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Effect of spacing on growth, carbon sequestration, and wood quality of 8-year-old clonal teak plantation for sustainable forest teak management in Java Monsoon Forest, Indonesia

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Abstract. *Rahmawati RB, Widiyatno, Hardiwinoto S, Budiadi, Nugroho WD, Wibowo A, Rodiana D. 2022. Effect of spacing on growth, carbon sequestration, and wood quality of 8-year-old clonal teak plantation for sustainable forest teak management in Java Monsoon Forest. Biodiversitas 23: 4180-4188.* Lowland monsoon forest dominated by teak was one of the tropical forest types that can contribute to producing wood production, carbon storage, reduction of emissions, and other ecosystem services. Increasing teak forest productivity could be obtained through teak breeding to get superior teak clones with high diameter growth. Thus, spacing is an important consideration for optimizing the growth, carbon sequestration, and wood properties of teak. However, the study of the growth, carbon sequestration, and wood quality of teak was conducted separately. This research used a selected teak clone aged 8 years with RCBD design with 4 blocks as replications. There were four different spacing as treatments, namely 10 m x 2 m, 8 m x 2 m, 6 m x 2 m, and 3 m x 3 m. The results showed that spacing was a significant effect on DBH, tree height, bole height, carbon sequestration, and volume of teak clones aged 8 years. On the other hand, spacing didn't significantly affect the physical and mechanical properties of wood. The wood quality test showed that the 6 m x 2 m spacing had high values of bending strength and compressive strength parallel. The highest percentage of heartwood was at a narrow spacing of 6 m x 2 m and did not differ significantly with wide spacing. This indicated that wide spacing was beneficial in terms of teak growth, but wide spacing didn't significantly affect on wood quality of the teak.

Keywords: Spacing, teak clones, teak growth, wood quality

INTRODUCTION

The tropical forest is an important area that has > 50% of biodiversity richness and global carbon stored as it has proper supporting factors (Reed et al. 2020; Estoque et al. 2019; Marimpan et al. 2022). One of the tropical forest types is the lowland monsoon forest whereas which is dominated by teak (Nair 2004). The global teak forest can contribute to reducing carbon emissions (Chayaporn et al. 2021). On the other hand, teak (*Tectona grandis* L.f) is a high economic valued wood in the international market (Wanneng et al. 2014; Pachas et al. 2019) with several benefits that are used for furniture, shipbuilding, indoor and outdoor equipment (Kokutse et al. 2004; Miranda et al. 2011; Thulasidas and Bhat 2012). Teak is also of good aesthetic quality (Thulasidas et al. 2006) and is easy to work with (Shukla and Viswanath 2014). One of the strategies to increase the wood production of teak is tree breeding which produces selected clones with high growth (Budiadi et al. 2017; Seta et al. 2021). The clonal teak plantation can increase forest productivity and harvest as a medium rotation (20-30 years) which the mean annual diameter increment (MADI) was above 2 cm per year (Budiadi et al. 2017; Seta et al. 2021). On the other hand, clonal teak plantations could increase wood production, carbon storage, reduction of emissions, and other ecosystem services (Nöltea et al. 2018).

The present area of teak forests is 4.35 million Ha and covers 69 countries (Berrocal et al. 2020). In Indonesia, it is mainly grown and developed on the lowland monsoon forest on Java island, with a total area of 1.2 million Ha (MoF 2012; Perhutani 2014; Rizanti et al. 2018). The species is also planted in community forests with an agroforestry system (Shukla and Viswanath 2014). Furthermore, a large-scale clonal teak plantation was propagated by shot cutting to maintain the genetic structure of the ancestor (Sawitri et al. 2020), to increase forest productivity, and teak wood quality (Seta et al. 2021).

