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Wood Physical and Mechanical Properties of Clonal Teak (*Tectona grandis*) Stands Under Different Thinning and Pruning Intensity Levels Planted in Java, Indonesia

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ABSTRACT

The objective of this study was to reveal the impact of thinning and pruning regimes on the physical and mechanical properties of clonal teak wood planted in Java. In this study, a 15-year-old clonal teak plantation was carried out and the obtained data were evaluated with analysis of variance (ANOVA). The results showed that different thinning intensities had a significant impact on the alteration of heartwood volume development (F = 25.63; $p < 0.0001$). Meanwhile, the impact of different thinning treatments in several physical properties depends on the pruning treatment levels [moisture content (F = 12.18, $p < 0.0001$); tangential shrinkage (F = 15.60, $p < 0.0001$); T/R ratio (F = 7.17, $p < 0.0001$); and volumetric shrinkage (F = 10.81, $p < 0.0001$)]. However, different thinning intensities had no significant impact on wood basic density alteration (F = 0.72, p = 0.486), while pruning intensities affect the differences between radial (F = 3.52, p = 0.030) and volumetric shrinkage (F = 3.13, p = 0.044). In mechanical properties, thinning intensity levels did not promote any significant differences [modulus of elasticity (F = 1.41, p = 0.248); modulus of rupture (F = 0.94, p = 0.392); compressive strength parallel to grain (F = 0.21, p = 0.813); and compressive strength perpendicular to the grain (F = 0.41, p = 0.669)]. Meanwhile, different pruning treatments and combination treatments were not significantly altered all mechanical properties. These results indicated that the thinning and pruning regimes can enhance the mechanical properties without having a serious alteration in the physical properties of clonal teak wood.

Keywords: clonal teak, thinning, pruning, physical properties, mechanical properties

1. INTRODUCTION

Teak (*Tectona grandis* L.f.) is a native tropical hardwood tree species from Asia which is highly valued in the global timber market (Kollert and Kleine, 2017). This ring-porous wood species is demanded of its natural durability, aesthetic properties, and mechanical resistance (CFC and ITTO, 2009; Ramasamy *et al.*, 2021). In Indonesia, the teak wood is used for furniture and construction material. In addition, it is also possible to be used as material of glued products as well as other species (Galih *et al.*, 2020; Iswanto *et al.*, 2020; Prabuningrum *et al.,* 2020; Sumardi *et al.*, 2022). However, the global teakwood supply from the natural teak forests has been dwindling since the early 21st century (FAO, 2009; Pandey and Brown, 2000). It has

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also been forecasted that the natural teak forests will not be able to sustainably meet the demand for teakwood in the global market due to some critical environmental issues (FAO, 2015; Kyaw *et al.*, 2020; Mon *et al.*, 2012). However, teak plantations have a good prospect of sustainably supplying teak timber in the global market since the cultivation has been successfully established in 65 countries outside its natural distribution (Koskela *et al.*, 2014). This has led to the development of several strategies to enhance productivity from all teak plantations to meet the increase in global demand (Kollert and Kleine, 2017; Lautenschlager, 2000; Midgley *et al.*, 2015).

In Indonesia, a genetic improvement program to increase timber production from teak plantations has been conducted since 1983 by selecting over 680 plus trees from various places. The two best clones, which were numbered 97 and 110 were determined in 1997, after long consecutive genetic trials (Na'iem, 2001, 2014; Siswamartana *et al.*, 2005). The productivity of those selected clones was reported to achieve more than 200 m^3/ha in a 20-year rotation (Budiadi *et al.*, 2017; Na'iem, 2014). Furthermore, intensive silvicultural practices must be incorporated and frequently applied in clonal teak plantation management protocols to maintain radial growth performance (Rahmawati *et al.*, 2021; Seta *et al.*, 2021).

Thinning and pruning were common silvicultural treatment practices used in maintaining the growth performance of timber plantations (Nyland *et al.*, 2016; Smith, 1986). These treatments successfully enhanced the radial growth of the remaining stands in various species, namely *Gmelina arborea* (Vallejos *et al.*, 2015), *Larix kaempferi* (Kim *et al.*, 2016), *Eucalyptus grandis* hybrid (Filho *et al.*, 2018), *Eucalyptus camaldulensis* (Aiso-Sanada *et al.*, 2019), and *Pinus koraiensis* (Seo *et al.*, 2019). In teak, previous studies reported that thinning and pruning treatments significantly increase the radial growth of the remaining stands (Budiadi *et al.*, 2017; Kanninen *et al.*, 2004; Víquez and Pérez, 2005). This showed that managing clonal teak plantations with thinning and pruning can improve teak timber production, thereby fulfilling the global demand.

Moreover, necessary precautions need to be taken during the implementation of thinning and pruning treatments to manage timber plantations. Previous studies reported that different intensities of these treatments can significantly affect the wood properties of various species. In 14-year-old clonal teak, different thinning intensities promoted significant differences in pilodyn penetration value, which was strongly related to basic density (BD; Seta *et al.*, 2021). In *Quercus acuta*, heavy thinning treatment significantly generated a lower mean value of wood air-dried density compared to the un-thinned treatment (Hong *et al.*, 2015). In *Gmelina arborea*, the values of specific gravity in higher thinning intensities were reported to be significantly reduced by approximately 7% compared to the lower intensity (Vallejos *et al.*, 2015). This also occurred in *Acacia salicina*, where the treatment had a decrease in specific gravity value by 3.8% (Hegazy *et al.*, 2014). However, a different result was reported in a 12-years-old *Eucalyptus camaldulensis* plantation, where the BD value was increased by 5.7%, without the alteration of the compressive strength parallel to grain (under green conditions; Aiso-Sanada *et al.*, 2019). In Calabrian pine (*Pinus nigra* Arnold subsp. *calabrica*), implementing thinning intensity at 25% and 50% also increased the mechanical properties [dynamic modulus of elasticity (DMOE)] of the remaining trees compared to the un-thinned stands (Russo *et al.*, 2019). Moreover, pruning treatment played an important role in the production of good-quality timber (Gartner *et al.*, 2005; Stener *et al.*, 2017; Víquez and Pérez, 2005).

There is limited information on the impact of thinning and pruning treatment on clonal teak wood properties. Therefore, this study aims to evaluate the physical and mechanical properties of clonal teak wood under thinning and pruning treatments. The results are designated to support new information on intensive silviculture practices in clonal teak cultivation.

2. MATERIALS and METHODS

2.1. Material

2.1.1. Study site and testing materials

The thinning and pruning trial was set on a clonal teak plantation at compartment 13, Wanagama Teaching Forest, Universitas Gadjah Mada, Yogyakarta, Java Island, Indonesia (7°54′S, 110°31′E) in December 2004 (Budiadi *et al.*, 2017). The trial was established at an altitude of 214 m above sea level. The average temperature of the location is 27.7℃, 80%–90% of relative humidity and 1,900 mm/year of annual precipitation. The topography of the location is flat with the soil order of Entisol (limestone as the parent material). The clonal teak plantation was established in bulk planted of two improved clones, numbered 97 and 110, which were yielded from the teak tree improvement program that was initiated in 1997 (Na’iem, 2001, 2014).

Furthermore, the plantation site covers an area of 8 ha, with an initial tree spacing of 6 m × 2 m. The used initial spacing mimicked one of several teak cultivation spacing systems in Java, which had been scientifically proven to successfully accommodate agroforestry practices in teak plantations (Prehaten *et al.*, 2021). It was considered to be narrow spacing in the teak cultivation system (Rahmawati *et al.*, 2022), and the new wider space needed to be added periodically to avoid high intraspecific competition among clonal teak stands (Rahmawati *et al.*, 2021). Adding new wider space periodically was proved to alleviate the growth stagnation of the stand since teak was determined to be an intolerant species (Pachas *et al.*, 2019; Rahmawati *et al.*, 2021). Therefore, the first thinning and pruning were applied 4.5 years after planting (Budiadi *et al.*, 2017). In addition, the practice was reported to be not significantly altered the stem form of the stand (Pérez and Kanninen, 2005), and the improved clones were genetically selected based on the growth characteristics and stem form performance (Wardani and Na'iem, 2008), which the uniformity of the stem form was strongly influenced by genetic traits (Rao *et al.*, 2001).

