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Full Length Research Article

The Importance of Spacing and Thinning to Improve Productivity and Wood Properties of Clonal Teak Plantation

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ABSTRACT

Clonal teak in Indonesia was produced through a tree improvement program that selected superior mother trees. These clones showed high growth and could produce more than 200 m^3/ha in 20 years after planting. The silvicultural treatment could improve the growth of clonal teak through spacing arrangements and thinning. However, studies combining the effects of spacing and thinning to improve forest productivity in clonal teak plantations remain limited. Therefore, this study aims to determine the effect of different spacing and thinning intensity on the productivity of a 13-year-old clonal teak plantation. A nested randomized complete block design was used with 3 blocks as replication. The treatment comprised 4 spacing types: 3 m × 3 m, 6 m × 2 m, 8 m × 2 m, and 10 m × 2 m. Meanwhile, 3 thinning intensities were nested within each spacing treatment: 0% (control), 25% (medium thinning), and 50% (heavy thinning). The results showed that at the age of 13 years old, spacing treatment affected the development of diameter at breast height (DBH), mean annual diameter increment (MADI), tree bole height (TBH), crown diameter (CD), canopy openness (CO), competition index (CI), and pilodyn penetration (PP) ($p < 0.05$). Spacing treatment did not affect height (H), volume (Vol), and stress wave velocity (SWV) ($p > 0.05$). The best spacing to improve DBH, MADI, CD, CO, and PP was 10 m × 2 m, yielding 29.68 cm, 2.30 cm/year, 5.18 m, 54.84%, and 20.21 mm, respectively. Additionally, thinning intensity, nested within spacing treatment, significantly affected DBH, MADI, Vol, CO, and CI ($p < 0.05$). In conclusion, a combination of spacing 10 m × 2 m and thinning intensity 50% is recommended to increase forest productivity in a clonal teak plantation.

1. Introduction

Teak is a commercially important tree species widely grown in lowland forests. This is due to the high economic value, strength, quality and durability of its wood (Chambi-Legoas et al. 2025). The global teak forest area, both natural forests and plantations, is estimated at 29 million ha and 4.35 to 6.89 million ha, respectively, across more than 69 countries on various continents (Berrocal et al. 2020; Midgley et al. 2015; Kollert et al. 2024). In Indonesia, the area of plantation is > 1.2 million ha (MOF 2025). Furthermore, global market demand for teak is 2–2.5 million m^3 per year, supplied by natural forests and plantations, at 0.5 million m^3/year and 1.5–2 million m^3/year, respectively. Approximately 60% of this wood is produced in India, Indonesia, and Myanmar (Kollert et al. 2024). In Indonesia, roundwood production from teak plantations in 2021 and 2022 reached 1.07 million m^3 and 0.94 million m^3, respectively (BPS 2023). The high demand for teak may be met by a relatively short felling rotation of 20–30 years, with fast growth and high wood quality (Jerez-Rico and de Andrade Coutinho 2017). Therefore, tree breeding activities are carried out to produce superior clones that can increase productivity in teak forest management.

Generally, teak breeding in Indonesia began in 1983 and continued until 1997, during which 680 mother trees were collected from various plantations across the country. A teak progeny test was conducted, followed by a clonal test, to select the best clones to support a productive plantation (Budiadi et al. 2017; Widiyatno et al. 2024). Selected clones from these tests were then planted in pruning gardens to produce shoot cuttings for clonal teak forestry (Widiyatno et al. 2024), making a potential stand of > 200 m^3/ha with a 20-year rotation (Budiadi et al. 2017; Widiyatno et al. 2024). These selected clones can be used to develop clonal teak forestry to increase productivity, as the genetic traits of mother trees are passed on to offspring.

Teak is used for carpentry and sawn timber; therefore, teak plantations aim to produce trees with large diameters, straight trunks, and high branch-free heights, which yield high-quality logs. Achieving these characteristics depends strongly on proper stand management, particularly the regulation of stand density or the number of trees per ha. Therefore, determining the optimal spacing for teak plantations is the initial step in establishing a spacing that supports plant growth. Spatial planning in the early stages of teak plantation establishment includes plant spacing; the optimal spacing for teak plantations is 3 m × 3 m, compared to other species (Zahabu et al. 2015). However, increasing spacing will increase the branching angle and, probably, reduce wood quality, because knots formed from large branches decrease the value and strength of sawn timber (Rahmawati et al. 2021). Furthermore, we need to determine the proper spacing in the teak plantation to balance sufficient growing space for diameter increment with adequate competition to encourage straight-stem growth and natural branch shedding.

During the management phase of teak plantations, thinning is one of the silvicultural practices used to promote the growth of the remaining trees, thereby producing high-quality saw timber and wood for construction (Wongprom et al. 2023). Thinning modifies the competitive dynamics within a stand by redistributing access to site resources, such as light, nutrients, and water, among the remaining trees (Moreau et al. 2020; Moreau et al. 2022). Timing and intensity of thinning operations are critical factors influencing stand development in teak plantations. When thinning is delayed, stand growth may decline or cease entirely. Conversely, thinning implemented very early or intensively can stimulate the development of side branches and epicormic shoots, diverting resources from the main stem. In a 3-year-old clonal teak plantation after thinning, thinning intensities at 50% significantly increased diameter and height growth compared to the control (Budiadi et al. 2017). Studies on spacing (growing space) and thinning intensity as silvicultural treatments should be conducted simultaneously to achieve optimal, high-quality teak growth per unit area. Therefore, this research aims to determine the combined effects of initial spacing and thinning intensity on the growth characteristics, competition index (CI), canopy openness (CO), and wood properties of a clonal teak plantation.

2. Materials and Methods

2.1. Study Location and Experimental Design

This research was conducted in a clonal teak plantation, specifically on plots 63c and 53i, Sidolaju Forest Management Resort (RPH), Kedunggalar Forest Management Sub-Unit (BKPH), Ngawi Forest Management Unit (KPH), East Java Regional Division of Perum Perhutani (**Fig. 1**). The research design used was a nested randomized complete block design (Nested RCBD) with 3 blocks as replications. The treatments were 4 spacing types: 3 m × 3 m, 6 m × 2 m, 8 m × 2 m, and 10 m × 2 m. Meanwhile, 3 levels of thinning intensity were nested within each spacing treatment. In comparison, the 3 thinning intensities in each spacing treatment were 0% (control), 25% (medium), and 50% (heavy) (**Table 1**). The thinning of teak was a systematic, mechanical approach. In the 0% thinning treatment, no trees are removed, and the stand is maintained at its original density as a control. For the 25% thinning treatment, approximately one-quarter of the trees in the stand are removed using a selective thinning method, mainly through low thinning. In the 50% thinning treatment, a more selective thinning is applied, removing about half of the trees in the plantation to provide wider growing space for the best-performing individuals. This treatment is often done by removing every second tree in a row or selecting suppressed trees and strong competitors surrounding selected superior trees. The criteria for cutting and thinning focused on eliminating trees with poor stem form, weak vigor, physical defects, or inferior growth performance. Therefore, the number of individuals per thinning intensity treatment (0%, 25%, and 50%) varied with spacing (**Table 1**). Furthermore, the plot size for each treatment was a square plot measuring 4 × 50 individual clonal teak plants.