In clonal teak planting, adjusting spacing is one of the silvicultural techniques for optimizing their growth. Fast-growing tree species, i.e. selected clonal teak, will produce high productivity, but they require the most suitable plant types and spacing arrangements (Sopacua et al. 2021). Research showed that the spacing increased the diameter growth and the branching angle (Zahabu et al. 2015; Pachas et al. 2019; Rahmawati et al. 2021) but decreased bole height (Rahmawati et al. 2021). It indicated that the wide spacing would probably increase the tree's wood volume, and carbon sequestration, but it can decrease the wood quality (Yunianti et al. 2011). It indicated that the spacing was an important aspect of increasing forest yield both forest productivity and forest economic value (Budiadi et al. 2017; Pachas et al. 2019; Seta et al. 2021). It can also interact with clones to provide various wood properties (Kokutse et al. 2016) by affecting the quality (Tun et al. 2018). Current research on the impact of spacing on the growth, carbon sequestration, and wood quality of teak was carried out separately. Thus, for a carpenter, the dimensions and strength of the teak are important factors in achieving a high yield of sawmill processing in the carpentering industry. Therefore, research on the effect of spacing needs to be carried out to support the future sustainability of teak clone forestry concessions.

MATERIALS AND METHODS

Research site

This research was conducted in a lowland monsoon forest and an 8-year-old teak clone plantation in Ngawi Forest Management Unit (FMU), Perhutani, East Java, Indonesia, at latitude -7º 22’ 52.829” and longitude 111º 18’17.466”. The mean annual rainfall was 1.172 mm, where the major precipitation falling is from November to April. The research was conducted with a Randomized Complete Blocks Design (RCBD) design with four replications as a block (Figure 1). The treatments were conducted with four spacing of 3 m x 3 m, 6 m x 2 m, 8 m x 2 m, 10 m x 2 m, and a plot size for each treatment was 4 x 50 trees.

Procedures

Teak growth

The collected data on teak growth were diameter at breast height (DBH), total height, bole height, carbon sequestration, and volume per hectare. DBH was measured at the height of 1.3 m by diameter tape, and hagameter measured the height and bole height of the teak. Volume and carbon sequestration for each teak’s individual was calculated using the formula developed by Perez and Kanninen (2003) and Basuki et al. (2008), respectively:

$$V_{1\text{-}N} = (-0{,}0884 + 0{,}0297 * DBH)^2$$

Where: V_1: log volume at first individual (m^3); V_n: log volume at *N*th individual (m^3), and DBH: diameter at breast height (cm).

$$CS_{1\text{-}N} = 0.231\ X^{1.0388}$$

Where: CS_1: carbon sequestration at first individual (ton C); CS_n: carbon sequestration at *N*th individual (m^3) ; and *X*: dbh^2

Furthermore, volume (V) and carbon sequestration (CS) per hectare were calculated at the stand level as the sum of the volume or carbon sequestration for each tree in the plot, which was expressed as m^3/ha, and ton C/ha.

Wood quality

Wood quality consists of physical and mechanical properties. The physical properties consisted of wood density and heartwood percentage. Meanwhile, the mechanical properties consisted of static bending strength and compression parallel to the grain. The static bending strength for Modulus of Elasticity (MOE) and Modulus of Rupture (MOR) was calculated using the compression parallel to grain from Maximum Crushing Stress (MCS). The wood density was taken on 5-cm-thick disks cut from 5 cm above heartwood sampling and was prepared from each disk on radial strips (2 cm in width x 2 cm in thickness x 2 cm in length). The wood density was computed as a ratio of oven-dry weight to the green volume.

$$\text{Wood Density} = \frac{\text{Oven dry weight (g)}}{\text{Green volume (cm}^3\text{)}}$$

Heartwood percentage was measured on disks 5 cm thick cut at 1.3 m above ground level (Figure 2). Furthermore, heartwood rang, bark thickness, pith, and disk thickness were measured. The percentage was calculated from the total wood and heartwood volume using the following formula (Wahyudi and Arifien 2005):

$$\text{Total wood volume (mm}^3\text{)} = [\pi\ (R\text{-}k)^2]t$$
$$\text{Heartwood volume (mm}^3\text{)} = [\pi\ (r\text{-}e)^2]t$$

Where: R: total rang (mm); k: bark thickness (mm); r: heartwood rang (mm); e: pith (mm); t: disk thickness (mm)

