

Evaluation of differences in radial variations of wood properties among families for producing the next-generation *Acacia mangium* in Indonesia

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Abstract

To produce the next generation of *Acacia mangium* Willd. in Indonesia, radial variations of wood fiber and vessel element length, air-dry density, modulus of elasticity (MOE), modulus of rupture (MOR), and compressive strength parallel to the grain were investigated for 20 half-sib families of the third-generation trees. A radial variation modeling approach was applied to detect the differences in the radial variation of wood properties among families. In addition, differences were also evaluated in the boundary position between core and outer wood among families. Based on the results of radial variation modeling, all measured properties showed the lowest values near the pith and increased toward the bark side. However, radial positions showing large among-family variations differed among the wood properties: pith side for air-dry density and MOE, and bark side for cell length and compressive strength. The boundary positions between the core and outer wood, determined by radial variation of multiple properties, ranged from 6.6 to 7.0 cm from the pith for 20 families. However, no significant differences in the boundary positions were found among families, suggesting that the timing of xylem maturation has a species-specific value. Based on the results, it is concluded that the next-generation families with both superior radial growth and high physical and mechanical properties of the wood can be produced from the third-generation *A. mangium* in Indonesia without considering the differences in the maturation timing of the xylem among families.

Keywords: air-dry density, cell length, compressive strength, MOE, MOR, heritability

Introduction

Acacia mangium Willd. belongs to Fabaceae and is a fast-growing species native to the Indonesian islands of Sula, Seram, Aru and Irian Jaya, Papua New Guinea, and northeastern Queensland, Australia (Lemmens et al., 1995; Krisnawati et al., 2011). It can be planted in various soil types with different pH compared to other tropical fast-growing tree species, such as *Acacia auriculiformis* A. Cunn. ex Benth. and *Eucalyptus urophylla* S. T. Blake (Kim et al., 2009; Hai et al., 2015). Therefore, it is widely used for commercial large-scale afforestation in tropical regions, mainly Southeast Asian countries and Africa (Hegde et al., 2013). These large plantations have been producing wood at short harvesting periods, and the wood has been used mainly as a raw material for pulp and paper (Hegde et al., 2013). However, pulp and paper materials are traded at lower prices than solid wood for structural lumber and furniture materials. Thus, final products from *A. mangium* have been tried to switch from pulp and paper to solid wood that is usually treated with high economic values (Wong et al., 1988; Ishiguri et al., 2013; Hidayati et al., 2019).

The Japan International Cooperation Agency (JICA) started a technical cooperation project on forest tree improvement in Indonesia in 1992 (Nirsatmanto et al., 2004; Kurinobu, 2005; Nirsatmanto, 2012). In this project, seedling seed orchards were established in several areas, and the sub-line method was adopted to repeat selection in the breeding

strategy (Kurinobu, 2005). The orchards were grouped based on two different seed origins, Papua New Guinea (PNG; sub-lines A and B) and Far North Queensland (FNQ; sub-lines C and D), Australia. In 1994, seedling seed orchards of the first-generation *A. mangium*, consisting of the four sub-lines, were established in South Kalimantan (sub-lines A and C) and South Sumatra (sub-lines B and D). The seedling seed orchards of the second generation were established in South Kalimantan in 2001, using the seeds collected from ten superior families in each of the four sub-lines of the first-generation orchards. Subsequently, ten families with superior growth characteristics per sub-line were selected from the second-generation seedling seed orchards for collecting the seeds. Using these third-generation seeds, a seedling seed orchard was established in 2012 in Wonogiri, Central Java, in Indonesia (Masendra et al., 2023). The criteria for selecting superior families in the first and second generations of this breeding program were mainly growth characteristics, such as diameter at breast height, tree height, and stem straightness (Nirsatmanto et al., 2003, 2004; Kurinobu, 2005; Nirsatmanto, 2012; Nirsatmanto and Sunarti, 2019). Nirsatmanto et al. (2003) reported that the diameter at breast height and tree height of the first generation of *A. mangium* grown in South Kalimantan and South Sumatra were larger by 10 to 15 % than those in local selection. They also reported that the genetic gains of growth characteristics in *A. mangium* of the second-generation seedling seed orchard in South Kalimantan were approximately 3 % for tree height, 5 % for diameter of breast height, and 4 % for stem straightness compared to those of trees from the same origin planted in the same place (Nirsatmanto et al., 2004).

Tree breeding of the fast-growing tree species in the tropics, including *A. mangium*, has been mainly based on growth characteristics, but the wood property of standing trees has also been non-destructively evaluated using stress-wave velocity and Pilodyn penetration (Raymond, 2002; Hidayati et al., 2019; Masendra et al., 2023). In the third generation of *A. mangium* planted in Indonesia, stress-wave velocity and Pilodyn penetration have also been investigated (Hidayati et al., 2019; Masendra et al., 2023). Masendra et al. (2023) reported that the broad-sense heritability of stress-wave velocity and Pilodyn penetration were 0.261 – 0.715 and 0.171 – 0.484, respectively, in families within four sub-lines of the third generation of ten-year-old *A. mangium*. These broad-sense heritability values were higher than those in diameter at breast height (0.014 – 0.444) and tree height (0.000 – 0.208), suggesting that the among-family variations in wood density and Young's modulus of stems were greater than those growth characteristics for the third-generation *A. mangium*. Unfortunately, they did not directly measure the density and Young's modulus of wood in these breeding materials. Thus, wood properties should be directly measured in the third generation of *A. mangium* in Indonesia to clarify the inheritance of wood properties in this species.