The trial was accomplished on a factorial randomized block design, where the tested factors were thinning and pruning intensities in three replications (Budiadi *et al.*, 2017). These include control, moderate, and heavy for thinning, and low, medium, and high for pruning. Detailed information on the treatment levels is shown in Table 1. The study was conducted when the clonal teak plantation aged 15 years old. During the 10 years of post-thinning and pruning application, several trees that were found in the outer rows recorded died in some plots due to unpropitious conditions. Since very small removal may not affect growth (Smith, 1986), it was assumed that the dead trees did not significantly change the density of those plots.

2.1.2. Selecting the representative trees

All trees in the thinning and pruning trial plots were assessed for their growth characteristic, which includes the diameter at breast high (DBH, 1.3 m above ground level) and total height (H). A total of 27 representative trees (one tree per treatment on every replicate) were harvested for wood properties analysis. The representative trees were selected based on the mean DBH of each thinning treatment since the differences in DBH growth were significantly different among the thinning treatments as presented in Table 2. The stem cross-sectional samples (disks) collection was based on the procedure of Pérez and Kanninen (2005), with modification in collecting base disks obtained from each harvested tree at 0.10 m and 1.3 m above ground level (DBH). From the height of 2.0 m above, sections were taken along the stem at 2.0 m intervals until the diameter of the upper stem reach 14–10 cm. Therefore, the collected disk samples

Table 1. Nine combinations of thinning and pruning treatments codes of clonal teak

Code	Treatment
A_0B_1	No thinning (control, A_0) and pruned 1/3 of crown height (low pruning, B_1)
A_0B_2	No thinning (control, A_0) and pruned 1/2 of crown height (medium pruning, B_2)
A_0B_3	No thinning (control, A_0) and pruned 2/3 of crown height (high pruning, B_3)
A_1B_1	Thinned 25% (moderate thinning, A_1) and pruned 1/3 of crown height (low pruning, B_1)
A_1B_2	Thinned 25% (moderate thinning, A_1) and pruned 1/2 of crown height (medium pruning, B_2)
A_1B_3	Thinned 25% (moderate thinning, A_1) and pruned 2/3 of crown height (high pruning, B_3)
A_2B_1	Thinned 50% (heavy thinning, A_2) and pruned 1/3 of crown height (low pruning, B_1)
A_2B_2	Thinned 50% (heavy thinning, A_2) and pruned 1/2 of crown height (medium pruning, B_2)
A_2B_3	Thinned 50% (heavy thinning, A_2) and pruned 2/3 of crown height (high pruning, B_3)

were considered to represent the wood properties of the whole tree and the differences in the height level represented the axial level factor. The two types of collected disks were those with (A) 8 cm thickness and (B) 5 cm thickness on each stem height interval. Disks-A were used to assess green moisture content (MCG), BD and shrinkage parameters [radial shrinkage (RS), tangential shrinkage (TS), shrinkage coefficient of anisotropy (T/R-ratio), and volumetric shrinkage (VS)]. Disks-B were used to assess the proportion content and the volume of heartwood [relative heartwood proportion (PHW) and volume of heartwood content (VHW)], respectively. Meanwhile, wood mechanical properties were assessed from log samples which were ± 58 cm in length, each, and were extracted from the stem height section between 1.3 m (DBH) to 2 m above ground level.

2.2. Method

2.2.1. Wood sample preparation

The disks with 5 cm thickness were used as samples during the assessment of heartwood. They were ground using a wood grinder on the surface of the transverse plane until the contrast differences between heartwood and sapwood areas emerged. Meanwhile, the disks with 8 cm thickness were prepared and cut to be two sample sets, namely (1) cube sample sets of 2 × 2 × 2 cm to measure wood moisture and wood MCG and BD, and (2) rectangular sample sets of 2 × 2 × 4 cm for shrinkage measurement. Those samples were taken along the radial strip at no interval from 0.5 cm after pith to bark for both sides. To prepare wood samples for assessing mechanical properties, the extracted logs were live-sawn in the middle of the log to obtain boards with 2.5 cm of thickness (radial strips). The boards were air-seasoned for a month until achieved air-dried conditions, which the wood's moisture content at 20%–15% (Cassens, 1980). After a month, the mean wood moisture content of boards was achieved at 16.7 ± 0.4%, which was feasible to be used as specimen material for wood mechanical properties testing (Djati *et al.*, 2015). Furthermore, the board were transformed into wood samples for mechanical properties testing, after reaching air-dried conditions (Djati *et al.*, 2015; Savero *et al.*, 2020). For the static bending test [modulus of elasticity (MOE) and modulus of rupture (MOR)], the sample dimension was 2 × 2 × 30 cm; and for the test of compression stress parallel (CSPL) and perpendicular to the grain (CSPD), a dimension of 2 × 2 × 6 cm was used. All samples were also taken along the radial strip (board) every 2 cm

Table 2. Result of variance analysis of thinning and pruning treatments' effect on growth characteristics and wood physical properties of clonal teak wood

Source of variance	*df*	Height		DBH	
		F-value	Var (%)	*F*-value	Var (%)
Block	2	29.81	92.6	1.22	0.6
Thinning	2	0.42^{ns}	0.0	37.91**	95.8
Pruning	2	0.61^{ns}	0.0	0.08^{ns}	0.0
Thinning × Pruning	4	2.30^{ns}	4.2	1.41^{ns}	1.1
		PHW		VHW	
Block	2	8.02	82.5	9.83	25.4
Thinning	2	1.49^{ns}	5.6	25.63**	70.9
Pruning	2	0.37^{ns}	0.0	0.02^{ns}	0.0
Thinning × Pruning	4	0.71^{ns}	0.0	1.29^{ns}	0.8
		MCG		BD	
Block	2	246.41	2.6	13.06	0.2
Thinning	2	9.51**	25.4	0.72^{ns}	0.0
AL (*Thinning*)	18	6.80**	17.3	11.71**	49.8
RL (*Thinning AL*)	53	5.21**	12.6	9.05**	37.5
Pruning	2	0.196^{ns}	1.9	0.62^{ns}	0.0
AL (*Pruning*)	12	1.10^{ns}	0.3	0.83^{ns}	0.0
RL (*Pruning AL*)	35	0.69^{ns}	0.0	0.77^{ns}	0.0
Thinning × Pruning	4	12.18**	33.3	2.37^{ns}	6.3
AL (*Thinning Pruning*)	22	2.20**	3.6	1.32^{ns}	1.5
RL (*Thinning Pruning AL*)	51	0.79^{ns}	0.0	1.00^{ns}	4.7
		TS		RS	
Block	2	37.01	0.4	30.27	1.4
Thinning	2	14.58**	40.3	0.29^{ns}	0.0
AL (*Thinning*)	18	3.24**	6.6	3.40**	26.8
RL (*Thinning AL*)	38	2.55**	4.6	3.55**	28.5
Pruning	2	1.54^{ns}	1.6	3.52*	28.16
AL (*Pruning*)	12	0.74^{ns}	0.0	1.19^{ns}	0.0
RL (*Pruning AL*)	27	0.96^{ns}	4.6	0.87^{ns}	0.0
Thinning × Pruning	4	15.60**	43.4	0.72^{ns}	0.0
AL (*Thinning Pruning*)	22	1.01^{ns}	0.02	1.35^{ns}	3.9
RL (*Thinning Pruning AL*)	44	0.50^{ns}	0.0	0.81^{ns}	0.0
		T/R ratio		VS	
Block	2	7.69	0.1	38.28	0.5
Thinning	2	11.99**	44.4	15.62**	48.3
AL (*Thinning*)	18	2.98**	8.0	2.25**	4.1
RL (*Thinning AL*)	38	4.95**	16.0	1.77**	2.5
Pruning	2	0.42^{ns}	0.0	3.13*	7.0
AL (*Pruning*)	12	1.09^{ns}	0.4	0.90^{ns}	0.0
RL (*Pruning AL*)	27	1.47^{ns}	1.9	0.78^{ns}	0.0
Thinning × Pruning	4	7.17**	25.0	10.81**	32.4
AL (*Thinning Pruning*)	22	0.79^{ns}	0.0	1.51^{ns}	1.7
RL (*Thinning Pruning AL*)	44	1.08^{ns}	0.3	0.45^{ns}	0.0

* Significant at α = 0.05; ** Significant at α = 0.01; ^{ns} No significant difference at α = 0.05.

df: degree of freedom, Var: variance components, DBH: diameter of breast high (1.3 m above ground level), PHW: relative heartwood proportion, VHW: volume of heartwood content, MCG: green moisture content, BD: basic density, AL: axial level, RL: radial level, TS: tangential shrinkage, RS: radial shrinkage, T/R ratio: shrinkage coefficient of anisotropy, VS: volumetric shrinkage.

from 0.5 cm after pith to bark for both sides. Therefore, the differences in the radial distances represented the radial level factor.

