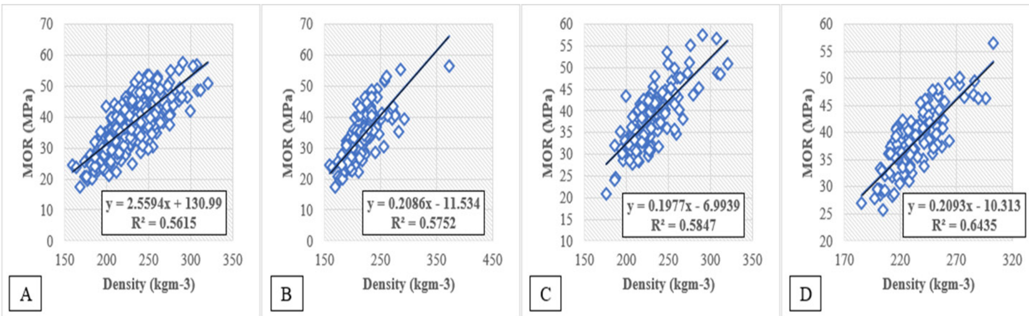

Figure 18. The relationship between density and MOR is based on age and vertical variation. Notes: A: 2.5 years, B: Top, C: Middle, D: Bottom

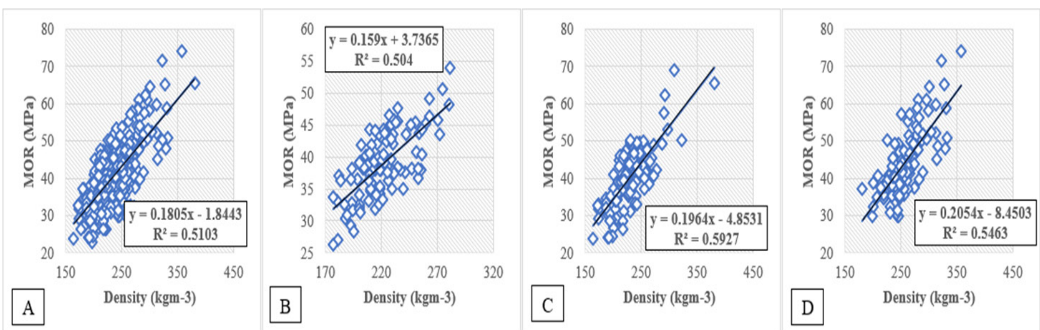

Figure 19. Relationship between Density and MOR based on age and vertical variation. Notes: A: 5 years, B: Top, C: Middle, D: Bottom

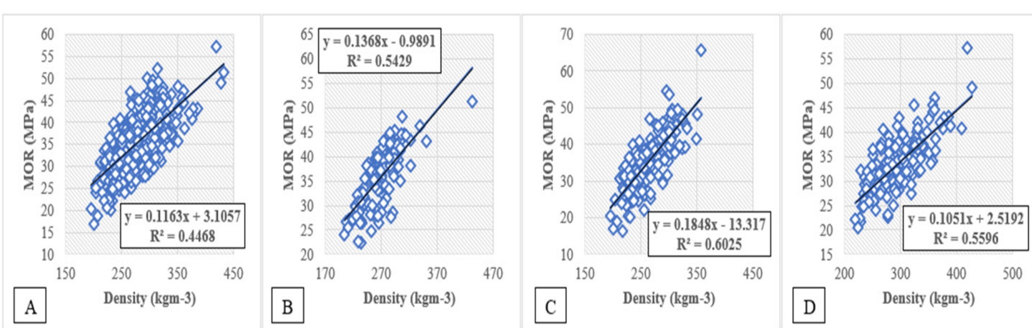

Figure 20. Relationship between Density and MOR based on age and vertical variation. Notes: A: 8 years, B: Top, C: Middle, D: Bottom

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^2 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^2 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^2 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^2 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.

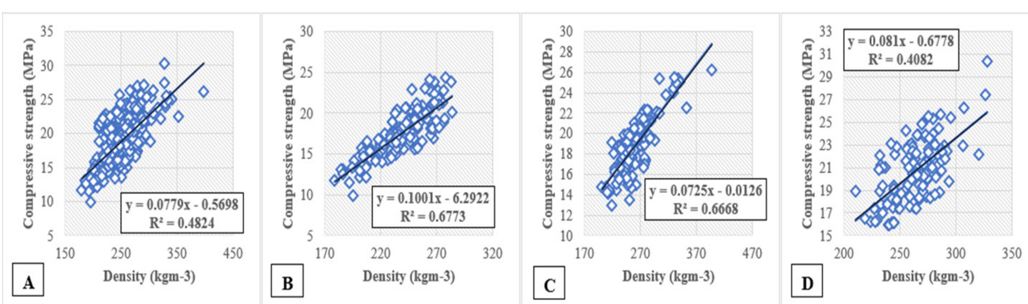

Figure 21. Relationship between Density and Compressive strength based on age and vertical variation. Notes: A: 2.5 years, B: Top, C: Middle, D: Bottom

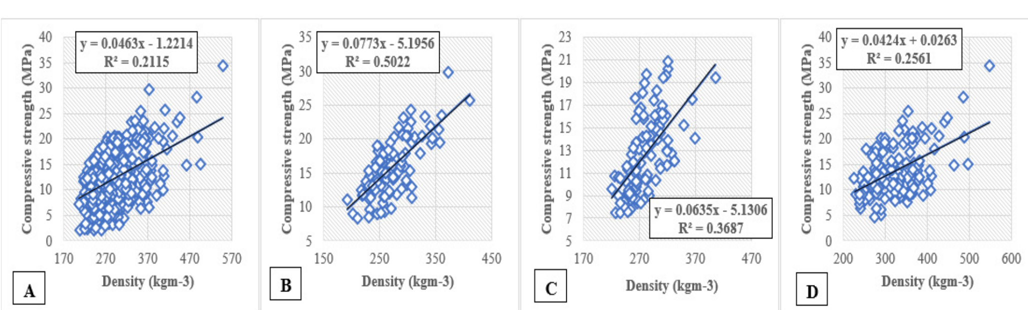

Figure 22. Relationship between Density and Compressive strength based on age and vertical variation. Notes: A: 5 years, B: Top, C: Middle, D: Bottom

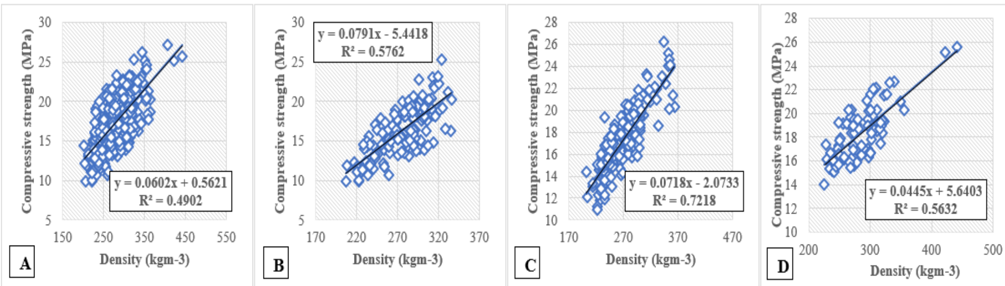

Figure 23. Relationship between Density and Compressive strength based on age and vertical variation. Notes: A: years, B: Top, C: Middle, D: Bottom

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 physico-mechanical 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.

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