Wood properties, such as cell length, density, and strength, vary from pith to bark; these changes are called radial variations (Zobel and van Buijtenen, 1989). Radial variations of wood properties have also been investigated in *A. mangium* (Yamamoto, 1998; Fujimoto et al., 2002; Honjo et al., 2005;

Hasegawa et al., 2009; Kim et al., 2009; Kojima et al., 2009; Makino et al., 2012; Nugroho et al., 2012; Ngadianto et al., 2020; Duong et al., 2022). The results revealed that the cell length, wood density, and mechanical properties showed lower values near the pith, and then increased toward the bark side (Yamamoto, 1998; Fujimoto et al., 2002; Honjo et al., 2005; Hasegawa et al., 2009; Kim et al., 2009; Kojima et al., 2009; Makino et al., 2012; Nugroho et al., 2012; Ngadianto et al., 2020). However, the effects of genetics on radial variation patterns in each wood property have yet to be clarified in *A. mangium*. In addition, the boundary between core and outer wood (similar to juvenile and mature wood in softwoods) in *A. mangium* has been determined by the radial variations of wood properties (Makino et al., 2012; Nugroho et al., 2012; Ngadianto et al., 2023). The previous researchers reported that the boundary positions were around 5 to 6 cm from the pith. However, it needs to be clarified whether the boundary positions from the pith differ among families or not in *A. mangium*.

The objectives of our study are to select families in the current third generation for producing the next generation of *A. mangium* with superior growth characteristics and wood property concerning solid wood production. In the present study, radial variations of cell length, air-dry density, bending properties, and compressive strength were investigated for 100 trees of the third-generation *A. mangium* from 20 families planted in the seedling seed orchard at Wonogiri, Central Java, in Indonesia. The radial variation was evaluated by the nonlinear mixed-effect models in each wood property. The correlations between growth characteristics and wood properties were also assessed. In addition, among-family variations of the boundary positions between the core and outer wood were evaluated in *A. mangium*. Based on the results, a possibility was discussed for producing the superior families of the fourth generation of *A. mangium* in Indonesia.

Material and methods

Materials

The third-generation *A. mangium* trees planted in the seedling seed orchard at Wonogiri, Special Purpose Forest Area in Alas Ketu, Wonogiri Regency, Central Java, Indonesia (S7°47' and E110°56') were used in the present study. The seedling seed orchard was established in 2012 using 40 families from four sub-lines (Figure 1, Nirsatmanto et al., 2015; Masendra et al., 2023). A total of 100 trees from five families with superior growth characteristics in each sub-line were harvested in June 2022 (10 years in tree age). Table 1 shows the mean and standard deviation of stem diameter at 1.3 m above the ground and tree height for all harvested trees. After felling, 30-cm logs were collected from 1.0 to 1.3 m above the ground in each tree. The log was sawn into a 30 mm thick radial board with the pith. The board was air-dried in the laboratory at an ambient temperature. After air-drying, a strip with the pith (10 mm in thickness) was collected from the board for measuring cell length. After that, the board was cut again in half at the pith position to prepare samples for mechanical testing of wood.

Table 1

Statistical values and broad-sense heritability of each property. Note: number of sample trees = 100 trees. SD, standard deviation; H^2 , broad-sense heritability; SE, standard error of H^2 ; MOE, modulus of elasticity; MOR, modulus of rupture. The mean and standard deviation of stem diameter and tree height in 100 trees from 20 families were recalculated using the data on 766 trees from 40 families in a previous paper (Masendra et al., 2023). The values of mean and SD in each wood property were calculated using individual tree values (average value from pith to bark side in each tree).

Property	Statistical value				Heritability	
	Minimum	Mean	Maximum	SD	H^2	SE
Stem diameter (cm)	9.5	19.1	29.5	4.5	0.762	0.440
Tree height (m)	7.0	14.3	27.0	4.4	0.033	0.307
Wood fiber length (mm)	0.93	1.07	1.21	0.06	0.293	0.362
Vessel element length (mm)	0.24	0.28	0.32	0.02	0.952	0.036
Air-dry density (g/cm ³)	0.36	0.51	0.63	0.05	0.840	0.448
MOE (GPa)	6.23	8.60	11.07	1.03	0.719	0.432
MOR (MPa)	55.8	89.1	123.3	11.8	0.531	0.404
Compressive strength (MPa)	36.2	48.3	60.3	4.8	0.461	0.392

Table 2

Fourteen radial variation models and their AIC values in each wood property. Note: Eq., equation number; AIC, Akaike Information Criterion; WFL, wood fiber length; VEL, vessel element length; AD, air-dry density; MOE, modulus of elasticity; MOR, modulus of rupture; CS, compressive strength; y_i , the value of each property at the i th cm from the pith; y_{ij} , the value of each property at the i th cm from the pith in the j th family; x_i , the i th cm from the pith; x_{ij} , the i th cm from the pith in the j th family; a_0 , a_1 , b_0 , b_1 , and b_2 , fixed-effect parameters; $Family_{0j}$, $Family_{1j}$, and $Family_{2j}$, random effect parameters of family j ; e_i and e_{ij} , residuals; –, the model failed to converge. The value with underline indicates the model with minimum AIC value in a property.