2.2.2. Wood physical properties assessment

In determining the physical properties of the thinning and pruning treatments' effect on clonal teak wood, some parameters had to be assessed. In this study, the PHW and the total VHW were the initial parameters to be assessed. Based on Pérez and Kanninen's (2005) method, the volume of heartwood was calculated by measuring the average heartwood diameter and total mean diameter (with and without bark) of two cross-sectional lengths (North-South and East-Weast direction) from disk B samples. The area of heartwood, sapwood and bark cross-sectional was determined as geometric circles (m^2). The PHW (%) was estimated as the area of heartwood relative to the full area of the discs. The VHW (m^3) was estimated employing the Smalian formulae (Clutter *et al.*, 1983) and the section from the last-taken disk to the apex of the tree was determined as a geometric cone.

The MCG, BD, and wood shrinkage parameters [RS, TS, VS, and T/R-ratio] were assessed after the wood sample making process was completed. All measurements of each parameter were carried out according to the British Standard methods (BS 373:57; British Standards Institution, 1957). Firstly, the weight of the wood sample was measured (immediately, after the wood samples were made) using a digital scale (XE-310, Denver Instrument, Göttingen, Germany) and was considered as the sample weight in green condition. Then, the volume of the wood sample was determined in two different approaches. The water displacement method was used in estimating the wood sample volume for BD (Marsoem *et al.*, 2014; Savero *et al.*, 2020). Whereas for VS, the wood sample dimensional volume was measured using a digital calliper (CD－6" CS, Mitutoyo, Kawasaki, Japan) by multiplying the dimensional measurement of the longitudinal (L), tangential (T), and radial (R) direction length of the wood samples (L × T × R). Those volume measurements were conducted in green condition, thus considered as the sample volume in green condition. Subsequently, the wood samples were oven-dried using laboratory ovens (UN55, Memmert, Büchenbach, Germany) until the weight was constant at 103 ± 2℃, thus considered as the wood sample weight under oven-dried conditions. Under oven-dried conditions, the volume measurement of the wood samples was conducted again using the same method used in the green conditions. Finally, the values of MCG, BD, and shrinkage parameters (RS, TS, VS, and T/R-ratio) from green to oven-dried conditions were respectively determined using Equations (1) to (4) as follows (British Standards Institution, 1957; Savero *et al.*, 2020):

$$\mathrm{MCG} = \frac{W_g - W_{od}}{W_{od}} \times 100 \qquad (1)$$

$$\mathrm{BD} = \frac{W_{od}}{V_g} \qquad (2)$$

$$xS_{g.o.} = \frac{L_{x.g.} - L_{x.o.}}{L_{x.g.}} \times 100 \qquad (3)$$

$$\mathrm{T/R-ratio} = \frac{\mathrm{TS}}{\mathrm{RS}} \qquad (4)$$

where MCG (%) is the green moisture content of wood, W_g (g) is the wood sample weight in green conditions, W_{od} (g) is the wood sample weight under oven-dried conditions, BD (g/cm^3) is the wood basic density, V_g (cm^3) is the wood sample volume in green condition, $xS_{g.o.}$ is the percentage of dimensional shrinkage (%) of certain dimension (RS, TS, and VS) from green to oven condition, $L_{x.g.}$ is the dimension length of certain direction (L, T, and R) in green condition (mm), $L_{x.o.}$ is the dimension length of certain direction (L, T, and R) in oven-dried condition (mm), and T/R-ratio is the shrinkage ratio of tangential (TS) and radial (RS) dimension from green to oven-dried condition.

2.2.3. Determination of wood mechanical properties

To determine the mechanical properties of the wood, several tests had to be conducted to obtain important information. These include the static bending test to estimate the value of the MOE and MOR of the wood samples. Moreover, the wood sample measurements of the compressive strength parallel to the grain (CSPL) and the compressive strength perpendicular to the grain (CSPD) were also conducted. These tests were carried out according to the British Standard methods (BS 373:57; British Standards Institution, 1957) for small clear specimens using Universal Testing Machine (UTM, Instron 3369, Instron, Norwood, MA, USA). Meanwhile, the static bending test was conducted using a single-point loading at the centre of the wood sample. The span and loading rate used was 28 cm and 2.54 mm/minute, respectively. Meanwhile, the loading rate used in CSPL and CSPD was 0.50 mm/minute and 0.60 mm/minute, respectively. The values of MOE, MOR, CSPL, and CSPD were respectively calculated using Equations (5) to (8) as stated below (British Standards Institution, 1957; Savero *et al.*, 2020):

$$\mathrm{MOE} = \frac{\triangle \mathrm{P}\ \mathrm{L}^3}{4\ \triangle \mathrm{Y}\ \mathrm{b}\ \mathrm{h}^3} \tag{5}$$

$$\mathrm{MOR} = \frac{3\ \mathrm{P}_{max}\ \mathrm{L}}{2\ \mathrm{b}\ \mathrm{h}^2} \tag{6}$$

$$\mathrm{CSPL} = \frac{\mathrm{P}_{max}}{\mathrm{A}_{parallel}} \tag{7}$$

$$\mathrm{CSPD} = \frac{\mathrm{P}_{max}}{\mathrm{A}_{perpendicular}} \tag{8}$$

where MOE is the modulus of elasticity (kg$_f$/cm^2, converted to GPa), ΔP is the load changes in proportion limit area (kg$_f$), L is the span length of the wood sample (cm), ΔY is deflection at mid-length at the limit of area (cm), b is the wood sample width (cm), h is the wood sample thickness (cm), MOR is the modulus of rupture (kg$_f$/cm^2, converted to MPa); P_{max} is the maximum load (kg$_f$), CSPL is the compressive strength parallel to the grain (kg$_f$/cm^2, converted to MPa), $A_{parallel}$ is the wood sample surface parallel to the grain (cm^2), CSPD is the compressive strength perpendicular to the grain (kg$_f$/cm^2, then converted to MPa), $A_{perpendicular}$ is the wood sample surface perpendicular to the grain (cm^2).

2.2.4. Statistical analysis

A two-way analysis of variance (ANOVA) was used to examine the different effects of thinning and pruning treatments on PHW and VHW. Furthermore, the nested-factorial ANOVA was employed for MCG, BD, TS, RS, T/R-ratio, VS, MOE, MOR, CSPL, and CSPD. In MCG, BD, TS, RS, T/R-ratio, and VS, different effects of thinning, pruning, the axial level (nested within thinning, pruning, and the interaction of thinning-pruning), and the radial levels (nested within thinning, pruning, the interaction of thinning-pruning, and axial level) were evaluated. Meanwhile, in MOE, MOR, CSPL, and CSPD, the different effects of thinning, pruning, and radial levels (nested within thinning, pruning, and the interaction of thinning-pruning treatments) were evaluated. In this study, all factors were considered fixed effects. The variance components were also estimated in each source of variation. Furthermore, Tukey's HSD tests were used for post hoc analysis of the treatments at α 0.05. Subsequently, statistical analysis was performed with the Statistical Analysis System (SAS) OnDemand for Academics (SAS Institute, Cary, NC, USA) and Microsoft Office Excel 2019 (Microsoft Corporation, Redmond, WA, USA).

3. RESULTS and DISCUSSION

3.1. Effect of thinning and pruning on clonal teak wood physical properties

3.1.1. Relative heartwood proportion (PHW) and total volume of heartwood content (VHW)

In teak, the existence of the heartwood content is an important factor in determining its grade and possible utility (Trockenbrodt and Josue, 1999). In this study, the PHW of clonal teak was not significantly different among thinning treatments (p = 0.2551), pruning treatments (p = 0.6980), and the combination of thinning and pruning treatments (p = 0.5946; Table 2). Although A_0 possessed the highest mean PHW, the differences between A_1 and A_2 were only approximately 3.01% and 1.19%, respectively (Table 3). Under various treatments, the mean PHW in this study was around 41.415 ± 4.83%–47.263 ± 4.30% (Tables 3 and 4). The results are almost similar to the findings of which 8 and 12 years old teak wood originated from seed sources (Wahyudi and Arifien, 2005). The heartwood content proportion was also noted to be higher compared to teakwood produced in the deciduous area in Ghana, where at the age of 20 years old, the heartwood content proportion was ± 7% less than the findings of this study (Amoah and Inyong, 2019). However, the results were lower compared to the older ages tree. In 70-year-old teak trees in East Timor, the average proportion of stands' heartwood was ± 40% higher than the findings in this study (Miranda *et al.*, 2011). This discrepancy was presumably caused by various influences, i.e., differences in the growth rate, type of stands, characteristics of the individual tree, age, genotype, topography, and site quality (Huh *et al.*, 2020; Kim *et al.*, 2020a, 2020b; Pinto *et al.*, 2004).