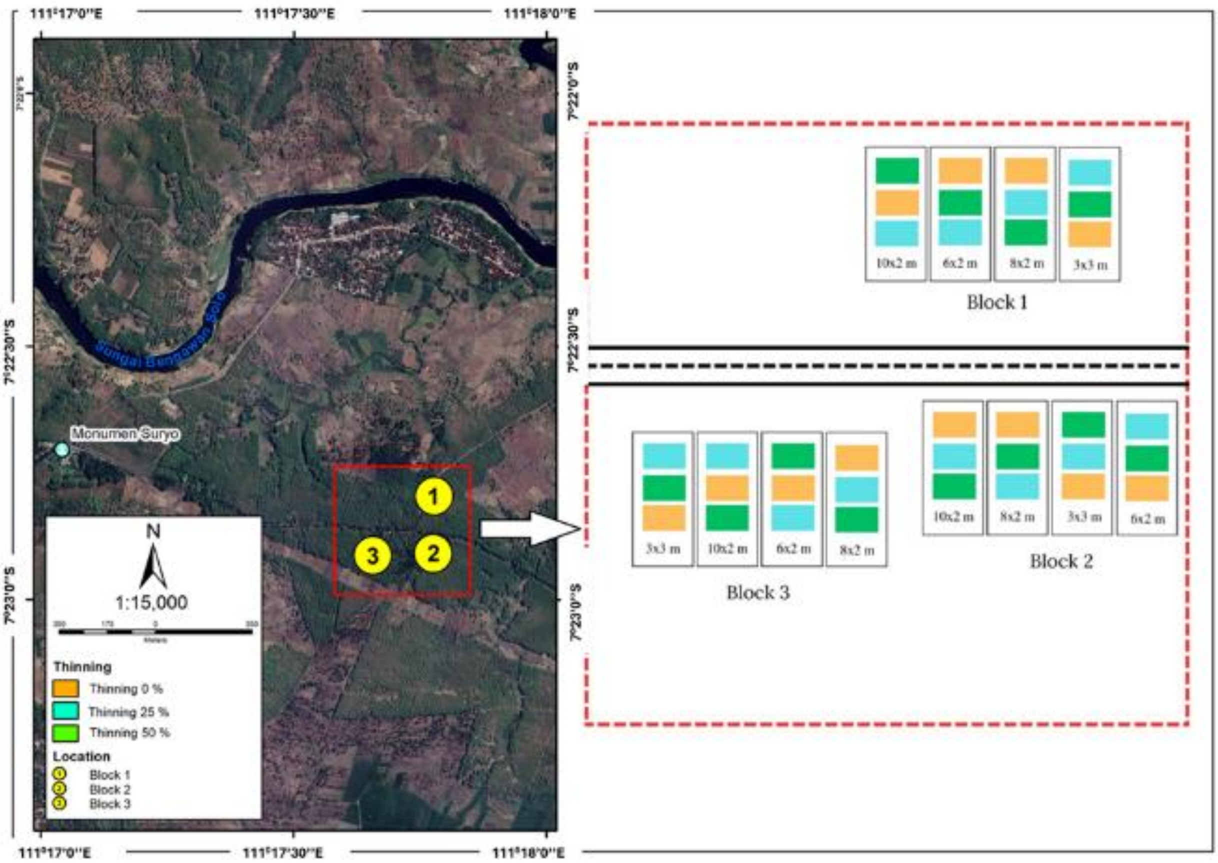

Fig. 1. Study site and research design.

Table 1. Planting density for each treatment combination

Spacing	Thinning/planting density (individual number per ha)		
	0%	**25%**	**50%**
3 m × 3 m	1,111	833	556
6 m × 2 m	833	625	417
8 m × 2 m	625	469	313
10 m × 2 m	500	375	250

2.2. Procedures for Assessment of Teak Growth, Pilodyn Penetration, and Stress Wave Velocity

The variables analyzed include diameter at breast height (DBH), mean annual diameter increment (MADI), height (H), tree bole height (TBH), volume (Vol), crown diameter (CD), canopy openness (CO), competition index (CI), as well as wood properties, namely pilodyn penetration (PP) and stress wave velocity (SWV). Diameter was measured at 1.3 m above ground level, and these measurements were used to calculate MADI (cm/year) and volume (m^3/ha). MADI was calculated using Equation 1.

$$MADI = \frac{DBH}{The\ age\ of\ forest\ plantation} \quad (1)$$

Tree volume (m^3) was converted to volume per ha (m^3/ha). Total height and bole height were measured using a Haga altimeter, while CD (m) was measured by taking 2 measurements, from north to south and west to east, using a roll meter, and the average value was calculated for analysis. Tree volume was calculated using Equation 2.

$$V = (-0.0884 + 0.0297\ x\ DBH)^2 \quad (2)$$

The tree competition index (CI) was evaluated using Equation 3 to quantify the extent to which a subject tree's growth was affected by nearby competing trees, as proposed by Hegyi (1974), which explains the competitive effects of trees in the forest (Sun et al. 2022). This assessment considered both the proximity of competitors to the subject tree and the overall number of competitors in the surrounding area.

$$CIi = \sum_{j=1}^{n} \frac{dj}{di * Lij} \quad (3)$$

where *CIi* is of the "i" tree's competition index, *n* is the total number of surrounding competitor trees of target tree "i", *dj* is the diameter/DBH of the competitor tree j (cm) of target tree "i", *di* is the DBH of the subject tree (cm), and *Lij* is the distance between the subject tree and the competitor tree (m).

Canopy openness (CO) was assessed using a camera equipped with a very wide-angle lens that provides 180-degree coverage and can be used to estimate forest CO (Winn et al. 2016). Hemispherical photography was analyzed with the free software Gap Light Analyzer (GLA), developed by Frazer et al. (1999), to calculate CO (Vargas et al. 2021).

Wood properties were assessed using non-destructive methods, specifically the Pilodyn tester and the Fakkop microsecond timer. A Pilodyn tester with an impact force of 6 J and a pin/needle diameter of 2.5 mm was used to estimate wood density from penetration depth. Pilodyn penetration (PP) was taken at 3 different positions on each tree without removing bark, at breast height (1.3 m above the ground) (Seta et al. 2021). Meanwhile, the Fakkop microsecond timer was used to measure SWV, a non-destructive testing (NDT) technique for assessing the mechanical properties of wood (Papandrea et al. 2022; Enkhbayar et al. 2025). SWV measurements were performed using 2 sensors, one at 150 cm and the other at 50 cm above the ground, both at a 45° angle. A small hammer struck Sensor 1, generating stress waves. When Sensor 2 detected the wave, the time it took to travel between the sensors was recorded as the transit time (µs) (**Fig. 2**).