Eq.	Regression formula	AIC					
		WFL	VEL	AD	MOE	MOR	CS
1	$y_i = a_i + e_i$	-599.88	-2625.45	-1230.40	3518.44	7039.65	5709.27
2	$y_{ij} = a_i + Family_{ij} + e_{ij}$	-592.72	-2647.52	-1250.79	3513.72	7032.08	5703.93
3	$y_i = a_0 x_i + a_1 + e_i$	-1351.05	-3309.95	-1843.88	2820.44	6443.95	5199.91
4	$y_{ij} = (a_0 + Family_{0j}) x_{ij} + a_1 + e_{ij}$	-1372.71	-3380.14	-1857.33	2785.75	6412.50	5157.45
5	$y_{ij} = a_0 x_{ij} + a_1 + Family_{ij} + e_{ij}$	-1351.64	-3358.25	-1865.72	2793.63	6417.84	5172.33
6	$y_{ij} = (a_0 + Family_{0j}) x_{ij} + a_1 + Family_{1j} + e_{ij}$	-1371.08	-3391.61	-1865.65	2782.52	6412.69	5158.75
7	$y_i = b_0 x_i / (b_1 + x_i) + b_2 + e_i$	-1655.86	-3357.98	-1977.94	2671.80	–	5059.93
8	$y_{ij} = (b_0 + Family_{0j}) x_{ij} / (b_1 + x_{ij}) + b_2 + e_{ij}$	-1689.70	-3437.55	-2032.27	–	–	<u>5004.24</u>
9	$y_{ij} = b_0 x_{ij} / (b_1 + Family_{ij} + x_{ij}) + b_2 + e_{ij}$	-1669.98	–	-2027.42	2624.37	<u>6170.81</u>	–
10	$y_{ij} = b_0 x_{ij} / (b_1 + x_{ij}) + b_2 + Family_{2j} + e_{ij}$	-1678.15	-3424.99	<u>-2034.85</u>	<u>2623.10</u>	–	5013.94
11	$y_{ij} = (b_0 + Family_{0j}) x_{ij} / (b_1 + Family_{1j} + x_{ij}) + b_2 + e_{ij}$	–	–	–	–	–	5006.78
12	$y_{ij} = (b_0 + Family_{0j}) x_{ij} / (b_1 + x_{ij}) + b_2 + Family_{2j} + e_{ij}$	<u>-1709.09</u>	<u>-3442.52</u>	–	2627.10	–	5007.26
13	$y_{ij} = b_0 x_{ij} / (b_1 + Family_{1j} + x_{ij}) + b_2 + Family_{2j} + e_{ij}$	–	–	–	–	–	–
14	$y_{ij} = (b_0 + Family_{0j}) x_{ij} / (b_1 + Family_{1j} + x_{ij}) + b_2 + Family_{2j} + e_{ij}$	–	–	–	–	–	–

Wood properties

In the present study, wood fiber length, vessel element length, air-dry density, static bending properties, and compressive strength parallel to the grain were measured as wood properties. Wood fiber length and vessel element length were measured using the strips. Small stick samples (1 x 1 x 5 mm) were taken from this strip every 1 cm from the pith to the bark. As a result, the stick samples were collected from 761 radial positions in 100 trees. The sample was put in a test tube and macerated with Schultze's solution (35 % nitric acid solution and 6 g of potassium chlorate) under heating for 1 hour at 70° C by a water bath (SB-450, EYELA, Tokyo, Japan). After heating, they were washed several times with distilled water. The macerated

sample was placed on a glass slide and mounted with a cover slip with a few drops of 75 % (v:v) glycerin aqueous solution. The macerated samples were projected onto the screen of a profile projector (V-12B, Nikon, Tokyo, Japan) with x 100 magnification, and the cell length was measured using a digital caliper (CD-15CX, Mitutoyo, Kawasaki, Japan). Cell length in each radial position was measured for 50 wood fibers and 30 vessel elements, respectively, and the average value was calculated as the representative value of the radial position.

Air-dried radial boards (30 mm in thickness) were planed into 10 mm in thickness to prepare the specimens for static bending test (10 [R] x 10 [T] x 160 [L] mm) and compressive test parallel to the grain (10 [R] x 10 [T] x 30 [L] mm). The specimens

without severe defects were successively obtained from pith to bark. A total of 743 specimens were obtained for both tests. The specimens were kept in an environmental chamber (KCL-2000, EYELA, Tokyo, Japan) at 20 °C and 65 % relative humidity for at least one week before the testing.

The three-pointed load static bending tests were performed using a universal testing machine (MSC-5/500-2, Tokyo Testing Machine, Tokyo, Japan) with a span of 140 mm and a loading speed of 2 mm/min. Load and deflection data were recorded on a personal computer connected to the testing machine. Using the data, the modulus of elasticity (MOE) and modulus of rupture (MOR) were calculated by the following formula (1 and 2):

$$\text{MOE (GPa)} = \frac{\Delta P l^3}{4\Delta Y b h^3} \times 10^{-3} \quad (1)$$

$$\text{MOR (MPa)} = \frac{3P_m l}{2bh^2} \quad (2)$$

where ΔP (N) is the difference in the load between 10 and 40 % values of the maximum load, l (mm) is the length of span, ΔY (mm) is deflection due to ΔP , b (mm) is the width of the specimen, h (mm) is the height of the specimen, and P_m (N) is the maximum load. After testing, a small block (10 [R] × 10 [T] × 20 [L] mm) without any visible defects was taken from each specimen to determine the moisture content and density at the bending test.

Compressive strength parallel to the grain was measured using a universal testing machine (RTF-2350, A&D, Tokyo, Japan) at a 0.5 mm/min loading speed. The compressive strength parallel to grain (σ) was calculated using the following formula (3):

$$\sigma \text{ (MPa)} = \frac{P}{A} \quad (3)$$

where P (N) is the maximum load and A (mm²) is the cross-sectional area of the specimen.