Furthermore, although the mean PHW of the clonal teak was not significantly altered by thinning treatment, the total heartwood volume content (VHW) of the clonal teak was significantly different among thinning intensity levels ($p < 0.0001$; Table 2). Meanwhile, the mean VHW of the conal teak was also not significantly differed by pruning treatments and the combination of thinning and pruning treatments (p = 0.9758 and p = 0.3156, respectively; Table 2). A_2 possessed 0.646 ± 0.11 m^3 in mean VHW, making it to be the highest and significantly different from other intensity levels (Table 3). This phenomenon was supposed to be induced by the nature of DBH growth under higher thinning intensity levels which tended to produce bigger log dimensions (Seta *et al.*, 2021). Pérez Cordero and Kanninen (2003) also reported that in multi-ages teak, the heartwood volume raised with increasing DBH and decreased with raising stand density. Since different thinning intensity levels did not significantly alter the PHW, significant differences in the growth of DBH tended to produce more heartwood volume. Therefore, incorporating both silvicultural practices would generate an outstanding stands dimension without adversely affecting the development of heartwood in the clonal teak plantations, which is very beneficial for further clonal teak wood utilization.

3.1.2. Green moisture content (MCG)

In this study, the mean MCG of the clonal teak wood was significantly different among various thinning intensity levels ($p < 0.0001$; Table 2). Thinning was regarded as a significant source of variation, which contributed approximately a quarter of the total variation of the mean MCG (Table 2). A significant increase in the mean MCG of the clonal teak was noted to be A_2, the highest among other thinning treatments (Table 3). However, the disparity of the mean MCG in A_2 between A_0 and A_1 was only less than 5% (Table 3). Meanwhile, the mean MCG of the clonal teak wood was not significantly different under various pruning intensity levels (p = 0.196), with a contribution of a total variation of only 1.9% (Table 2). Nevertheless, the increase in the mean

Table 3. Comparison of mean values for physical and mechanical properties of clonal teak wood under different thinning and pruning treatments

Characteristic	A_0		A_1		A_2	
	Mean	SD	Mean	SD	Mean	SD
PHW (%)	45.493^{ns}	5.75	42.402^{ns}	4.24	44.298^{ns}	4.37
VHW (m^3)	0.358^{b}	0.01	0.449^{b}	0.13	0.646^{a}	0.11
MCG (%)	104.910^{b}	20.43	105.870^{b}	21.83	109.560^{a}	18.53
BD (g/cm^3)	0.488^{ns}	0.04	0.487^{ns}	0.04	0.485^{ns}	0.04
TS (%)	6.866^{b}	2.01	7.392^{a}	2.32	7.774^{a}	2.24
RS (%)	3.601^{ns}	0.98	3.552^{ns}	1.02	3.605^{ns}	0.99
T/R ratio	1.997^{b}	0.60	2.203^{a}	0.67	2.297^{a}	0.65
VS (%)	10.640^{c}	2.37	11.217^{b}	2.59	11.723^{a}	2.51
MOE (GPa)	10.877^{ns}	1.60	11.329^{ns}	1.81	10.954^{ns}	1.68
MOR (MPa)	78.325^{ns}	11.86	80.214^{ns}	12.46	77.279^{ns}	14.09
CSPL (MPa)	42.342^{ns}	5.49	42.102^{ns}	5.73	42.828^{ns}	5.62
CSPD (MPa)	14.410^{ns}	2.10	14.760^{ns}	2.28	14.946^{ns}	2.43

	B_1		B_2		B_3	
PHW (%)	44.957^{ns}	4.54	43.666^{ns}	4.74	43.571^{ns}	5.39
VHW (m^3)	0.480^{ns}	0.13	0.489^{ns}	0.14	0.483^{ns}	0.14
MCG (%)	106.160^{ns}	21.21	107.240^{ns}	20.24	107.90^{ns}	19.34
BD (g/cm^3)	0.486^{ns}	0.05	0.488^{ns}	0.04	0.485^{ns}	0.04
TS (%)	7.236^{ns}	2.19	7.465^{ns}	2.18	7.526^{ns}	2.26
RS (%)	3.461^{b}	1.06	3.657^{a}	1.01	3.636^{a}	0.91
T/R ratio	2.217^{ns}	0.66	2.188^{ns}	0.65	2.161^{ns}	0.64
VS (%)	10.973^{b}	2.68	11.414^{a}	2.35	11.424^{a}	2.55
MOE (GPa)	10.843^{ns}	1.75	11.077^{ns}	1.52	11.235^{ns}	1.82
MOR (MPa)	77.168^{ns}	14.11	78.979^{ns}	11.60	79.476^{ns}	13.01
CSPL (MPa)	42.055^{ns}	5.77	43.789^{ns}	5.22	41.573^{ns}	6.13
CSPD (MPa)	15.102^{ns}	2.06	15.001^{ns}	2.44	14.127^{ns}	2.42

A_0, A_1, and A_2 are the control, moderate thinning, and heavy thinning regimes, respectively.
B_1, B_2, and B_3 are low pruning, medium pruning, and high pruning, respectively.
$^{a–c}$ Mean marked with different superscript letters are significantly different at $\alpha = 0.05$.
^{ns} No significant difference at $\alpha = 0.05$.
PHW: relative heartwood proportion, VHW: volume of heartwood content, MCG: green moisture content, BD: basic density, TS: tangential shrinkage, RS: radial shrinkage, T/R ratio: shrinkage coefficient of anisotropy, VS: volumetric shrinkage, MOE: modulus of elasticity, MOR: modulus of rupture, CSPL: compressive strength parallel to the grain, CSPD: compressive strength perpendicular to the grain.

Table 4. Mean comparison and summary of the statistic of wood physical properties of clonal teak in nine treatment combinations