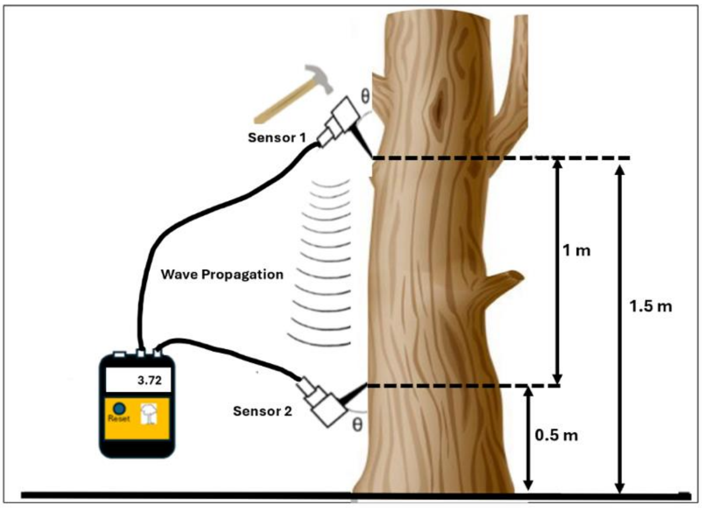

Fig. 2. Illustration of SWV measurement (modified from Proto et al. 2017; Seta et al. 2021; Widiyatno et al. 2024).

Each tree was measured 10 times, and the average of these readings was used for analysis (Widiyatno et al. 2024), as shown in Equation 5.

$$Tm = \frac{Treading}{LD} \quad (5)$$

where *Tm* (µs m^{-1}) is the wave propagation time per unit distance, *Treading* (µs) is the average propagation time of the voltage wave, and *LD* is the distance between Sensor 1 and Sensor 2. The stress wave value (SWV) (km s^{-1}) was determined using Equation 6.

$$SWV = \frac{1 \times 1000}{Tm} \quad (6)$$

2.3. Data Analysis

Factorial analysis of variance (ANOVA) was used to assess the effects of plant spacing and thinning on tree and stand growth. RStudio statistical software was used to perform an ANOVA test. Differences between groups were assessed using Tukey's test at the 5% and 1% significance levels ($\alpha = 0.05$ and $\alpha = 0.01$).

3. Results and Discussion

3.1. Analysis of Variance (ANOVA) Under Different Spacing and Thinning Intensity

The spacing treatment had a significant impact on DBH (F=109.48; $p < 0.0001$), MADI (F = 103.09; $p < 0.0001$), TBH (F = 3.03; $p = 0.049$), CD (F = 38.33; $p < 0.0001$), CO (F = 3.47; $p = 0.034$), CI (F = 7.87; $p = 0.01$), and P (F = 4.08; $p = 0.019$). However, height (H), volume (Vol), and SWV were not significantly changed by wider spacing ($p > 0.05$). Thinning intensity (nested in spacing) had a significant effect on DBH (F = 4.32; $p = 0.003$), MADI (F = 2.78; $p = 0.027$), Vol (F = 8.07; $p < 0.0001$), CO (F = 2.38; $p = 0.05$), and CI (F = 8.31; $p < 0.0001$), but this treatment did not have a significant impact on H, TBH, CD, P, and SWV ($p > 0.05$) (**Tables 2** and **3**).

Table 2. ANOVA summarizes the effects of spacing and thinning intensity (nested in spacing) on DBH, MADI, H, TBH, and Vol of 13-year-old teak stands after planting

Source of variance	df	DBH		MADI		H		TBH		Vol	
		MS	F	MS	F	MS	F	MS	F	MS	F
Block	2	22.54	17.55	0.13	15.88	3.89	2.86	0.55	0.61	19724.8	17.94
Spacing	3	140.63	109.48**	0.87	103.09**	1.99^{ns}	1.47	2.69	3.03*	872.3	0.79^{ns}
Thinning (spacing)	8	5.543	4.32*	0.024	2.78*	0.283	0.21^{ns}	0.395	0.45^{ns}	8873.8	8.07**
Error	22	1.285		0.008		1.353		0.889		1099.68	

Notes: DBH = Diameter at breast height at 1.3; MADI = Mean annual diameter increment; H = Height; TBH = Tree bole height; Vol = Volume; df = Degree of freedom; MS = Mean square; F = F value; * = Significant at tα ≤ 0.05; ** = Significant at tα ≤ 0.01; ns = Non-significant at tα = 0.05.

Table 3. ANOVA summarizes the effects of spacing and thinning intensity (nested in spacing) on CD, CO, CI, P, and SWV of 13-year-old teak stands after planting

Source of variance	df	CD		CO		CI		P		SWV	
		MS	F	MS	F	MS	F	MS	F	MS	F
Block	2	0.08	0.44	0.07	0.01	0.17	4.74	4.91	9.18	0.06	8.76
Spacing	3	6.85	38.33**	44.11	3.47*	0.27	7.87**	2.18	4.08*	0.01	2.12^{ns}
Thinning (spacing)	8	0.19	1.09^{ns}	30.27	2.38*	0.29	8.31**	0.33	0.62^{ns}	0.004	0.65^{ns}
Error	22	0.18		12.72		0.03		0.54		0.01	

Notes: CD = Crown diameter; CO = Canopy openness; CI = Competition index; P = Pilodyn penetration; SWV = Stress wave velocity; df = Degree of freedom; MS = Mean square; F = F value; * = Significant at tα ≤ 0.05; ** = Significant at tα ≤ 0.01; ns = Non-significant at tα = 0.05.

The best average DBH, MADI, CD, CO, and PP were at a spacing of 10 m × 2 m with respective values of 29.68 ± 0.47 cm, 2.30 ± 0.03 cm/year, 5.18 ± 0.14 m, 54.84 ± 0.97%, and 20.21 ± 0.23 mm. Spacing of 3 m x 3 m produced the smallest average development of DBH, MADI, CD, CO, and PP compared to other treatments at 20.56 ± 0.61 cm, 1.58 ± 0.04 cm/year, 3.22 ± 0.12m, 50.59 ± 1.84%, and 19.2 ± 0.22 mm, respectively (**Table 4**).