Data analysis

A statistical analysis software (R version 4.3.2, R Core Team, 2023) was used for the analysis. Linear or nonlinear mixed-effects models were developed to clarify the radial variation of each wood property and its among-family variation. The models were developed using the lmer package (Bates et al., 2015) and the nlme package (Pinheiro and Bates, 2000). As the regression models for radial variation of wood properties, two equations (linear and Michaelis-Menten equations) were used (Table 2). In the models for explaining radial variations of wood properties, distance from the pith was regarded as the explanatory variable, and family was considered a random effect. Of the 14 models, the model showing the lowest Akaike Information Criterion (AIC, Akaike, 1998) was regarded as the best one. Based on the selected radial variation model in each wood property, the variance component ratio (%) of the family to the total variance was calculated.

The variance component of the family in each measured property was estimated using the breedR package (Muñoz and

Sanchez 2020). The variance components in each property were estimated using the following linear model (4):

$$Y_{ij} = \mu + F_j + e_{ij} \quad (4)$$

where Y_{ij} is the individual mean of property at the i th tree of the j th family, μ is the mean value, F_j is the additive genetic effect of the j th mother trees, and e_{ij} is residual.

The broad-sense heritability of each wood property was estimated to assess the magnitude of genetic effects. It was calculated by the following formula (5):

$$H^2 = \sigma_f^2 / (\sigma_f^2 + \sigma_e^2) \quad (5)$$

where H^2 is broad-sense heritability, and σ_f^2 is the family variance component, and σ_e^2 is the residual variance component.

To evaluate the relationships between measured properties, the phenotypic and genetic correlations were calculated between stem diameter at 1.3 m above the ground, tree height, stress-wave velocity of stems, or Pilodyn penetration, and each wood property. The data of stress-wave velocity of stems and Pilodyn penetration were cited from the previous study (Masendra et al., 2023). Genetic correlations were calculated as Pearson's correlation coefficients of the breeding values in each measured property (Hiraoka et al., 2019; Hanaoka and Kato, 2022).

Figure 1 represents the methods for determining the boundary between core and outer wood. The method was modified from that described by Ngadiant et al. (2023). First, each wood property was estimated at 0.1-cm intervals using the selected model (Table 2) with the fixed-effect parameters (Table 3) and random effect of each family (Figure 1a). Then, the increasing ratio was estimated at 0.1-cm intervals in all properties for each family (Figure 1b). The data for increasing ratios of all properties were regressed to the following exponential model with plateau (formula [6]) and exponential model (formula [7]) at the family level (Figures 1c and 1d):

$$y_1 = a_1 b_1 x_1 + c_1 \quad (6)$$

$$y_2 = a_2 b_2 x_2 \quad (7)$$

where c_1 is the plateau value in the exponential function model. When y_2 in formula (7) equaled c_1 in formula (6), x (distance from the pith) was regarded as the boundary between the core and outer wood (Figure 1e).

Results

The mean values of wood fiber length, vessel element length, air-dry density, MOE, MOR, and compressive strength for 100 trees were 1.07 mm, 0.28 mm, 0.51 g/cm³, 8.60 GPa, 89.1 MPa, and 48.3 MPa, respectively (Table 1). The broad-sense heritability values were 0.293 for wood fiber length, 0.952 for vessel element length, 0.840 for air-dry density, 0.719 for MOE, 0.531 for MOR, and 0.461 for compressive strength (Table 1).