Treatment	n	PHW (%)				VHW (m^3)			
		Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
A$_0$B$_1$	3	45.452^{ns}	3.76	40.76	50.14	0.351^{ns}	0.01	0.24	0.46
A$_0$B$_2$	3	45.495^{ns}	7.42	40.81	50.18	0.361^{ns}	0.15	0.20	0.47
A$_0$B$_3$	3	45.531^{ns}	7.18	40.83	50.22	0.362^{ns}	0.12	0.23	0.47
A$_1$B$_1$	3	42.155^{ns}	3.52	37.47	46.84	0.407^{ns}	0.10	0.30	0.51
A$_1$B$_2$	3	43.637^{ns}	0.05	38.95	48.32	0.429^{ns}	0.16	0.25	0.53
A$_1$B$_3$	3	41.415^{ns}	4.83	36.73	46.10	0.511^{ns}	0.14	0.41	0.62
A$_2$B$_1$	3	47.263^{ns}	4.30	42.57	51.95	0.682^{ns}	0.15	0.57	0.79
A$_2$B$_2$	3	41.865^{ns}	4.30	37.18	46.55	0.677^{ns}	0.04	0.57	0.78
A$_2$B$_3$	3	43.766^{ns}	5.30	39.08	48.45	0.577^{ns}	0.11	0.47	0.68
		TS (%)				RS (%)			
A$_0$B$_1$	3	6.844^{c}	2.10	3.47	12.78	3.560^{ns}	1.14	1.46	6.34
A$_0$B$_2$	3	6.862^{c}	1.70	3.52	11.87	3.581^{ns}	0.88	1.88	5.69
A$_0$B$_3$	3	6.888^{c}	2.22	3.09	13.97	3.654^{ns}	0.94	1.80	5.88
A$_1$B$_1$	3	6.394^{d}	1.76	3.44	13.01	3.279^{ns}	0.97	1.55	5.98
A$_1$B$_2$	3	7.234^{b}	2.44	1.45	13.92	3.713^{ns}	1.14	1.89	6.16
A$_1$B$_3$	3	8.439^{a}	2.23	3.40	14.37	3.667^{ns}	0.90	1.93	5.69
A$_2$B$_1$	3	8.160^{a}	2.40	3.57	13.95	3.553^{ns}	1.07	1.23	6.35
A$_2$B$_2$	3	7.997^{a}	2.14	3.23	13.33	3.663^{ns}	0.99	1.28	6.24
A$_2$B$_3$	3	7.130^{b}	2.07	2.20	14.38	3.594^{ns}	0.89	1.34	5.84
Treatment	n	MCG (%)				BD (g/cm^3)			
		Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
A$_0$B$_1$	3	107.090^{bc}	20.61	55.75	143.92	0.487^{ns}	0.04	0.41	0.60
A$_0$B$_2$	3	97.883^{d}	21.03	50.45	132.82	0.492^{ns}	0.04	0.39	0.59
A$_0$B$_3$	3	109.407^{ab}	18.02	66.72	147.92	0.486^{ns}	0.05	0.39	0.59
A$_1$B$_1$	3	99.925^{d}	23.70	51.95	160.97	0.483^{ns}	0.04	0.39	0.59
A$_1$B$_2$	3	107.459^{bc}	21.93	66.11	168.03	0.483^{ns}	0.03	0.41	0.56
A$_1$B$_3$	3	110.017^{ab}	18.65	70.91	146.34	0.492^{ns}	0.05	0.40	0.59
A$_2$B$_1$	3	110.842^{ab}	17.99	72.76	158.60	0.488^{ns}	0.05	0.39	0.60
A$_2$B$_2$	3	112.554^{a}	16.26	85.17	160.66	0.489^{ns}	0.03	0.42	0.57
A$_2$B$_3$	3	105.011^{c}	20.55	73.15	161.35	0.478^{ns}	0.04	0.40	0.58
		T/R ratio				VS (%)			
A$_0$B$_1$	3	2.023^{c}	0.62	0.79	3.66	10.520^{c}	2.72	5.96	17.40
A$_0$B$_2$	3	2.023^{c}	0.67	0.93	3.82	10.687^{c}	1.79	6.38	15.57
A$_0$B$_3$	3	1.950^{c}	0.63	0.69	3.62	10.698^{c}	2.56	6.51	17.39
A$_1$B$_1$	3	2.098^{b}	0.79	0.78	5.03	10.102^{d}	2.03	6.30	16.37
A$_1$B$_2$	3	2.080^{b}	0.86	0.50	5.22	11.146^{b}	2.68	5.72	17.08
A$_1$B$_3$	3	2.403^{a}	0.74	0.90	4.67	12.301^{a}	2.55	7.07	19.10
A$_2$B$_1$	3	2.428^{a}	0.80	1.19	4.83	11.958^{a}	2.83	6.69	19.92
A$_2$B$_2$	3	2.365^{a}	0.95	0.90	5.51	12.047^{a}	2.26	7.44	17.27
A$_2$B$_3$	3	2.086^{b}	0.75	0.73	4.94	11.121^{b}	2.33	5.13	18.14

A$_0$, A$_1$, and A$_2$ are the control, moderate thinning, and heavy thinning regimes, respectively.
B$_1$, B$_2$, and B$_3$ are low pruning, medium pruning, and high pruning, respectively.
$^{a\text{–}d}$ Mean marked with different superscript letters are significantly different at α = 0.05.
n: number of trees, PHW: relative heartwood proportion, VHW: volume of heartwood content, MCG: green moisture content, BD: basic density, Min: minimum, Max: maximum, TS: tangential shrinkage, RS: radial shrinkage, T/R ratio: shrinkage coefficient of anisotropy, VS: volumetric shrinkage.

MCG under thinning treatments could be influenced by the level of pruning treatments, as indicated by the significance of the interaction effect of thinning and pruning treatments combination, which contributed to approximately a third of the total variation ($p < 0.0001$; Table 2). In the combination treatments, A_2B_2 had the highest mean MCG (Table 4). However, A_2B_2 differed significantly from A_2B_3, whereas A_2B_3 did not differ significantly from A_0B_1 (Table 4). Therefore, the increase of the mean MCG under thinning treatments indeed depended on the level of pruning treatments. Meanwhile, different axial levels within thinning treatments tended to strongly affect MCG mean values ($p < 0.0001$; Table 2).

Thinning and pruning practices were understood to affect the transpiration mechanism of the stands. This was because stand density reduction in thinning treatment increased the water availability in the soil by minimizing soil water stress due to a decrease in stand transpiration and canopy interception (Bréda *et al.*, 1995; Forrester, 2015). Meanwhile, transpiration could be immediately reduced by removing part of the leaf areas of the trees as part of the pruning treatment mechanism (Forrester *et al.*, 2012). These transpiration-reducing mechanisms led to increasing water use efficiency in which the water was used for wood formation (Forrester *et al.*, 2012). In general, the mean MCG under all treatments (Tables 3 and 4) were almost similar to a previous study of 30 to 31 years old teak from various clones in India (Shukla *et al.*, 2011). However, the results were higher compared to the finding in 8-year-old clonal teak from Muna island (Savero *et al.*, 2020). Moreover, it was reported that MCG from a fresh-cut tree would be around 33%–249% of the absolute wood-dried weight, which is strongly affected by differences in the part of the stem, site, age, harvested season, and tree dimension (Shmulsky and Jones, 2011).

The moisture content in green condition (MCG) is one of the main parameters in determining wood quality since it determines the effectivity in the log hauling and wood drying process (Marsoem *et al.*, 2014). Moreover, 10 years after the application of the treatments, thinning and pruning still significantly affected the mean MCG of clonal teak wood, suggesting the importance of both practices in clonal teak plantation management. Since higher thinning and pruning intensities tended to produce higher MCG (Table 3), additional treatment must be conducted to alleviate the adverse effect of high MCG on the clonal teak wood's further utilization. The Implementation of girdling as a pre-harvest treatment could be an option for alleviating the inimical effect of high MCG on the thinned clonal teak stands. Girdling is a pre-harvest treatment that reduces the moisture content of the standing tree's stem as a result of photosynthates flow impediment from reaching the root system by creating inward incisions encircling the stem from the periphery to the cambium zone (Basri *et al.*, 2015; Noel, 1970). This method has been practiced for decades as part of the teak stand management in India, Indonesia (Java), Myanmar, and Thailand (Strugnell, 1932). Previous studies reported that several months of girdling in young ages trees was effective in reducing MCG by more than 50% from the initial MCG in teak (Rini, 2013), *Acacia mangium* (Basri *et al.*, 2015), and various coniferous species (Laurila *et al.*, 2014). Therefore, it was suggested to conduct girdling as a pre-harvest treatment when practising thinning and pruning regimes on the clonal teak plantation to alleviate the adverse impact of high MCG on clonal teak wood from both silvicultural practices.

3.1.3. Basic density (BD)

BD is one of the most important aspects of wood properties. The result of ANOVA showed that different thinning and pruning intensities did not significantly affect the mean value of the clonal teak wood BD ($p = 0.486$ and $p = 0.536$, respectively; Table 2). Furthermore, the combination of thinning and pruning treatments also did not significantly alter the mean value of BD (p = 0.052; Table 2). In this study, although not significantly different, A_0 had the highest mean value of BD compared to other thinning treatments and A_2 possessed the lowest (Table 3). Meanwhile, B_2 possessed the highest mean value of BD among the other pruning treatments (Table 3). These results were similar to a previous study in Costa Rica, in which different thinning intensities were reported to have no significant impact on the BD of teak wood from generative seed source origin plantations (Pérez and Kanninen, 2005). However, a previous study reported that different thinning intensities promoted significant alteration in the BD value of the clonal teak wood based on the significant differences in the mean value of pilodyn penetration toward the treatments (Seta *et al.*, 2021). This discrepancy can be caused by the differences in the BD estimation approach. In this study, BD was estimated as the mean of the whole stem, which was assessed from various parts of the stem (axially and radially). Furthermore, the differences could also occur because the pilodyn penetration was more correlated to the wood density of the outer portion than the inner section of the stem (Wessels *et al.*, 2011; Wu *et al.*, 2010).

Furthermore, the effect of different axial levels within thinning was the biggest contributor to the total variation of mean BD (49.8%) as shown in Table 2, which was considered to be significant (p < 0.0001). Under various axial levels within thinning treatments, mean BD, in general, tended to decrease along with the increase in tree height (Fig. 1). The decreasing axial trend in the mean BD of this study corresponds to the results of a previous study on young teak wood (Moya Roque and Ledezma, 2003). However, in more mature ages of teak wood, the gradual changing pattern of mean BD was reported different, where the base level is lower compared to the near crown level (Miranda *et al.*, 2011; Pérez Cordero and Kaninen, 2003). Meanwhile, the effect of different radial levels within thinning and axial levels contributed 37.5% to the total variation of mean mean BD, also considered to be significant (p < 0.0001; Table 2). The significance of radial level to the source of wood density variation has also been reported in previous studies of teak from Ghana (Amoah and Inyong, 2019) and *Acacia melanoxylon* from Portugal (Machado *et al.*, 2014). However, the radial variations in the mean BD of clonal teak wood were predicted to be less significant with the increase in the tree age (Miranda *et al.*, 2011; Rahman *et al.*, 2004).