Table 4. Comparisons of average growth characteristics, CI, CO, and wood properties across spacing treatments

Research variable	Spacing			
	3 m × 3 m	6 m × 2 m	8 m × 2 m	10 m × 2 m
DBH (cm)	$20.56(0.61)^{d}$	$24.45(0.8)^{c}$	$27.48(0.64)^{b}$	$29.68(0.47)^{a}$
MADI (cm/year)	$1.58(0.04)^{d}$	$1.89(0.06)^{c}$	$2.13(0.04)^{b}$	$2.3(0.03)^{a}$
H (m)	$25.14(0.28)^{ns}$	$25.49(0.4)^{ns}$	$26.16(0.45)^{ns}$	$26.01(0.33)^{ns}$
TBH (m)	$14.38(0.19)^{a}$	$14.08(0.25)^{a}$	$14.02(0.42)^{ab}$	$13.11(0.23)^{b}$
Vol (m^3/ha)	$233.05(26.8)^{ns}$	$254.26(21.48)^{ns}$	$244.32(18.88)^{ns}$	$234.52(18.27)^{ns}$
CD (m)	$3.22(0.12)^{c}$	$3.68(0.11)^{c}$	$4.49(0.17)^{b}$	$5.18(0.14)^{a}$
CO (%)	$50.59(1.84)^{b}$	$51.31(1.5)^{b}$	$54.65(0.82)^{ab}$	$54.84(0.97)^{a}$
CI	$1.24(0.14)^{a}$	$1.16(0.13)^{a}$	$0.94(0.1)^{b}$	$0.87(0.04)^{b}$
P (mm)	$19.2(0.22)^{b}$	$19.57(0.28)^{ab}$	$20.18(0.4)^{a}$	$20.21(0.23)^{a}$
SWV (km/s)	$3.78(0.03)^{ns}$	$3.8(0.04)^{ns}$	$3.87(0.03)^{ns}$	$3.82(0.03)^{ns}$

Notes: DBH = Diameter at breast height at 1.3 m; MADI = Mean annual diameter increment; H = Height; TBH = Tree bole height; Vol = Volume; CD = Crown diameter; CO = Canopy openness; CI = Competition index; P = Pilodyn penetration; SWV = Stress wave velocity. Different letters in the mean values indicate significant differences in treatment at $p < 0.01$. The standard error of each variable is shown in parentheses.

A spacing of 3 m × 3 m produced the highest TBH and CI values among all treatments, with averages of 14.38 ± 0.19 m and 1.24 ± 0.14, respectively. The 10 m × 2 m spacing treatment produced the lowest average TBH and CI values of 13.11 ± 0.23 m and 0.87 ± 0.04, respectively (**Table 4**). Increasing spacing significantly affected CD development in teak trees. The largest crown width was 2.74 m at a spacing of 10 m × 2 m, while the smallest was found at 3 m × 3 m (**Tables 3** and **4**).

3.2. Effect of Spacing on Growth Characteristics, Competition Index, Canopy Openness, and Wood Properties

The research results showed that increasing the spacing width improved the development of DBH, MADI, CD, CO, and PP, but simultaneously decreased TBH and CI of the stands. The highest development of DBH, MADI, CO, and PP was achieved at a spacing of 10 m × 2 m (**Table 4**). Meanwhile, the narrow spacing significantly increased TBH and CI values. This indicated that increasing spacing improved the crown width. Plants with the widest crown are better positioned to compete for environmental factors, such as light, nutrients, and water (Sharma et al. 2016), enhancing photosynthesis and growth, particularly DBH (Dey et al. 2021; Rahmawati et al. 2021).

Based on the results, increasing spacing did not affect the CO percentage in teak trees at 13 years of age. The percentage of CO at a spacing of 10 m × 2 m increased by 8.84% compared with 3 × 3 m (**Table 4** and **Fig. 3**). Wider spacing during the initial planting phase led to greater spatial openness during the initial growth phase. Still, after 13 years, CO between treatments was not significantly different. This was due to morphological adaptation in plants, particularly in intolerant species (e.g., *Tectona grandis*), indicating that plant canopies could grow plastically, widening at looser spacing or becoming taller and narrower at tighter spacing. However, the overall canopy volume still efficiently filled the vertical space.

Differences in spacing did not affect height growth but significantly affected TBH development in a 13-year-old clonal teak plantation (**Table 2**). This indicated that stand density influenced TBH development in a clonal teak plantation. A high tree density tended to produce higher TBH because it fostered self-pruning, while wider spacing produced trees with lower bole height (Rahmawati et al. 2021). This occurred because low stand density influenced the growth of unwanted branches and increased branch size (Isaac-Renton et al. 2020). Therefore, to achieve adequate spacing that resulted in low TBH, maintenance activities such as pruning were necessary to maintain plants with high TBH and minimize wood knots. High DBH under wide spacing still produced high-quality wood at the time of felling (Rahmawati et al. 2021).

The increase in DBH at wider spacing was due to a decrease in CI. Increasing spacing successfully reduced competition among individuals in the stands; hence, a 10 m × 2 m spacing reduced CI by 29.7% compared to 3 m × 3 m (**Table 5**). The CI value decreased as the distance between the subject and the competitor tree increased (Rahmawati et al. 2021). This is because wider spacing provides more growing space for each tree, thereby reducing competition between individuals. Therefore, increasing the age of clonal teak plantation without regular thinning can increase competition for growth. It could reduce the current annual increase (CAI) of the plants. At the age of 13 years, CI at a spacing of 3 m × 3 m was 1.24, while at the age of 7 years with the same spacing, the teak plant CI was 1.14 (Rahmawati et al. 2021). The increase in CI also heightened competition between the subject tree and competitors within the stands.