Spacing	Stand Density (stems/ha)
3 x 3 m	1,111
6 x 2 m	833
8 x 2 m	625
10 x 2 m	500

Figure 1. Research Design

From the volume calculation, the heartwood percentage from total wood volume in the disk was calculated as follows:

$$\text{Heartwood percentage } (\%) = \frac{\text{Heartwood volume}}{\text{Total wood volume}} \times 100\%$$

The mechanical properties were taken on 1-m-length disks cut from 5 cm above physical properties sampling with 3-cm-thick disks around the pith. Meanwhile, Static Bending Strength (Modulus of elasticity and Modulus of rupture) was calculated according to the formula below:

$$\text{Modulus of elasticity } (\text{N/mm}^2) = \frac{P^1L^3}{4\Delta bd^2}$$

$$\text{Modulus of rupture } (\text{N/mm}^2) = \frac{3PL}{2bd^2}$$

Where: P: maximum load in Newton (N); L: the sample span length in mm; B: the sample width in mm; d: the sample depth in mm; P^1: load at the limit proportionality in Newton; Δ: deflection at mid-length at the limit of proportionality in mm

The compressive strength parallel to grain (maximum crushing stress-MCS) was calculated using the following formula:

$$\text{Maximum crushing stress} = \frac{P}{bd}$$

Where: P: maximum load in Newton (N); b: the sample width in mm; d: the sample depth in mm

Data analysis

One-way analysis of variance (ANOVA) was used to estimate the effect of spacing on DBH, total height, bole height, total volume per hectare, carbon sequestration, wood density, heartwood percentage, modulus of elasticity, modulus of rupture, and compression parallel to the grain using SPSS 18.0. In addition, Pearson correlation was used to evaluate the relationship between diameter and clone teak's physical and mechanical properties. Thus, the difference among treatments was analyzed using Duncan's Multiple Regression Test (DMRT) at tα 0.05.

RESULTS AND DISCUSSION

Effect of spacing on teak growth

Spacing affected the growth of DBH (F = 135.49; P < 0.001), height (F = 16.75; P < 0.001), bole height (F=56.66; P < 0.001), volume per ha (F = 21.62; P < 0.001) and carbon sequestration per ha (F = 9.23; P < 0.005) on 8-year-old teak clones (Table 1). The DBH average of 10 m x 2 m spacing was 23.97% greater than the 3 m x 3 m (Figure 3). Thus, MADI of spacing 10 m x 2 m and 3 m x 3 m were 3.1 cm/year and 2.3 cm/year, respectively (Figure 3). The height of 6 m x 2 m was the highest height parameter of all treatments (Figure 4). Furthermore, spacing 10 m x 2 m had the lowest bole height (Figure 5), volume per hectare (Figure 6), and carbon sequestration per hectare (Figure 7).