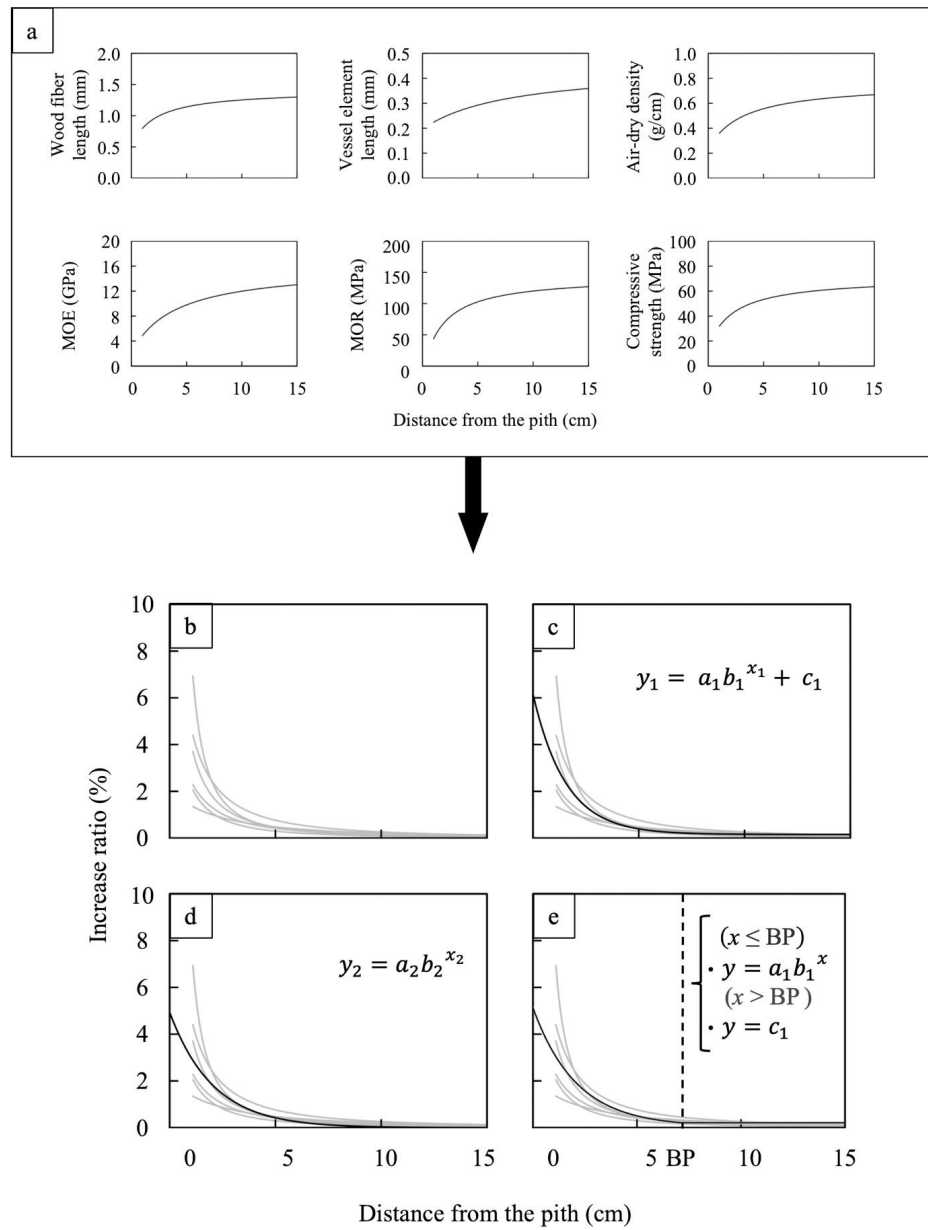


Figure 1

A modified estimation method of radial position where xylem maturation starts. Note: The method used in the present study is modified from that described by Ngadianto et al. (2023). a, a regression curve of each property was based on the selected model (Table 2) with fixed-effect parameters (Table 3) and random-effect parameters of the family. b, the absolute values of the increase ratio were estimated at 0.1-cm intervals based on the fixed-effect parameter in the selected model for each wood property. c, an exponential model with a plateau was fitted to the data to increase the ratio in each property. d, an exponential model was fitted to the data to increase the ratio. e, the intersection of the two equations was defined as the boundary between core and outer wood. BP, the value of the distance from the pith as the boundary position between core and outer wood.

Table 3

Fixed and random effects of the selected model for explaining radial variation in each wood property. Note: Eq., selected equation number listed in Table 2; SE, standard error; σ^2 , variance component; VC, variance component ratio; MOE, modulus of elasticity; MOR, modulus of rupture; $Family_{0j}$, $Family_{1j}$, and $Family_{2j}$, random effect of family for asymptote, slope, and intercept; e_{ij} , residuals. The variance component ratio was calculated as the ratio of family or residual variance to the total variance. The equation of the selected model in each property is represented in Table 2.

Property	Eq.	Fixed effect					Random effect		
		Parameter	Estimate	SE	t-value	p-value	Parameter	σ^2	VC (%)
Wood fiber length	12	b_0	0.908	0.038	24.105	≤ 0.001	$Family_{0j}$	0.01805	61.3
		b_1	2.084	0.234	8.914	≤ 0.001	$Family_{2j}$	0.00583	19.8
		b_2	0.501	0.037	13.698	≤ 0.001	e_{ij}	0.00557	18.9
Vessel element length	12	b_0	0.250	0.019	12.994	≤ 0.001	$Family_{0j}$	0.001816	72.7
		b_1	7.945	1.351	5.880	≤ 0.001	$Family_{2j}$	0.000115	4.6
		b_2	0.196	0.005	39.689	≤ 0.001	e_{ij}	0.000568	22.7
Air-dry density	10	b_0	0.523	0.014	37.591	≤ 0.001	$Family_{2j}$	0.000544	13.7
		b_1	3.144	0.540	5.824	≤ 0.001	e_{ij}	0.003439	86.3
		b_2	0.236	0.021	10.994	≤ 0.001			
MOE	10	b_0	13.894	0.406	34.261	≤ 0.001	$Family_{2j}$	0.237	11.0
		b_1	4.012	0.626	6.411	≤ 0.001	e_{ij}	1.922	89.0
		b_2	2.061	0.426	4.835	≤ 0.001			
MOR	9	b_0	160.769	6.579	24.437	≤ 0.001	$Family_{0j}$	0.0565	0.0
		b_1	1.607	0.235	6.843	≤ 0.001	e_{ij}	237.3425	100.0
		b_2	-18.676	8.542	-2.186	0.029			
Compressive strength	8	b_0	56.256	2.157	26.079	≤ 0.001	$Family_{0j}$	17.9	27.5
		b_1	2.289	0.427	5.355	≤ 0.001	e_{ij}	47.1	72.5
		b_2	14.740	3.057	4.822	≤ 0.001			