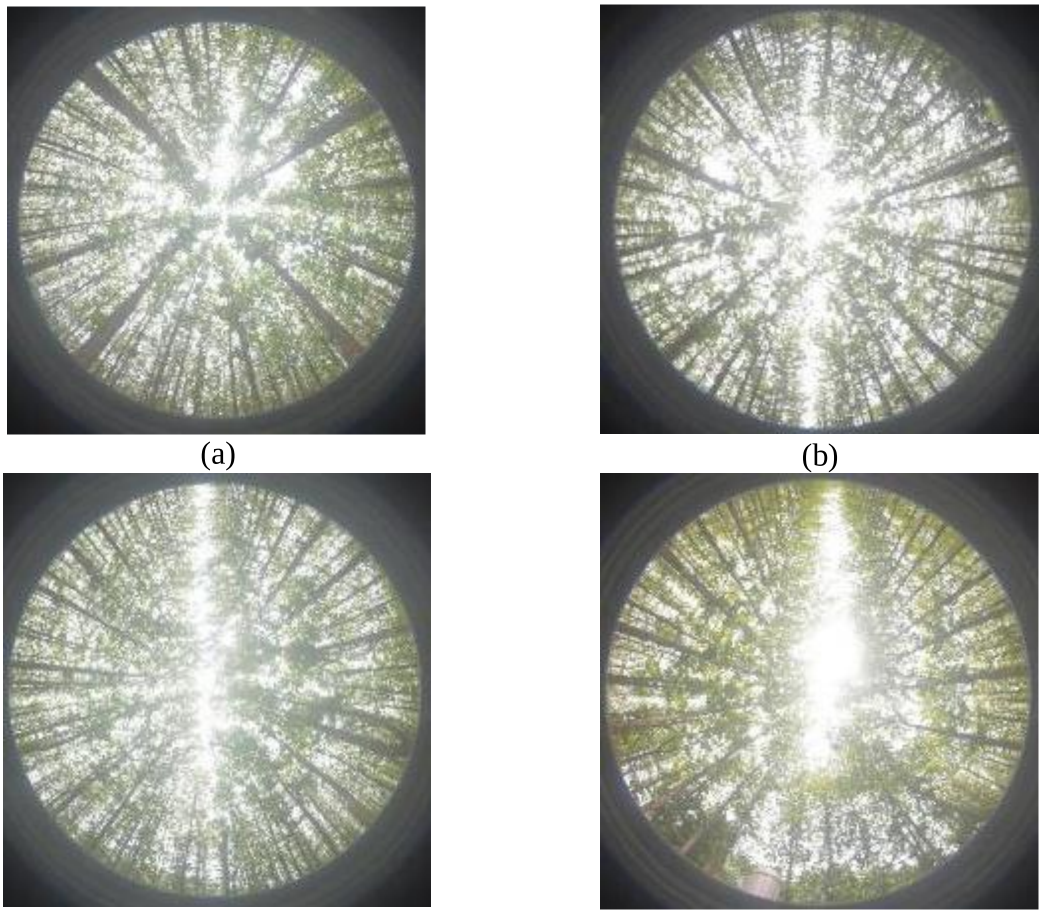

Fig. 3. Canopy openness (CO) of 13-year-old clonal teak stands captured by a hemisphere camera at different spacing: (a) 3 m × 3 m; (b) 6 m × 2 m; (c) 8 m × 2 m; (d) 10 m × 2 m.

Table 5. Distribution of teak stand diameter classes across spacing treatment per plot

Diameter class (cm)	Number of individuals in each spacing per block			
	3 m × 3 m	6 m × 2 m	8 m × 2 m	10 m × 2 m
10–14.99	4 ± 1.5	-	-	-
15–19.99	14 ± 2.9	5 ± 1.5	2	-
20–24.99	19 ± 1.2	30 ± 5.9	11 ± 2.7	6 ± 1.8
25–29.99	3 ± 2.0	17 ± 3.8	29 ± 3.8	20 ± 4.0
≥ 30	-	4 ± 2.7	10 ± 4.4	25 ± 6.8

PP is a non-destructive indicator for assessing the physical properties and density of wood. The results showed that increasing spacing from 3 m × 3 m to 10 m × 2 m enhanced PP by 5.2%. High PP values at wide interindividual distances indicated low wood density, greater void volume, and thinner cell walls, compared with high-density wood, which could reduce wood strength (Seta et al. 2021). However, the highest PP value in this study was 20.21 mm at a spacing of 10 m × 2 m, lower than the PP value of 23.43 mm for 14-year-old teak stands with a spacing of 6 m × 2 m without thinning treatment (Seta et al. 2021). Based on the results, a spacing of 10 m × 2 m produced higher wood density values than those reported in the study on teak wood density development conducted by Seta et al. (2021). These differences in results indicate that the PP value of the teak plantation is determined not only by spacing but also by the site.

SWV is a non-destructive technique used to assess the mechanical characteristics and structural integrity of wood. It serves as an indicator of the Modulus of Elasticity (MOE) and the Modulus of Rupture (MOR) of wood (Tumenjargal et al. 2020). Our results indicated that spacing treatments had no significant effect on SWV values in the clonal teak plantation 13 years after planting. The highest average value was observed in the 8 m × 2 m spacing treatment, namely 3.87 km/s (**Table 5**). This suggests that a high SWV indicates a high MOE, implying high resistance to deformation (Simic et al. 2019), a key property for determining the suitability of wood for various structural products (Vaughan et al. 2021). The high SWV value indicates that teak wood in this study has a high bending resistance. Additionally, a study on SWV in 10-year-old plants derived from generative propagation and shoot cuttings also had lower values of 3.65 ± 0.04 km/s and 3.75 ± 0.03 km/s, respectively (Widiyatno et al. 2024). The results showed that several factors, including stand age, growing location, and teak seed origin, affected SWV in teak plants.

3.3. Effect of Thinning Intensity on Growth Characteristics, Competition Index, Canopy Openness, and Wood Properties

Thinning is one of the silvicultural techniques in forest plantations to ensure optimal growth and timber quality. Our results showed that thinning intensity reduced the number of individual trees in the remaining stands and affected the development of DBH, MADI, Volume, CI, and CO in the clonal teak plantation. The best treatment was 50% across all spacings, with the largest increase in DBH development at a spacing of 6 m × 2 m, namely 13.82% compared to the control (0%). Meanwhile, the spacings of 3 m × 3 m, 8 m × 2 m, and 10 m × 10 m increased by 8.56%, 12.20%, and 6.24%, respectively, compared to the control (**Fig. 4**).

(a) (b) (c)

Fig. 4. Canopy Openness (CO) of 13-year-old clonal teak stands captured by a hemisphere camera at a spacing of 6 m × 2 m with thinning of (a) 0%, (b) 25%, and (c) 50%.

The highest development of MADI in the remaining stands was identified at a spacing of 10 m × 2 m, namely 2.36 cm/year (**Fig. 5**). This suggests that thinning is implemented by selectively removing plantation trees to reduce competition for light, water, and nutrients as well as to provide growing space for the remaining trees, thereby improving the yield and wood quality (Ashton and Kelty 2018; Bose et al. 2018). DBH development in clonal teak plantation requires optimal growing space and stand density (Vigulu et al. 2019; Seta et al. 2021).