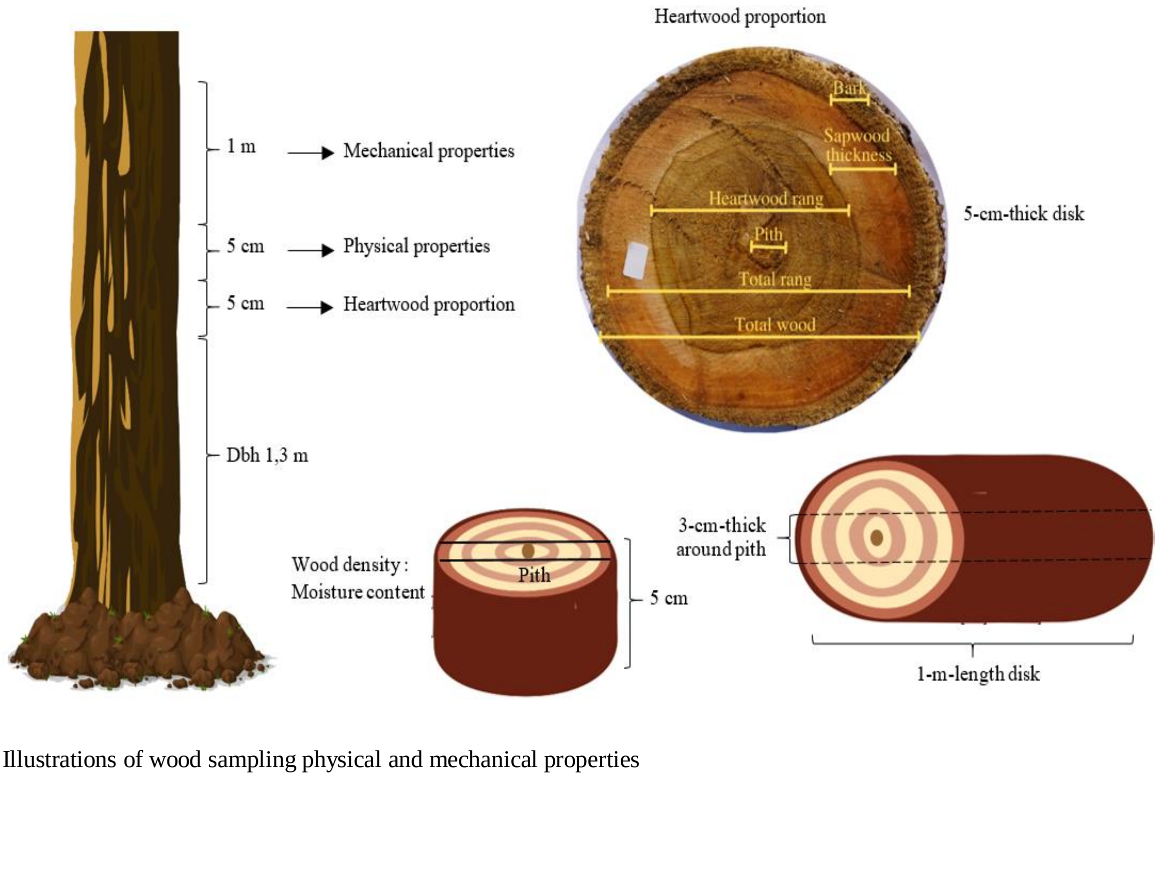

Figure 2. Illustrations of wood sampling physical and mechanical properties

Table 1. Result of variance analysis of spacing effects on clonal teak growth

Source of variation	df	DBH (cm)		Height (m)		Bole height (m)		Volume per ha (m^3/Ha)		Carbon sequestration (ton C/ha)	
		Mean square	F	Mean square	F	Mean square	F Sig.	Mean square	F	Mean square	F
Block	3	342.44	45.15**	139.78	88.11**	7.44	1.32ns	230109.89	47.56**	136513.05	107.80*
Spacing	3	1027.59	135.49**	26.57	16.75**	318.14	56.66**	104596.09	21.62**	11698.84	9.23*

Note: * significant at $p \leq 0.05$, ** significant at $p \leq 0.01$, ns: non-significant different at tα 0.05

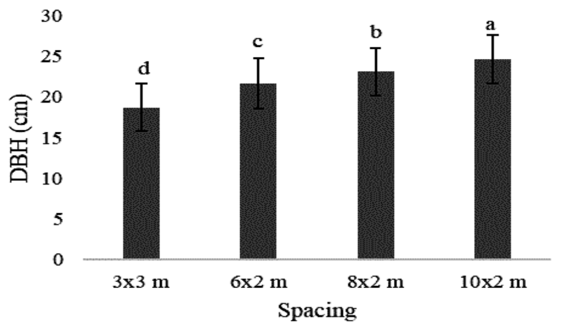

Figure 3. Means and standard deviation for DBH for each treatment. Different letters indicate significance among treatments at tα 0.05