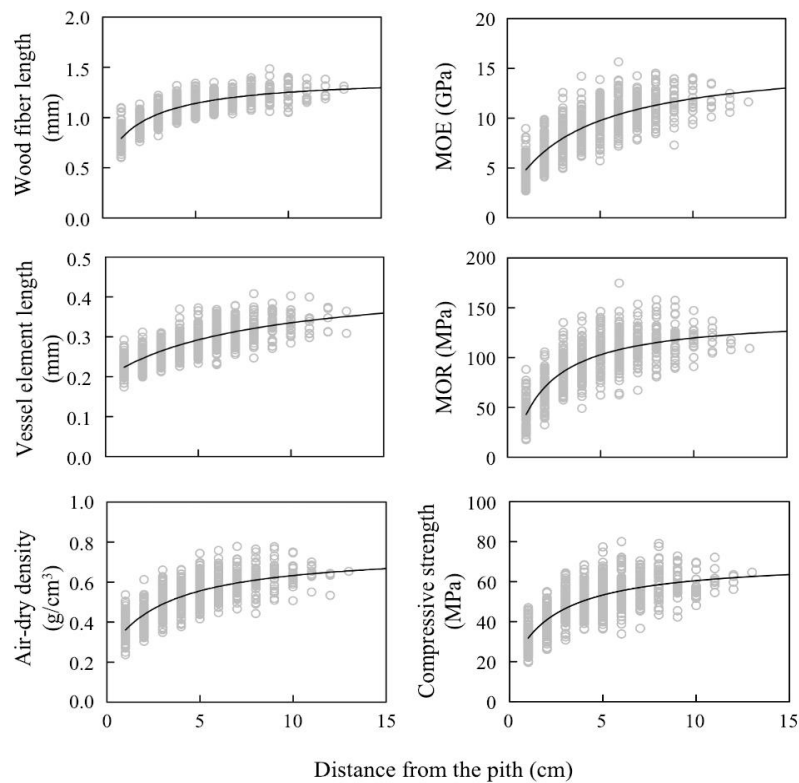


Figure 2

Radial variations of wood properties. Note: MOE, modulus of elasticity; MOR, modulus of rupture; circle, measured values; solid curve, regression curve based on the fixed-effects parameters (Table 3) in the selected model for each wood property (Table 2).

Of the 14 developed radial variation models, the selected models were Eq. 12 for wood fiber length and vessel element length, Eq. 10 for air-dry density and MOE, Eq. 9 for MOR, and Eq. 8 for compressive strength (Table 2). Figure 2 shows the regression curves for radial variations of wood properties based on the fixed-effects parameters of the selected model in each property (Table 3). For all properties, the lowest values were found near the pith and then increased toward the bark side (Figure 2). In the selected model of radial variation for each wood property, the variance component ratio of the family to the total variance was 81.1 % (61.3 % for *Family_{0j}* and 19.8 % for *Family_{2j}*) for the wood fiber length, 77.3 % (72.7 % for *Family_{0j}* and 4.6 % for *Family_{1j}*) for the vessel element length, 13.7 % for the air-dry density, 11.0 % for the MOE, 0.0 % for the MOR, and 27.5 % for the compressive strength (Table 3).

Significant positive phenotype correlations were obtained between stem diameter and all wood properties except for compressive strength (Table 4). On the other hand, no significant phenotypic correlations were found between tree height and each wood property. Significant positive genetic correlations existed between stem diameter and vessel element length or air-dry density and between tree height and MOR (Table 4).

The boundary position of each family determined by anatomical characteristics and wood properties was 6.7 to 7.0 cm from the pith (Figure 3). When the boundary position was determined by the regression curve with only fixed-effect parameters in the selected model (Tables 2 and 3), the boundary position was 6.8 cm from the pith (Figure 3).

Discussion

Mean values of wood properties

The comparison of mean values in wood properties in *A. mangium* is shown in Table 6. Although the planting place and ages of the sample trees were different, the value for each property obtained in present study was within the range of the values in the previous studies (Fujimoto et al., 2002; Chowdhury et al., 2005; Hasegawa et al., 2009; Makino et al., 2012; Nugroho et al., 2012; Jusoh et al., 2014; Ngadianto et al., 2020; Duong et al., 2022).

Radial variations of wood properties

Radial variations of wood properties in *A. mangium* trees growing in several countries have been reported by many researchers (Yamamoto, 1998; Fujimoto et al., 2002; Honjo et al., 2005; Hasegawa et al., 2009; Kim et al., 2009; Kojima et al., 2009; Makino et al., 2012; Nugroho et al., 2012; Duong et al., 2022; Ngadianto et al., 2023). Honjo et al. (2005) reported that wood fiber length was 0.5 – 0.6 mm near the pith and then gradually increased toward the bark, while vessel element length was stable from the pith to the bark in 2 to 13-year-old *A. mangium* planted in Indonesia and Malaysia. In addition, wood fiber length increased to 5 cm from the pith and then stabilized toward the bark in 23-year-old *A. mangium* planted in Indonesia (Nugroho et al., 2012). Similar radial variation patterns in wood fiber length and vessel element length reported by Honjo et al. (2005) and Nugroho et al. (2012) were also found in 4-year-old *A. mangium* planted in Vietnam (Kim et al., 2009), 11-year-old *A. mangium* planted in Indonesia (Hasegawa et al., 2009), and 11-year-old *A. mangium* planted in Malaysia (Kojima et al., 2009). Duong et al. (2022) found that air-dry density, MOE, and MOR in the bark side were higher than those near the pith in 5-year-old plantation trees of *A. mangium* in Vietnam. In addition, Ngadianto et al. (2023) reported that basic density, MOE, MOR, and compressive strength increased from the pith toward the bark for 7-year-old *A. mangium* planted in

Table 4

Phenotypic and genetic correlation coefficients between stem diameter or tree height, and each wood property. Note: r_p , phenotypic correlation coefficient; r_g , genetic correlation coefficient; MOE, modulus of elasticity; MOR, modulus of rupture. Values in parentheses indicate p -values. Underlined correlation coefficients indicate correlation coefficients with p -values less than 0.05. The values of stem diameter, and tree height were cited from Masendra et al. (2023).