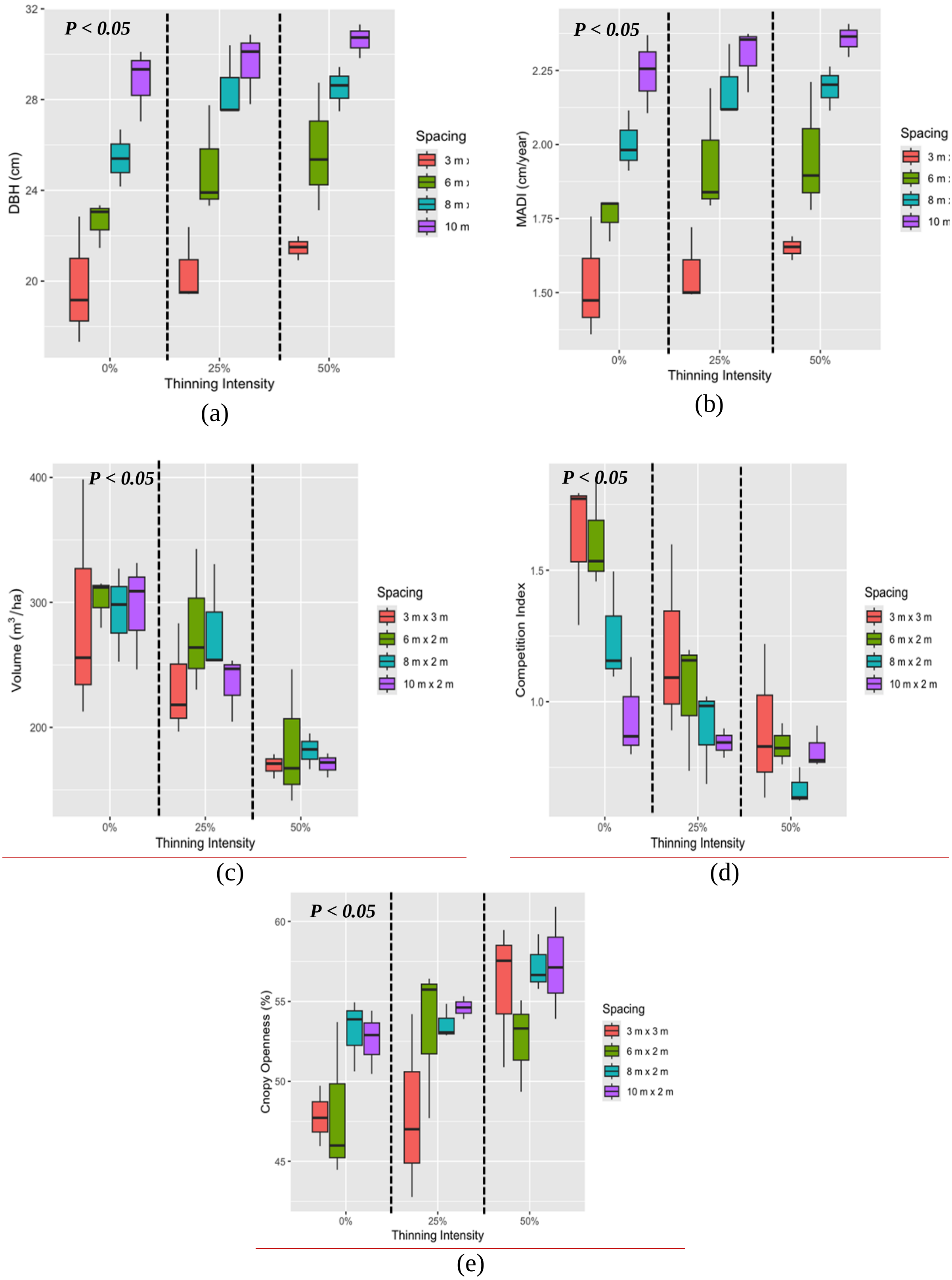

Fig. 5. The effect of different thinning intensities on growth characteristics, competition index, and canopy openness across all spacing treatments in the remaining stand of clonal teak plantation, for the following parameters: (a) DBH, (b) MADI, (c) vol, (d) Competition index, and (e) Canopy openness.

Therefore, thinning should be carried out intensively and frequently to maintain and optimize DBH and MADI growth until the end of the cycle (**Fig. 5a** and **Fig. 5b**). Other studies also reported that thinning significantly affected plant DBH, but it did not affect the height growth (Medeiros et al. 2017; Seta et al. 2021). Increasing thinning intensity reduced the volume of remaining stands (**Fig. 5c**). A 50% increase in intensity reduced the volume of remaining stands by a range of 31.63% to 40.02%. This was attributed to reduced numbers of individuals due to thinning activities, which reduced stand volume per unit area (Vigulu et al. 2019; Seta et al. 2021). A 50% thinning intensity increased the number of individuals in the large-diameter class. For example, a 0% thinning intensity at a spacing of 3 m × 3 m did not produce any individuals in the diameter class ≥ 30 cm. In contrast, a thinning intensity of 50% with a spacing of 10 m × 2 m produced 9 ± 1.8 individuals with a diameter class ≥ 30 cm (**Table 6**). The enlargement of the diameter class size was due to increased thinning intensity, which increased CO and reduced CI (**Fig. 5d** and **Fig. 5e**).

Table 6. Distribution of diameter classes and number of individuals under each thinning intensity per plot in each block

Diameter class (cm)	Number of individuals in each thinning intensity plot per block (m x m)											
	0%				25%				50%			
	3 × 3	6 × 2	8 × 2	10 × 2	3 × 3	6 × 2	8 × 2	10 × 2	3 × 3	6 × 2	8 × 2	10 × 2
10–14.99	3 ± 1.3	1 ± 0.3	-	-	1 ± 0.7	-	-	-	-	-	-	-
15–19.99	6 ± 1.5	4 ± 1.3	3 ± 0.3	2 ± 0.9	5 ± 1.0	1 ± 0.6	-	-	3 ± 0.7	-	-	-
20–24.99	5 ± 1.5	14 ± 0.6	6 ± 1.9	3 ± 1.5	6 ± 1.2	8 ± 2.8	3 ± 0.9	2 ± 0.3	8 ± 1.5	8 ± 3.4	2 ± 0.6	1 ± 0.3
25–29.99	1 ± 1.3	5 ± 1.5	10 ± 2	7 ± 3.7	1 ± 0.7	7 ± 0.9	8 ± 2.6	8 ± 1.2	1 ± 0	5 ± 1.9	10 ± 1.7	5 ± 0.6
≥ 30	-	-	2 ± 1.3	8 ± 2.4	1 ± 0.7	1 ± 1.3	5 ± 1.5	8 ± 2.6	0 ± 0	2 ± 1.5	3 ± 1.9	9 ± 1.8

High-intensity thinning (50%) increased crown development in teak stands. The open growing space after thinning enabled the remaining stands to increase crown development, allowing them to compete more effectively for important growth-supporting resources, such as light. This positively impacted the rate of plant photosynthesis, which ultimately played a crucial role in cell enlargement, including DBH development. Although a 50% thinning intensity reduced stand volume per unit area, this treatment simultaneously increased managers' and landowners' income. This was because the DBH of the remaining stands after 50% intensity thinning was larger and had a greater number of DBH than at 0% and 25% at all spacings. A higher thinning intensity also increased the distribution and number of large-diameter classes in the remaining stands. Therefore, the remaining stands generated higher revenues compared to the control, as the price of teak per unit volume was partly determined by the diameter (**Table 6**) (Stewart et al. 2020; Seta et al. 2021).

The results showed that increasing thinning intensity did not affect the PP of teak wood. PP at thinning intensities of 0%, 25%, and 50% was 19.57 mm, 19.91 mm, and 19.89 mm, respectively. This result indicated that variations in stand density after thinning did not substantially alter this wood property. Moreover, the relatively similar PP values across all thinning treatments indicate that teak trees maintained stable wood formation despite differences in available growing space. Furthermore, the value was higher than the PP reported in other studies on teak plantations aged 12, 15 and 24 years (Hidayati et al. 2019; Seta et al. 2021). It suggested that the teak wood in this study had comparatively better characteristics, likely associated with favorable site quality, silvicultural practices, climatic conditions, or the genetic sources used in the plantation. The finding also implies that moderate-to-heavy thinning can be applied to improve stand growth and diameter increment without adversely affecting the PP of teak wood, which is important for maintaining timber quality while optimizing plantation productivity.