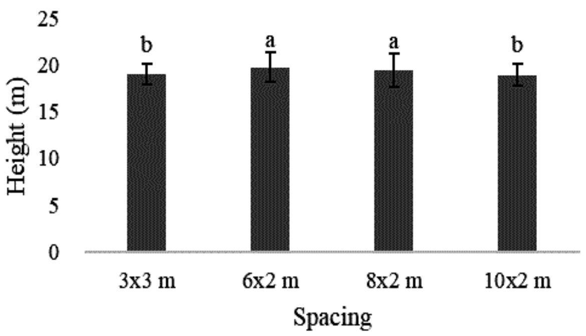

Figure 4. Means and standard deviation for the height of each treatment. Different letters indicate significance among treatments at tα 0.05

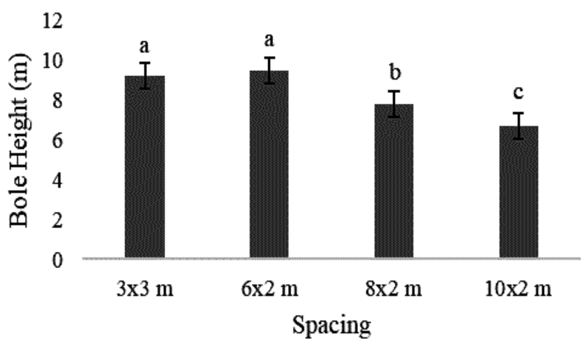

Figure 5. Means and standard deviation for bole height of each treatment. Different letters indicate significance among treatments at tα 0.05

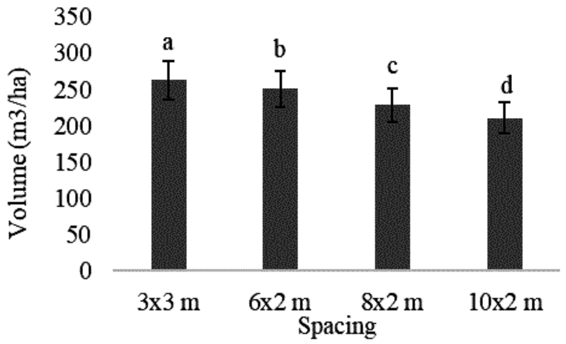

Figure 6. Means and standard deviation for the volume of each treatment. Different letters indicate significance among treatments at tα 0.05

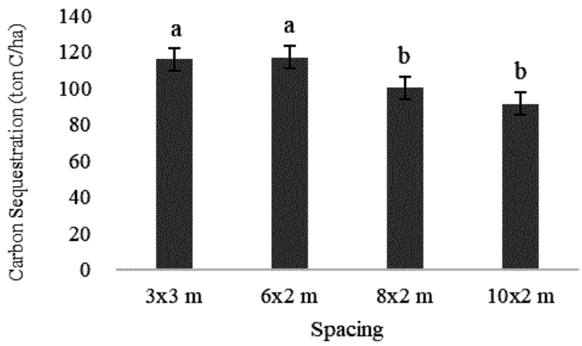

Figure 7. Means and standard deviation for carbon sequestration of each treatment. Different letters indicate significance among treatments at tα 0.05

The diameter increased with the wider spacing due to a lower stand density (Vigulu et al. 2019). Wide spacing produces a larger DBH (Rahmawati et al. 2021), and an initial stand density has a more substantial influence on tree diameter than height (Isaac-Renton et al. 2020). The wider spacing could increase crown, and root density due to less competition among trees in the forest area (Zahabu et al. 2015; Rahmawati et al. 2021). Competition between trees was related to the density of stands, where their closeness can increase the competition between them. The increase in planting density significantly affected the diameter of the canopy (Rahmawati et al. 2021) and DBH (Charlton et al. 2020). This confirmed that teak was intolerant of competition between trees (Pachas et al. 2019).

The spacing of 6 m x 2 m and 10 m x 2 m had the highest, and lowest tree height values of 19.7 m and 18.9 m (Figure 4). Narrow spacing has a higher tree height value than wide, except for spacing 3 m x3 m, and this is consistent with Berrocal et al. (2020), where stand density also showed a statistically significant effect not only with DBH but also with high growth (Berrocal et al. 2020). Differences in height growth in teak were influenced by site quality (Cardoso et al. 2013; Medeiros et al. 2018) and genetics (Pachas et al. 2019).