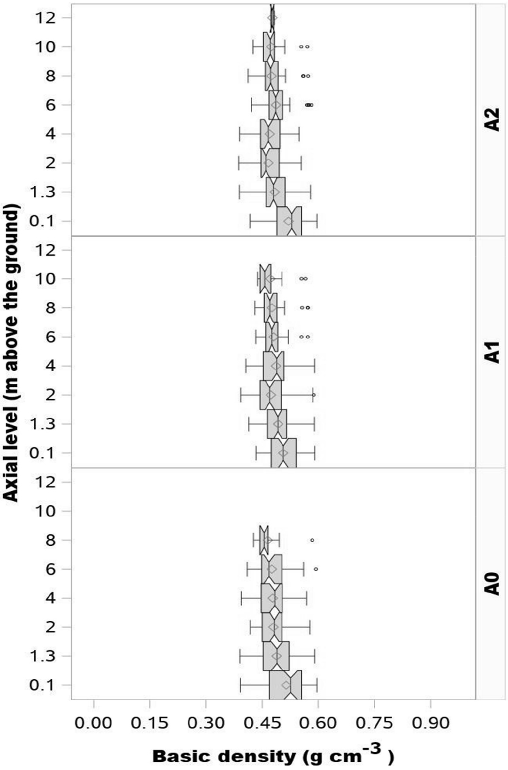

Fig. 1. Wood basic density of clonal teak wood under various axial levels within thinning treatments. A_0, A_1, and A_2 are the control, moderate thinning, and heavy thinning regimes, respectively. The notches of the boxes represent the median's 95% confidence interval.

In general, the mean values of BD under all treatments showed to be around 0.478–0.492 g/cm^3 (Tables

3 and 4). This is relatively similar to a previous report in Laos on 25 years old teak trees (Wanneng *et al.*, 2014). However, the results were lower than the 50–70 years old teak trees from East Timor which possessed ± 17%–22% higher mean BD than the findings of this study (Miranda *et al.*, 2011). Therefore, the application of thinning and pruning regimes in the clonal teak stands, based on our findings, did not promote any inimical effects on mean BD.

3.1.4. Wood shrinkage and dimensional stability

Under different thinning intensity levels, the mean TS, T/R-ratio, and VS were significantly different ($p < 0.0001$, $p < 0.0001$, and $p < 0.0001$ respectively; Table 2). Thinning was identified as an important source of variation, which contributes to more than 40% of the total variation in the mean TS, T/R-ratio, and VS (Table 2). Meanwhile, it was not considered a significant contributor to the total variation in RS ($p = 0.747$; Table 2). In this study, A_2 had the highest mean TS, T/R-ratio, and VS compared to other thinning treatments, which was significantly different from A_0 (Table 3). Furthermore, A_1 was also found to be significantly different to A_0 in the mean TS, T/R-ratio, and VS (Table 3). However, only in mean VS, A_1 was found to be significantly different from A_2 (Table 3). Despite its insignificance, A_2 promoted the highest mean RS compared to other thinning treatments which significantly alter the mean TS and T/R-ratio ($A_2 \approx A_1 > A_0$; Table 3). Meanwhile, the higher thinning intensities were applied, the bigger the mean VS would be ($A_2 > A_1 > A_0$; Table 3). Whereas thinning did not promote any significant differences in mean RS ($A_0 \approx A_1 \approx A_2$; Table 3).

Furthermore, under different pruning intensity levels, the mean RS and VS were significantly different ($p = 0.0303$ and $p = 0.0445$, respectively; Table 2). The results also showed that pruning contributed to approximately 28.16% and 7% of the total variation in the mean RS and VS, respectively. However, it was not considered to be a significant contributor to the total variation in TS and T/R-ratio ($p = 0.215$ and $p = 0.6583$, respectively; Table 2). Meanwhile, B_2 performed the highest mean RS compared to other pruning treatments, which was also significantly different from B_1 (Table 3). In addition, the highest mean VC (11.424 ± 0.74%) was possessed by $B_{3,}$ which also varied from B_1 (Table 3). Furthermore, B_3 and B_2 were also found to be significantly different to B_1 in the mean RS and VS, respectively (Table 3). Therefore, pruning tended to significantly alter the mean RS and VS ($B_2 \approx B_1 > B_0$) and did not promote any differences in mean TS and T/R-ratio ($B_0 \approx B_1 \approx B_2$).

This study showed that the increase in the mean TS, T/R-ratio, and VS under thinning treatments depended on the level of pruning, as indicated by the significance of the interaction effect of both treatments ($p < 0.0001$, $p < 0.0001$, and $p < 0.0001$, respectively; Table 2). The interaction of thinning and pruning treatments in mean TS, T/R-ratio, and VS contributed to the total variation of approximately 43%, 25%, and 32%, respectively (Table 2). In contrast, it did not significantly differ from the alteration in mean RS ($p < 0.0001$; Table 2). Increasing pruning intensity levels in any of the A_0 treatments did not significantly alter the mean TS, T/R-ratio, or VS (Table 4). Meanwhile, in A_1 treatments, an increase in pruning intensity levels escalated the mean TS, T/R-ratio, and VS significantly (Table 4). However, when the highest pruning intensity level was applied in A_2, there was a significant decrease in the mean of TS, T/R-ratio, and VS (Table 4). Axial variation (within thinning) tended to significantly differentiate the mean values of wood dimensional shrinkage variables (Table 2). The mean T/R-ratio and VS decreased gradually as the tree height increased, with significant differences from the base to the highest level (Fig. 2).

Furthermore, compared to 11-year-old clonal teak and

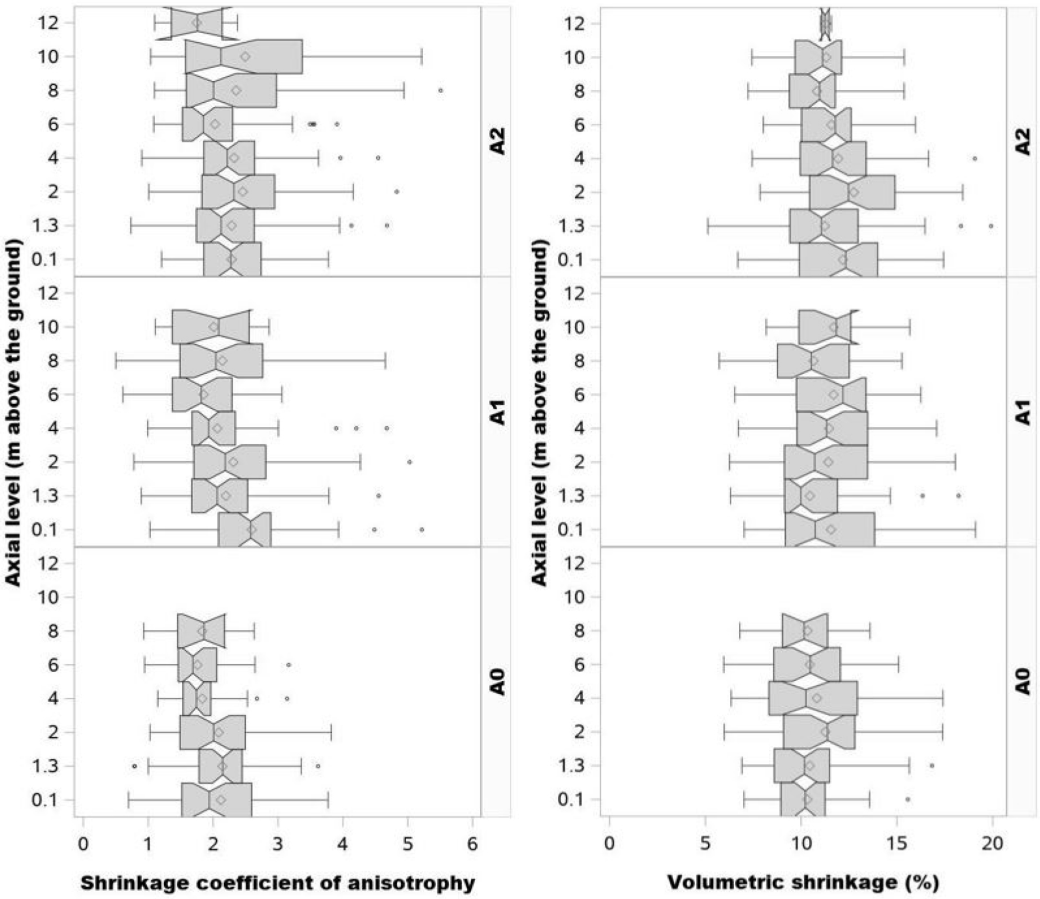

Fig. 2. Shrinkage coefficient of anisotropy (T/R-ratio) and volumetric shrinkage of clonal teak wood under various radial levels within thinning treatments. A_0, A_1, and A_2 are the control, moderate thinning, and heavy thinning regimes, respectively. The notches of the boxes represent the median's 95% confidence interval.