Based on the results, variations in thinning intensity across different spacings exerted minimal influence on the PP value, which served as an indicator of the wood's basic density. Since SWV is a nondestructive method for measuring the mechanical properties of wood (Masendra et al. 2023), the stress velocity in this study showed no significant differences across the various thinning intensities. Clonal teak wood in various thinning levels did not affect the dynamic Young's modulus, as SWV was correlated with mechanical properties. Thinning intensity at various spacings in a clonal plantation affected wood properties, as PP and SWV were correlated with physical properties (Seta et al. 2021). Moreover, it did not affect the wood quality of the clonal teak plantation (Widiyatno et al. 2024).

4. Conclusions

In conclusion, the productivity of clonal teak plantation was improved by adjusting spacing and thinning treatments. Increasing spacing affected the development of DBH, MADI, CD, CO, and PP. The increase in DBH development at relatively wide spacing was due to higher CD and CO, and lower CI values. However, the rise in DBH due to wide spacing reduced TBH of the remaining stand. Maintenance activities, such as pruning, are silvicultural actions that should be carried out to ensure the remaining stands have straight trunks, large DBH, and optimal TBH. Therefore, at the end of the cycle, high-quality clonal teak wood would be obtained. This study demonstrated that thinning intensity treatment applied at every level of spacing treatment increased DBH, MADI, volume, CO, and reduced CI values. Heavy thinning (50%) produced residual stands with larger DBH, and more trees in the large DBH class were recorded at a spacing of 10 m × 2 m.

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Author Contributions

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Conflict of Interest

The authors declare no conflict of interest.

Declaration of Generative AI And AI-Assisted Technologies in the Manuscript Preparation

Not applicable.

References

Ashton, M. S., and Kelty, M. J. 2018. *The Practice of Silviculture: Applied Forest Ecology*. 10th ed. John Wiley, New York, USA. pp. 776.

Berrocal, A., Gaitan-Alvarez, J., Moya, R., Fernández-Sólis, D., and Ortizmalavassi, E. 2020. Development of Heartwood, Sapwood, Bark, Pith, and Wood Density of Teak (*Tectona grandis*) in Fast-Growing Plantation in Costa Rica. *Journal of Forestry Research* 31(2): 667–676. DOI: 10.1007/s11676-018-0849-5

Bose, A. K., Weiskittel, A., Kuehne, C., Wagner, G. R., Turnblom, E., and Burkhart, H. E. 2018. Tree-Level Growth and Survival Following Commercial Thinning of Four Major Softwood Species in North America. *Forest Ecology and Management* 27: 355–364. DOI: 10.1016/j.foreco.2018.06.019

BPS-Statistics Indonesia. 2023. *Statistics of Timber Culture Estate 2022*. Vol. 23. Badan Pusat Statistik, Jakarta, Indonesia. pp. 116.

Budiadi, Widiyatno, and Ishii, H. 2017. Response of a Clonal Teak Plantation to Thinning and Pruning in Java, Indonesia. *Journal of Tropical Forest Science* 29(1): 44–53.

Chambi-Legoas, R., Carpio-Mendoza, N. E., Collazos-Mendoza, B. R., and Portal-Cahuana, L. A. 2025. Technological Characterization of Teak Wood from Plantation Thinnings in the Southeastern Peruvian Amazon. *Journal of the Korean Wood Science and Technology* 53(5): 455–470. DOI: 10.5658/wood.2025.53.5.455

Dey, T., Ahmed, S., and Islam, M. A. 2021. Relationships of Tree Height-Diameter at Breast Height (DBH) and Crown Diameter-DBH of *Acacia auriculiformis* Plantation. *Asian Journal of Forestry* 5(2): 71–75. DOI: 10.13057/asianjfor/r050203

Enkhbayar, B., Dagdan, T., Khurelbaatar, B., Erdene-Ochir, T., Tumenjargal, B., Nezu, N., Ohshima, J., Yokota, S., and Ishiguri, F. 2025. Growth Characteristics and Stress-Wave Velocity of Standing Trees of Three *Populus* Tree Species in Mongolia. *Forest Science and Technology* 21(1): 15–20. DOI: 10.1080/21580103.2024.2427949

Frazer, G. W., Canham, C. D., and Lertzman, K. P. 1999. *Gap Light Analyzer (GLA), Version 2.0: Imaging Software to Extract Canopy Structure and Gap Light Transmission Indices from True-Colour Fisheye Photographs, Users Manual and Program Documentation*. Simon Fraser University, Burnaby, British Columbia, and the Institute of Ecosystem Studies, Millbrook, New York. pp. 36.

Hidayati, F., Lukmandaru, G., Indrioko, S., Sunarti, S., and Nirsatmanto, A. 2019. Variation in Tree Growth Characteristics, Pilodyn Penetration, and Stress-Wave Velocity in 65 Families of *Acacia mangium* Trees Planted in Indonesia. *Journal of the Korean Wood Science and Technology* 47(5): 633–643. DOI: 10.5658/wood.2019.47.5.633

Isaac-Renton, M., Stoehr, M., Statland, C. B., and Woods, J. 2020. Tree Breeding and Silviculture: Douglas-Fir Volume Gains with Minimal Wood Quality Loss Under Variable Planting Densities. *Forest Ecology and Management* 465(1): 118094. DOI: 10.1016/j.foreco.2020.118094

Jerez-Rico, M., and de Andrade Coutinho, S. 2017. Establishment and Management of Planted Teak Forests. In Kollert, W., and Kleine, M. (Eds.), *The Global Teak Study: Analysis, Evaluation and Future Potential of Teak Resources*. International Union of Forest Research Organizations (IUFRO), Vienna, Austria. pp. 49–65.

Kollert, W., Sandeep, S., and Sreelakshmy, M. P. 2024. *Global Teak Resources and Market Assessment 2022*. IUFRO World Series No. 44. International Union of Forest Research Organizations (IUFRO), Vienna, Austria. pp. 92.

Liang, S. Q., and Fu, F. 2007. Comparative Study on Three Dynamic Modulus of Elasticity and Static Modulus of Elasticity for Lodgepole Pine Lumber. *Journal of Forest Research* 18(4): 309–312. DOI: 10.1007/s11676-007-0062-4

Masendra, Nezu, N., Ishiguri, F., Hidayati, F., Nirsatmanto, A., Sunarti, S., Surip, Kartikaningtyas, D., Takashima, Y., Takahashi, Y., Ohshima, J., and Yokota, S. 2023. Variations of Growth and Wood Traits in Standing Trees of the Third-Generation *Acacia mangium* Families in Indonesia. *Silvae Genetica* 72(1): 150–162. DOI: 10.2478/sg-2023-0016

Medeiros, R. A., de Paiva, H. N., Soares, A. A. V., da Cruz, J. P., and Leite, H. G. 2017. Thinning from Below: Effects on Height of Dominant Trees and Diameter Distribution in *Eucalyptus* Stands. *Journal of Tropical Forest Science* 29(2): 238–247.