Property	Stem diameter		Tree height	
	r_p	r_g	r_p	r_g
Wood fiber length	<u>0.57</u> (0.01)	0.38 (0.10)	0.04 (0.86)	−0.28 (0.23)
Vessel element length	<u>0.62</u> (0.00)	<u>0.48</u> (0.03)	0.25 (0.29)	0.23 (0.33)
Air-dry density	<u>0.70</u> (0.00)	<u>0.54</u> (0.02)	0.04 (0.86)	0.40 (0.08)
MOE	<u>0.58</u> (0.01)	0.40 (0.08)	0.01 (0.98)	0.12 (0.61)
MOR	<u>0.59</u> (0.01)	0.37 (0.10)	−0.01 (0.95)	<u>0.51</u> (0.02)
Compressive strength	0.28 (0.23)	0.10 (0.69)	0.03 (0.89)	0.09 (0.72)

Table 5

The boundary position between the core and outer wood in each family. Note: BP, Boundary position from the pith.

Family ID	$y = a_2 \cdot b_2^x$ ($x \leq BP$)	$y = c_1$ ($x > BP$)	BP (cm from the pith)
5	$y = 4.942 \cdot 0.612^x$	$y = 0.159$	7.0
6	$y = 5.690 \cdot 0.599^x$	$y = 0.171$	6.8
7	$y = 5.633 \cdot 0.598^x$	$y = 0.169$	6.8
9	$y = 5.803 \cdot 0.587^x$	$y = 0.165$	6.7
10	$y = 6.020 \cdot 0.589^x$	$y = 0.174$	6.7
12	$y = 5.308 \cdot 0.604^x$	$y = 0.164$	6.9
13	$y = 5.742 \cdot 0.584^x$	$y = 0.160$	6.6
14	$y = 5.845 \cdot 0.587^x$	$y = 0.166$	6.7
17	$y = 5.801 \cdot 0.592^x$	$y = 0.169$	6.7
19	$y = 5.787 \cdot 0.591^x$	$y = 0.168$	6.7
22	$y = 5.808 \cdot 0.589^x$	$y = 0.167$	6.7
25	$y = 5.682 \cdot 0.591^x$	$y = 0.165$	6.7
27	$y = 5.432 \cdot 0.604^x$	$y = 0.168$	6.9
28	$y = 6.042 \cdot 0.589^x$	$y = 0.173$	6.7
29	$y = 5.394 \cdot 0.599^x$	$y = 0.163$	6.8
32	$y = 5.710 \cdot 0.584^x$	$y = 0.159$	6.7
33	$y = 5.622 \cdot 0.595^x$	$y = 0.166$	6.8
35	$y = 5.270 \cdot 0.596^x$	$y = 0.156$	6.8
37	$y = 5.134 \cdot 0.604^x$	$y = 0.158$	6.9
38	$y = 5.731 \cdot 0.596^x$	$y = 0.169$	6.8

Table 6

Comparison of average values for wood properties in *A. mangium*. Note: WFL, wood fiber length; VEL, vessel element length; WD, wood density; MOE, modulus of elasticity; MOR, modulus of rupture; CS, compressive strength; ¹⁾, basic density; ²⁾, air-dry density measured by soft X-ray densitometry; ³⁾, air-dry density; ⁴⁾, compressive strength parallel to the grain under green condition.

Country	Tree age (year)	WFL (mm)	VEL (mm)	WD (g/cm ³)	MOE (GPa)	MOR (MPa)	CS (MPa)	Reference
	10	1.07	0.28	0.51	8.60	89.1	48.7	Present study
	7	–	–	0.43 ¹⁾	8.92	97.3	42.4	Ngadianto et al. (2020)
Indonesia	5 and 7	–	–	0.42 and 0.45 ¹⁾	–	–	30.0 and 32.8 ⁴⁾	Makino et al. (2012)
	23	0.89 to 0.94	–	0.56 to 0.60 ²⁾	–	–	–	Nugroho et al. (2012)
	11	1.12	–	–	–	–	–	Hasegawa et al. (2009)
Malaysia	7	0.93	–	0.46 ¹⁾	9.99	78.0	53.0	Jusoh et al. (2014)
	30	–	–	0.498 ¹⁾	12.2	106.5	59.4	Fujimoto et al. (2002)
Vietnam	5	–	–	0.473 ³⁾	7.70	75.89	–	Duong et al. (2022)
Bangladesh	10, 15, and 20	–	–	0.56 ¹⁾	–	–	–	Chowdhury et al. (2005)

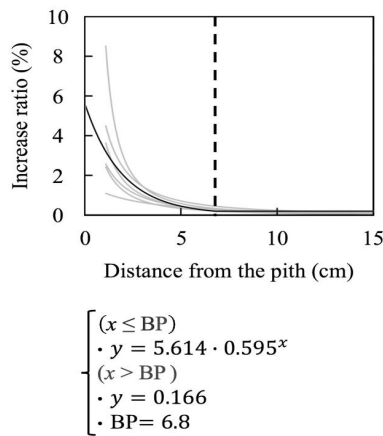


Figure 3

The boundary between core and outer wood calculated from fixed-effect parameters in the best model for each property listed in Table 2. Note: BP, the value of the distance from the pith as the boundary position between core and outer wood; y, increasing ratio; x, distance from the pith; Solid curve with gray color, the absolute changing ratios of each property. Solid curve with black color, regression curve of the increasing ratios for all properties.

al., 2012). In the present study, the model based on the Michaelis-Menten equation was selected as the best one for all wood properties (Eqs. 8, 9, 10, or 12 in Table 2), indicating that these properties increased near the pith and then stabilized toward the bark (Figure 2). Thus, the radial variation patterns of wood properties in the present study were similar to those in the previous studies (Fujimoto et al., 2002; Honjo et al., 2005; Hasegawa et al., 2009; Kim et al., 2009; Kojima et al., 2009; Makino et al., 2012; Nugroho et al., 2012; Ngadianto et al., 2023), except for vessel element length. Based on the results, the radial variation patterns of wood properties might be specific for *A. mangium*, regardless of differences in plantation area and tree age.