On the other hand, the wide spacing reduced bole height (Figure 5). The narrow spacing, i.e. 3 m x 3 m and 6 m x 2 m, has a higher bole height than the wider spacing (8 m x 2 m and 10 m x 2 m). The wide spacing not only reduced the bole height but also increased the branching angle (Rahmawati et al. 2021). This would affect larger wood defects, thereby reducing the wood quality due to increasing branch and knot diameters (Isaac-Renton et al. 2020). Thus, maintenance pruning should be conducted on a wider spacing clonal teak plantation to produce wood with fewer knot defects, promote straight, and increase the economic value of the remaining teak stands (Thulasidas and Bhat 2012; Shukla and Viswanath 2014; Budiadi et al. 2017; Seta et al. 2021).

Moreover, the wider spacing would also reduce the volume, and carbon sequestration per hectare of clonal teak plantation due to the low stand density per hectare (Figures 6, and 7). Even though, for each individual, the volume and carbon sequestration of wide spacing is greater than the narrow spacing due to the difference in DBH among individuals (Ruslim et al. 2021). At 8 years old, our teak clones have 91-116 C ton/ha with the highest at a stand density of 625 per hectare. Meanwhile, the total carbon stock of teak plantation propagated by seed at the same stand density was 220 C ton/ha at 35 years (Boonyanuphap and Kongmeesup 2016). It suggested that clonal teak plantation increased the carbon stored in the forest plantation that could contribute to reducing forest emissions as climate change mitigation (Zeng et al. 2018; Pandey et al. 2019).

Effect of planting spacing for cloned teak heartwood formation

Our results showed that spacing had no significant effect on wood's physical and mechanical properties (Table 2). The highest percentage of heartwood at a spacing of 6 m x 2 m (40.95%) did not differ much from 10 m x 2 m (40.86%). Meanwhile, the lowest percentage of heartwood was at a spacing of 3 m x 3 m (31.09%) (Table 3). The heartwood parameter was an important value for teak because of the aesthetic properties desired by consumers (Moya and Perez 2008). In addition, the heartwood is a naturally durable part of the wood that is not susceptible to organic destruction (Anish et al. 2015). It was also an important factor in determining teak wood quality (Kokutse et al. 2004; Anish et al. 2015), with a high selling price (Moya et al. 2014; Amoah and Stephen 2019; Seta et al. 2021).

The range of clonal teak heartwood formation in our research was 31.09-40.86% at 8 years after planting. Meanwhile, Basri and Wahyudi (2012) reported that the percentage of clonal teak heartwood in spacing 3 m x 3 m was 25% at 9 years old after planting. Moreover, the heartwood percentage on teak plantations propagated by seed in spacing 2 m x 2 m; 3m x 3 m; and 4 m x 4 m in LFP were 24%; 27%; and 31% at 14-year-old teak plantations (Zahabu et al. 2015) that was not significantly different among spacing. Furthermore, the heartwood percentage of 40-year-old teak plantation propagated by seed was higher than that of 10-year-old clonal teak (Rizanti et al. 2018), but at the same age, clonal teak has a higher heartwood percentage than teak plantation propagated by seed (Krisdianto and Sumarni 2006; Hidayati et al. 2015). It indicated that the heartwood formation was affected by tree age, and soil fertility (Amoah and Stephen 2019). Thus, the highest percentage of heartwood tends to have better teak quality, specifically its physical properties (Woesono 2011) that would increase with age and DBH increment (Tewari and Mariswamy 2013).