14-year-old seed source teak planted in Java, it was discovered that TS and RS were lower, but the T/R-ratio was relatively higher (Hidayati *et al.*, 2016). Meanwhile, the TS, RS, and VS of this study were also higher compared to the study in mature-aged teak wood (Marsoem *et al.*, 2014; Miranda *et al.*, 2011). The T/R-ratio is an important wood dimensional stability parameter that indicates the best use of wood in terms of drying quality, which leads to dimensional stability (Christoforo *et al.*, 2016). The T/R-ratio was generally around 1.5 to 2.5 for all species of tree, therefore, the lower the value, the more stable the wood for not being bent during board making (Quarles and Valachovic, 2012).

The wood's dimensional stability is an important property that determines how much wood shrinks or swells with changing moisture content, which shows its suitability for various applications (Sargent, 2019). Thus, significant changes in wood dimensional stability parameters must be considered an important issue in the process of teak timber production. This study discovered that thinning, pruning, or both treatments had a significant impact on the TS, RS, T/R-ratio, and VS of clonal teak wood (Table 2). Those practices tended to increase the wood shrinkage rate in all directions and were considered detrimental to wood dimensional stability (Shmulsky and Jones, 2011). Therefore, necessary precautions had to be taken in the implementation of these silvicultural practices on clonal teak stands. The application of further treatment could be considered when both silvicultural practices were implemented. Girdling could also be applied as a pre-harvest treatment because of its ability to reduce TS, RS, and T/R-ratio significantly, indicating increased wood dimensional stability (Basri *et al.*, 2015).

3.2. Effect of thinning and pruning on clonal teak wood mechanical properties

3.2.1. Static bending strength

The mean MOE and MOR did not differ significantly across all thinning treatment intensity levels (p = 0.2481 and p = 0.3922; Table 5). Although not statistically significant, A_1 had a higher mean MOE and MOR than A_0 and A_2 (Table 3). Furthermore, A_1 increased the mean MOE of ± 4% from A_0 but under A_2, the mean MOE only increased by 0.7% (Table 3). In MOR, the trend was slightly different, A_1 promoted an increase of MOR by approximately 2.4% from A_0 but A_2 tended to decrease MOR by approximately 1.3% from A_0 (Table 3).

The effect of different pruning intensity levels on mean MOE and MOR was also not significantly different (p = 0.4111 and p = 0.5925, respectively; Table 5). Although not significant, B_3 had the highest mean MOE and MOR under pruning treatments, while B_1 had the lowest (Table 3). Therefore, the higher the pruning intensity levels applied, the more MOE and MOR increased (Table 3). The combination of thinning and pruning treatments gave insignificant changes in both mean MOE and MOR (p = 0.7816 and p = 0.4925, respectively; Table 5). Radial levels within thinning treatments, however, had a significant effect on mean MOE and MOR variations (p < 0.0001 and p < 0.0001, respectively), which contributed more than 85% of the total variation (Table 5).

In this study, the mean MOE ranged from 10.843 ± 1.75 to 11.235 ± 1.82 GPa across all treatments, while the mean MOR, across all treatments, ranged from 77.168 ± 14.11 to 80.214 ± 12.46 MPa (Table 3). These results were superior to previous studies on the 8-year-old clonal teak from Muna Island (Savero *et al.*, 2020); 11-year-old clonal teak trees from Java (Hidayati *et al.*, 2016); and 10–20-year old teak trees from Ghana’s dry region (Amoah and Inyong, 2019). Furthermore, the mean MOE was also more than the 12-year-old teak stands from three different agroforestry management systems in India, where the mean MOR was within the range (Shukla and Viswanath, 2014). The mean MOE values in this study were in range with previous investigations on 21-year-old teak (Bhat and Priya, 2004), 35-year-old teak (Thulasidas and Bhat, 2012), and 50-70 years teak (Miranda *et al.*, 2011). However, when compared to the older ages of teak trees, the mean MOR in this study was relatively lower (Bhat and Priya, 2004; Miranda *et al.*, 2011; Thulasidas and Bhat, 2012). Moreover, a previous report showed the importance of radial level as the source of MOE and MOR variation in teak (Amoah and Inyong, 2019). A gradual increase was observed in both MOE and MOR from the area near the pith to the area near the bark at various radial levels within thinning treatments (Fig. 3). This gradual increasing trend on radial levels had also been identified, whether in young (15－20-year-old) or mature (50－70-year-old) teak trees (Amoah and Inyong, 2019; Miranda *et al.*, 2011). However, only young teak showed significant differences at various radial levels, and the area near the pith was lower than the area near the bark (Amoah and Inyong, 2019).

Table 5. Result of variance analysis of thinning and pruning treatments effect on mechanical properties of clonal teak wood

Source of variance	*df*	MOE		MOR	
		F-value	Var (%)	*F*-value	Var (%)
Block	2	1.48^{ns}	0.1	2.40^{ns}	0.3
Thinning	2	1.41^{ns}	3.0	0.94^{ns}	0.0
RL (*Thinning*)	7	13.08^{**}	89.0	11.46^{**}	90.2
Pruning	2	0.90^{ns}	0.0	0.53^{ns}	0.0
RL (*Pruning*)	6	0.13^{ns}	0.0	0.36^{ns}	0.0
Thinning × Pruning	4	0.44^{ns}	0.0	0.86^{ns}	0.0
RL (*Thinning Pruning*)	7	1.08^{ns}	0.5	1.09^{ns}	0.8
		CSPL		CSPD	
Block	2	7.64^{**}	5.2	2.77^{ns}	2.3
Thinning	2	0.21^{ns}	0.0	0.41^{ns}	0.0
RL (*Thinning*)	7	3.11^{**}	38.0	2.07^{ns}	30.3
Pruning	2	2.07^{ns}	19.3	2.03^{ns}	29.0
RL (*Pruning*)	6	1.95^{ns}	17.2	1.20^{ns}	5.7
Thinning × Pruning	4	1.08^{ns}	1.4	1.16^{ns}	4.4
RL (*Thinning Pruning*)	7	1.06^{ns}	1.0	0.75^{ns}	0.0

** Significant at $\alpha = 0.01$; ^{ns} Non-significant difference at $\alpha = 0.05$.
df: degree of freedom, MOE: modulus of elasticity, MOR: modulus of rupture, Var: variance components, RL: radial level, CSPL: compressive strength parallel to the grain, CSPD: compressive strength perpendicular to the grain.

The MOE and MOR represent wood stiffness and strength, which are important mechanical properties for structural or construction timber (Ross, 2010; Shmulsky and Jones, 2011). Teak is one of the tropical tree species whose timber has been used for structural or construction purposes since antiquity (Ramasamy *et al.*, 2021; Thulasidas and Bhat, 2012). Therefore, the information on the alteration of MOE and MOR in the teak timber production process was critical. In this study, thinning and pruning treatments did not affect the alteration of mean MOE and MOR of clonal teak wood (Table 3). This was in line with previous results, where heavy and moderate thinning programs on teak in India and Myanmar did not significantly change the strength properties (Kadambi, 1972). Therefore, the implementation of both treatments will not adversely affect the MOE and MOR of the clonal teak stands.