Midgley, S., Mounlamai, K., Flanagan, A., and Phengsoph, K. 2015. *Global Markets for Plantation Teak: Implications for Growers in Lao PDR*. Australian Centre for International Agricultural Research (ACIAR), Canberra, Australia. pp. 74.

Ministry of Forestry (MOF). 2025. *Ministry of Forestry Statistics 2024*. Ministry of Forestry Indonesia, Jakarta.

Moreau, G., Auty, D., Pothier, D., Shi, J., Lu, J., Achim, A., and Xiang, W. 2020. Long-Term Tree and Stand Growth Dynamics After Thinning of Various Intensities in a Temperate Mixed Forest. *Forest Ecology and Management* 473(1): 118311. DOI: 10.1016/j.foreco.2020.118311

Moreau, G., Chagnon, C., Achim, A., Caspersen, J., D'Orangeville, L., Sánchez-Pinillos, M., and Thiffault, N. 2022. Opportunities and Limitations of Thinning to Increase Resistance and Resilience of Trees and Forests to Global Change. *Forestry* 95(5): 595–615. DOI: 10.1093/forestry/cpac010

Papandrea, S. F., Cataldo, M. F., Bernardi, B., Zimbalatti, G., and Proto, A. R. 2022. The Predictive Accuracy of Modulus of Elasticity (MOE) in the Wood of Standing Trees and Logs. *Forests* 13(8): 1273. DOI: 10.3390/f13081273

Proto, A. R., Macrì, G., Bernardini, V., Russo, D., and Zimbalatti, G. 2017. Acoustic Evaluation of Wood Quality with a Non-Destructive Method in Standing Trees: A First Survey in Italy. *iForest* 10(4): 700–706. DOI: 10.3832/ifor2065-010

Rahmawati, R. B., Hardiwinoto, S., Amin, Y., and Hasanusi, H. 2021. Space Planting, Competition, and Productivity of a Seven-Year-Old Clonal Teak Plantation in the East Java Monsoon Forest Area. *Jurnal Manajemen Hutan Tropika* 27(2): 123–131. DOI: 10.7226/jtfm.27.2.123

Seta, G. W., Widiyatno, Hidayati, F., and Na'iem, M. 2021. Impact of Thinning and Pruning on Tree Growth, Stress Wave Velocity, and Pilodyn Penetration Response of Clonal Teak (*Tectona grandis*) Plantation. *Forest Science and Technology* 17(2): 57–66. DOI: 10.1080/21580103.2021.1911865

Sharma, R. P., Vacek, Z., and Vacek, S. 2016. Individual Tree Crown Width Models for Norway Spruce and European Beech in Czech Republic. *Forest Ecology and Management* 366(1–2): 208–220. DOI: 10.1016/j.foreco.2016.01.040

Simic, K., Gendvilas, V., O'Reilly, C., and Harte, A. M. 2019. Predicting Structural Timber Grade-Determining Properties Using Acoustic and Density Measurements on Young Sitka Spruce Trees and Logs. *Holzforschung* 73(2): 39–149. DOI: 10.1515/hf-2018-0073

Stewart, H., Rohadi, D., Schmidt, D. M., Race, D., Dovita, D. A., Silvia, D., and Darisman, A. 2020. *Financial Models for Smallholder Sengon and Teak Planting in the Pati District*. ACIAR, Canberra, Australia. pp. 67.

Sun, Z., Wang, Y., Pan, L., and Sun, Y. 2022. Hegyi Competition Index Decomposition to Improve Estimation Accuracy of *Larix olgensis* Crown Radius. *Ecological Indicators* 143(2): 109322. DOI: 10.1016/j.ecolind.2022.109322

Tumenjargal, B., Ishiguri, F., Takahashi, Y., Nezu, I., Baasan, B., Chultem, G., Aiso, H., Ohshima, J., and Yokota, S. 2020. Predicting the Bending Properties of *Larix sibirica* Lumber Using Nondestructive Testing Methods. *International Wood Products Journal* 11(3): 115–121. DOI: 10.1080/20426445.2020.1735754

Vargas, T. F., Vázquez, I. T., and Gómez, R. A. 2021. Remote Sensing Based Forest Canopy Opening and Their Spatial Representation. *Forest Science and Technology* 17(4): 214–224. DOI: 10.1080/21580103.2021.2002198

Vaughan, D., Auty, D., Dahlen, J., Sánchez, A. J., and Meador, M. K. 2021. Modelling Variation in Wood Stiffness of *Pinus ponderosa* Using Static Bending and Acoustic Measurements. *Forestry* 94(2): 232–243. DOI: 10.1093/forestry/cpaa030

Vigulu, V., Blumfield, T. J., Reverchon, F., Hosseini, B. S., and Xu, Z. 2019. Growth and Yield of 5 Years Old Teak and Flueggea in Single and Mixed Species Forestry Systems in the Solomon Islands. *New Forests* 50(4): 629–642. DOI: 10.1007/s11056-018-9684-y

Widiyatno, Wibowo, A., Novitasari, D., Seta, G. W., Prehaten, D., Hidayati, F., Nugroho, W. D., Hardiwinoto, S., Na'iem, M., and Tani, N. 2024. Effect of Improved Planting Stock on Tree Growth, Wood Properties, and Soil Fertility of Teak Plantation 10 Years After Planting. *Forest Science and Technology* 20(1): 8–15. DOI: 10.1080/21580103.2023.2277190

Winn, M. F., Palmer, A. J., Lee, S. M., and Araman, P. A. 2016. *ForestCrowns: A Transparency Estimation Tool for Digital Photographs of Forest Canopies*. e-Gen. Tech. Rep. SRS–215. U.S. Department of Agriculture Forest Service, Southern Research Station, Asheville, NC, USA. pp. 10.

Wongprom, J., Maelim, S., Chandaeng, W., Teejuntuk, S., Sommeechai, M., and Duangnamon, D. 2023. Effect of Thinning on Growth and Wood Production of Naturally Regenerated 8-Year-Old *Acacia mangium* Willd. Plantation on Abandoned Mining Area, Southern Thailand. *BIOTROPIA* 30(3): 308–317. DOI: 10.11598/btb.2023.30.3.1919

Zahabu, E., Tumaini, R., Shabani, A., Omari, C., Iddi, S., and Rogers, E. 2015. Effect of Spacing Regimes on Growth, Yield, and Wood Properties of *Tectona grandis* at Longuza Forest Plantation, Tanzania. *International Journal of Forestry Research* 1: 469760. DOI: 10.1155/2015/469760