Table 2. Result of variance analysis of spacing effects on wood quality

Wood quality	Source: Spacing (n=3) Mean square	F
Physical properties		
Wood density	0.001	0.679^{ns}
Heartwood percentage	67.990	1.733^{ns}
Mechanical properties		
Static bending strength:		
MOE	84955	2250^{ns}
MOR	237.500.762	0.495^{ns}
Compressive Strength:		
MCS	19.423	2.293^{ns}

Note: MOE: Modulus Elasticity; MOR: Modulus Rupture; MCS: Compression parallel to grain: Maximum Crushing Stress; ns: non significant

Table 3. Mean values for physical properties of clonal teak

Physical properties	Value	Spacing			
		10m x 2m	8m x 2m	6m x 2m	3m x 3m
Heartwood percentage (%)	Mean	40.86	40.62	40.95	31.09
	SD	2.72	7.73	7.06	6.32
Wood density (gr/cm^3)	Mean	0.48	0.46	0.45	0.45
	SD	0.01	0.04	0.03	0.03

Note: SD: Standard Deviation

Table 4. Mean values for mechanical properties of clonal teak

Mechanical properties	Value	Spacing (m^2)			
		10 x 2	8 x 2	6 x 2	3 x 3
MOE (N/mm^2)	Mean	8219.83	7939.35	8430.19	8590.11
	SD	561.84	208.94	403.82	1182.24
MOR (N/mm^2)	Mean	60.29	55.52	67.14	65.71
	SD	5.86	8.08	5.51	4.58
MCS (N/mm^2)	Mean	28.19	31.12	33.75	33.32
	SD	4.19	2.29	2.28	2.44

Note: MOE: Modulus Elasticity; MOR: Modulus Rupture; MCS: Compression parallel to grain; SD: standard deviation

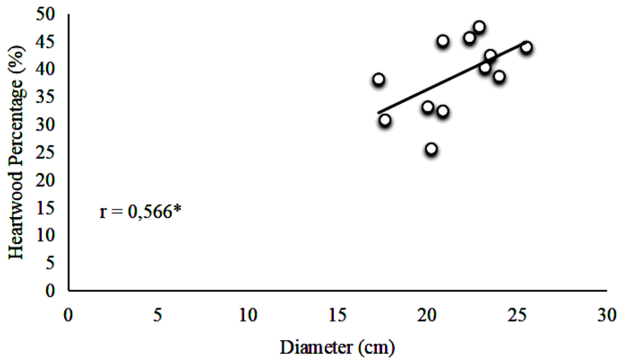

Figure 8. Relationship between diameter and heartwood percentage of four spacing. Indicate significance at the 5% level

However, an 8-year-old clonal teak plantation with a large diameter did not produce the highest percentage of heartwood because it was categorized as juvenile growth (Moya et al. 2014). Therefore, there was no significant difference between spacing. Instead, the percentage was significantly and positively correlated with a diameter (Figure 8). This research is in line with previous research, where the percent of heartwood and DBH were positively and significantly correlated in young trees (Kokutse et al. 2004; Moya et al. 2014). On the other hand, the heartwood percentage was also affected by the stand density and the tree's age (Moya and Perez 2008).

Moreover, wood density showed that the wider the spacing, the higher the density, and different spacing on teak had no significant effect on wood density (Moya et al. 2014). For example, the spacing of 10 m x 2 m had the highest wood density (0.48 gr/cm^3), while the value at a spacing of 8 m x 2 m; 6 m x 2 m; 3 m x 3 m were 0.46 gr/cm^3; 0.45 gr/cm^3, and 0.45 gr/cm^3, respectively (Table 3). The wood density of our research was characterized as the medium category for class III (Seng 1990). Therefore, wood with the wood density of class III has been included in the requirements for furniture raw materials (Fernandes and Andrian 2013). At 9 years old in Central Java, Indonesia, the wood density of teak wood was 0.51 gr/m^3 (Basri and Wahyudi 2012). It suggested that the density would increase with the tree's age (Hidayati et al. 2015; Gaitan-alvarez et al. 2019). This property can be influenced by site quality, geographical location, and climate (Wanneng et al. 2014). Wood density is a significant variable in determining the quality parameters of teak, both in terms of physical and mechanical properties, because these two variables serve to protect the value and use of wood and overshadow the importance of others (Shukla and Viswanath 2014; Sinha et al. 2017). In addition, one of the physical properties had a significant impact on yield, processing, and wood quality, specifically wood strength (Shi et al. 2007; Marsoem et al. 2014).