3.2.2. Compression strength

In the compressive strength measurements, either mean CSPL or mean CSPD were not significantly different across all thinning treatment intensity levels ($p = 0.8134$ and $p = 0.6693$, respectively; Table 5). Although not statistically significant, A_2 promoted approximately 1.1% and 3.7% increase from A_0 in mean CSPL and CSPD, respectively (Table 3). There was no difference between the effect of various pruning intensity levels on mean CSPL and CSPD ($p = 0.1382$; and $p = 0.1449$, respec-

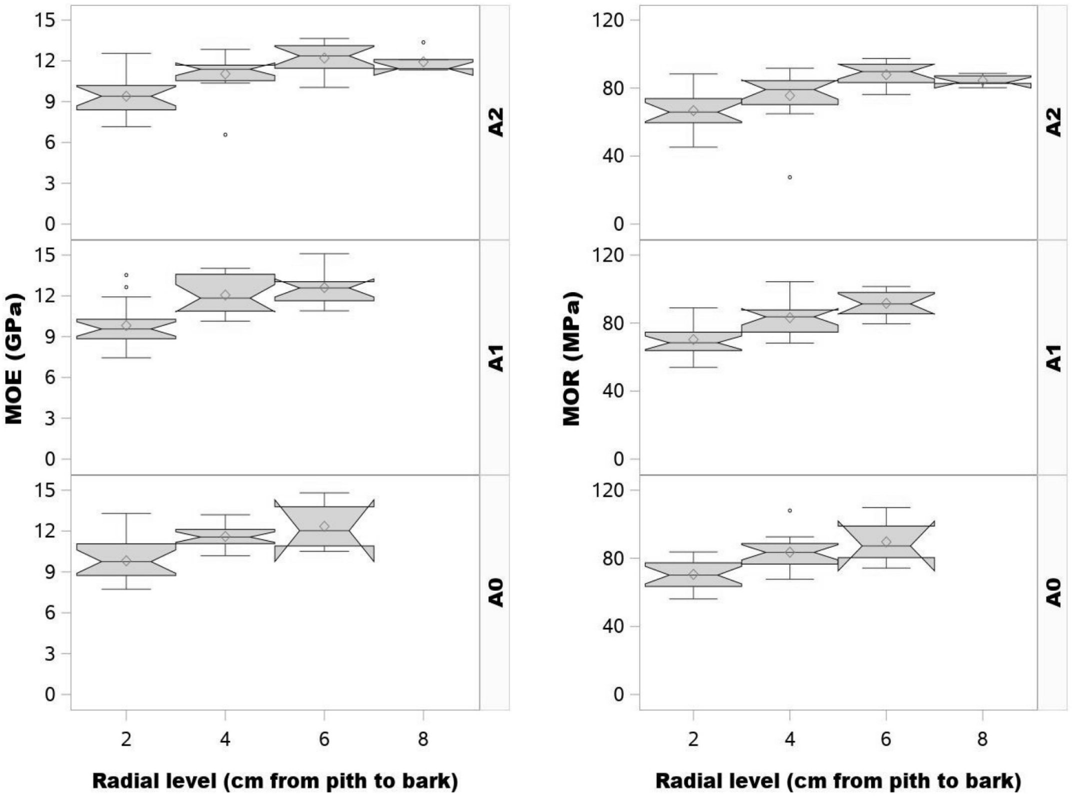

Fig. 3. MOE and MOR of clonal teak wood under various radial levels within thinning treatments. A_0, A_1, and A_2 are the control, moderate thinning, and heavy thinning regimes, respectively. The notches of the boxes represent the median's 95% confidence interval. MOE: modulus of elasticity, MOR: modulus of rupture.

tively; Table 5). In pruning treatment, the highest mean CSPL was B_2, while in mean CSPD was B_1 (Table 5). The combination of both treatments gave insignificant changes in CSPL and CSPD (p = 0.3789 and p = 0.3445, Table 5).

In this study, the mean CSPL ranged from 41.573 ± 6.13 to 43.789 ± 5.22 MPa across all treatments (Table 3). Meanwhile, the mean CSPD under all treatments ranged from 14.127 ± 2.42 to 15.102 ± 2.06 MPa (Table 3). The CSPL values were significantly higher compared to studies of younger-aged clonal teak trees at 8 years (Savero *et al.*, 2020), 10 years (Hidayati *et al.*, 2015), and 11 years (Hidayati *et al.*, 2016). Furthermore, in comparison with 10–20 year teak trees from Ghana, the mean CSPL showed lower values (Amoah and Inyong, 2019). In older-age teak trees, the obtained values were also lower, compared to 21 years (Bhat and Priya, 2004), 32 years (Thulasidas and Bhat, 2012), and 50–70 years (Miranda *et al.*, 2011). Meanwhile, the mean CSPD in this study were also considered to be lower compared to a previous report in the same region, which ranged from 15.28 MPa to 21.83 MPa (Marsoem *et al.*, 2014).

In addition, radial levels within thinning treatments had a significant effect on mean CSPL but not on mean CSPD variations (p = 0.0093 and p = 0.0683, respectively; Table 5). This phenomenon could be caused by the variation of lignin content, in which the lignin content decreased significantly from the outer part of the wood to the inner part of the wood of clonal teak (Lukmandaru *et al.*, 2016). Since the resistance of the wood structures to the comprehensive force was determined by lignin content, therefore, parts of wood with high lignin content tended to possess better strength (Fagerstedt *et al.*, 2015; Iswanto *et al.*, 2021). The CSPL and CSPD are also important compression strength parameters in determining the quality of the wood's mechanical properties (Ross, 2010). In structural timber application, CSPL will determine the load a column carries, while CSPD is important in the design of building connections between wood members and beam supports (Shmulsky and Jones, 2011). Therefore, the information on the alteration of both strengths is essential in teak timber production, which is one of the best construction materials (Ramasamy *et al.*, 2021; Thulasidas and Bhat, 2012). In this study, thinning and pruning treatments did not affect the alteration of mean CSPL and CSPD of clonal teak wood (Table 5). This was in line with a previous report, where heavy and moderate thinning regimes on teak in India and Myanmar did not change the strength properties (Kadambi, 1972). Therefore, the implementation of both treatments did not adversely affect the CSPL and CSPD of the clonal teak stands.

3.3. Implications for intensive silvicultural practices and wood utilization

This study suggests that the implementation of thinning and pruning regimes in the clonal teak plantation as part of intensive silvicultural techniques did not have a significant adverse effect on its heartwood development (PHW and VHW), BD, and mechanical properties (MOE, MOR, CSPL, and CSPD; Tables 2, 3, and 5). The results showed that moderate thinning had the highest mean MOE and MOR, while heavy thinning promoted the greatest mean value in both CSPL and CSPD (Table 3). It had also been reported that thinning practices at certain intensities tended to improve the mechanical properties of the stand (Russo *et al.*, 2019; Seta *et al.*, 2021; Wang *et al.*, 2005). Meanwhile, necessary precautions were needed to be taken in implementing higher thinning and pruning intensities since those practices significantly altered the mean of MCG and dimensional stability (TS, RS, T/R-ratio, and VS) of the clonal teak wood (Tables 3 and 5). To diminish the adverse impact of high MCG and wood shrinkage parameters, additional pre-harvest treatment must be incorporated as an integral component of clonal teak plantation management when thinning and pruning regimes were implemented. Girdling is one of the pre-harvest treatments that have been scientifically proven to reduce MCG and wood dimensional shrinkage of the stands in various species (Basri *et al.*, 2015; Laurila *et al.*, 2014; Rini, 2013). Therefore, it is suggested that girdling has to be incorporated when thinning and pruning regimes will be applied in managing genetically-improved clonal teak plantations.

4. CONCLUSIONS

The implementation of thinning and pruning regimes as part of the clonal teak plantation silvicultural activities had no detrimental effects on the alteration in mean PHW, VHW, BD, MOE, MOR, CSPL, and CSPD. This showed that both regimes had a positive impact on the clonal teak's mechanical properties. However, various thinning intensity levels caused significant differences in the mean MCG, TS, T/R-ratio, and VS, where the mean alteration was influenced by the levels of the pruning treatment. The variations in mean RS and VS were also produced by several pruning intensity levels. The results also showed that reducing stand density by 50% (heavy thinning) will increase MCG, T/R-ratio, and VS by 4.65%, 15%, and 1.08%, respectively. When thinning and pruning regimes in clonal teak plantations will be applied, necessary consideration must be given to the considerable impact on MCG, TS, RS, T/R-ratio, and VS. To alleviate the adverse impact on high MCG and wood shrinkage parameters, additional pre-harvest treatment needs to be incorporated as an integral component of clonal teak plantation management when thinning and pruning regimes are implemented. Therefore, the inclusion of thinning and pruning regimes into the clonal teak plantation management protocol will not significantly affect the wood properties.

CONFLICT of INTEREST

No potential conflict of interest relevant to this article was reported.

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