Effect of spacing on mechanical properties of wood

Spacing had no significant effect on all variables of the mechanical properties of wood. Spacing of 6 m x 2 m dominated the highest values for static bending strength (MOR) and parallel compressive strength (MCS), each of which was 67.14 N/mm^2; 33.75 N/mm^2 (Table 4).

Static bending strength (MOE) was the highest at the spacing (3 m x 3 m), which was 8590.11 N/mm^2, while MOR was at a spacing of 6 m x 2 m (Table 4). The spacing of 10 m x 2 m was the lowest of MOE and MOR. It means that wider spacing can increase diameter growth, but can relatively reduce the mechanical properties of wood (Woesono 2011; Yunianti et al. 2011). The mechanical properties (MOE and MOR) of a 40-year-old teak plantation propagated by seed were higher than that of 10-year-old fast-growing teak (Rizanti et al. 2019). However, teak in the planted forest has almost the same properties as teak from nature at the same age, especially in the strength of wood (Thulasidas and Baillères 2017). It suggested that increasing age would improve MOE and MOR due to incrementing cellular wall thickness and reducing vessel frequency (Viquez and Perez 2005; Moya and Perez 2008).

Furthermore, the mechanical parameters were carried out in a static bending test as the indicators in determining the strength of wood, and some of the outputs were MOE and MOR as the most significant mechanical properties (Thulasidas and Bhat 2012). Wood treated with four spacing had MOE and MOR in the class IV and III categories. This was included in class III and IV strength for a spacing of 10 m x 2 m (Seng 1990) when viewed from the compression strength parallel to the fiber (MCS). The clonal teak wood at 8 years old probably could be acceptable for a variety of wood products for both outdoor and indoor applications (Wanneng et al. 2014), even though the utilization would be restricted to some extent due to the domination by sapwood with a high amount of juvenile wood (Rizanti et al. 2018).

Implication for sustainable forest management of clonal teak in monsoon forest

Lowland forest in Java is dominated by teak plantations where the coverage area of teak plantations was 67% of Java's forest production area (Perhutani 2014). The teak forest continues to decline due to illegal logging or expansion of agricultural areas (Tsujino et al. 2016). Rehabilitation efforts were urgently needed to cover the land, one of which is the use of selected clonal teak. Clonal teak propagated by vegetative propagation has succeeded in increasing land productivity (Wirabuana et al. 2022) and supporting the rehabilitation of degraded lowland monsoon forests (Hardiwinoto et al. 2021).

Sustainable management of clonal teak plantations could be achieved by increasing growth, forest productivity, and teak wood quality. For instance, the clonal teak plantation would produce carpentry wood. Thus, it needed a large diameter (Damayanti et al. 2018) and good wood quality (Thulasidas and Baillères 2017). In this regard, spacing management was the key success to improving tree growth and maintaining the wood quality. On the other hand, a wide spacing would result in a large DBH and decrease volume per unit area but would result in a low bole height. For this reason, pruning maintenance activity was an alternative to producing a high bole height (Pramono et al. 2010) so that it would minimize wood defects and produce good wood quality. Thus, the growth of the clonal teak was faster than unimproved seed teak (Na'iem 2012), so it would accelerate the cover land cover, carbon sequestration, and sustainable forest management of lowland monsoon forest (Hardiwinoto et al. 2021).

In conclusion, spacing significantly affected DBH, tree height, bole height, carbon sequestration, and the volume of teak clones aged 8 years. This means the wider the spacing, the larger the diameter, but the lower the volume per hectare, the lower bole height, and the lower carbon sequestration. Spacing had no significant effect on the physical and mechanical wood properties, and the quality test showed that the narrow spacing (6 m x 2 m) dominated the highest values, specifically the bending strength and compressive strength parallel to the grain. The percentage of heartwood was higher at 6 m x 2 m; 10 m x 2 m; and 8 m x 2 m spacing compared to 3 m x 3 m. The quantity of cloned teak wood with wide spacing was beneficial in diameter growth.

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