Among measured properties, the selected model for explaining the radial variation of wood fiber length and vessel element length included the random effect of the family in the asymptote and intercept (Eq. 12 in Table 2). The results indicate that wood fibers and vessel elements elongate from the pith and then converge the different lengths at the family level. In addition, the cell length at the innermost might differ among families. Thus, the differences between the innermost and the outermost values might differ among families for wood fiber and vessel element length. On the other hand, the model with a random intercept of the family (Eq. 10 in Table 2) was selected for air-dry density and MOE, suggesting that specific values are present at the family levels in these properties. In addition, the model including the random effect for the rate of change in the family (Eq. 9 in Table 2) was selected as the best one for MOR, indicating that the rate of change concerning the

distance from the pith differs among families for MOR. Furthermore, the radial variation of compressive strength was well fitted for the model with the random effect of the family in the asymptotic value (Eq. 8 in Table 2), suggesting that the compressive strength increases near the pith side and then reaches different values toward the bark side at the family levels. Based on the results, in the third generation of *A. mangium*, the genetic effects on the radial variation of wood properties might differ depending on the properties.

Broad-sense heritability and inheritance of radial variation

The values of narrow- and broad-sense heritability for growth characteristics and wood properties of *Acacia* species have been reported by many researchers (Nirsatmanto and Kurinobu, 2002; Ginwal and Mandal, 2004; Nirsatmanto, 2012; Hidayati et al., 2019; Chan and Isik, 2021; Masendra et al., 2023). In the previous study (Masendra et al., 2023) using the same samples as this study, the broad-sense heritability of stem diameter, tree height, stress-wave velocity, and Pilodyn penetration were 0.014 – 0.352, 0.000 – 0.208, 0.261 – 0.715, and 0.171 – 0.484 in each sub-line, respectively. As shown in Table 1 of this study, medium to high broad-sense heritability values were found in all wood properties. Based on these results, wood quality might be controlled by genetic factors as well as wood quantity in the third-generation *A. mangium*.

Among the selected models for radial variation of measured properties, the variance component ratio of the family was high for wood fiber length and vessel element length (Table 3). For these properties, the variance component ratio of the family in asymptotic value was higher than that in intercept (Table 3), suggesting that among-family variation is larger in converged values than the values at the pith side. In addition, the variance component of the family in compressive strength was medium value (27.5 %), indicating that the converged value at the bark side differs for compressive strength as well as cell length. On the other hand, small variance component ratios of the family were found in air-dry density (13.7 %) and MOE (11.0 %) (Table 3), suggesting that among-family variations of radial variation in these properties are smaller compared to those in cell length and compressive strength. In addition, the variance component ratio of the family was zero for MOR (Table 3). Thus, the radial variation of MOR might be almost the same regardless of the differences of families.

Relationships between stem diameter or tree height and each wood property

Significant positive phenotypic correlations were found between stem diameter and all wood properties at the family level, except for between stem diameter and compressive strength (Table 4), suggesting that the wood with longer wood fiber and higher wood density and strength properties can be obtained from the trees with larger diameter. This result might be due to the diameter-growth dependency of the secondary xylem maturation in *A. mangium*: wood properties vary in relation to diameter growth rather than cambial age (Honjo et al., 2005; Kojima et al., 2009; Makino et al., 2012). On the other hand, no significant phenotypic correlations were found bet-

ween tree height and all wood properties (Table 4), suggesting that height growth is independent of wood properties. Although p -values exceeded 0.05 in almost all genetic correlation coefficients, with a few exceptions, the trend of genetic correlation coefficients between measured properties was nearly the same as phenotypic correlation coefficients. Based on the results, the families with both superior radial growth and high physical and mechanical properties of wood can be selected in the third-generation *A. mangium* for developing the fourth generation to promote the solid wood production of this species.

Boundary position between core and outer wood

The boundary between the core and outer wood of *A. mangium* determined by wood properties has been reported by several researchers (Makino et al., 2012; Nugroho et al., 2012; Ngadianto et al., 2023). Makino et al. (2012) reported that the boundary position between the core and outer wood was 6 cm from the pith based on the basic density and compressive strength of 5- and 7-year-old *A. mangium* planted in Indonesia. In addition, the boundary determined by the radial variation of wood fiber length was 5 cm in 23-year-old *A. mangium* planted in Indonesia (Nugroho et al., 2012). Furthermore, Ngadianto et al. (2023) found that the radial position at 6.1 cm from the pith was the boundary between the core and the outer wood based on the basic density, MOE, MOR, and compressive strength for 7-year-old *A. mangium* planted in Indonesia. In the present study, the position of the boundary between core and outer wood ranged from 6.6 to 7.0 cm for 20 families of 10-year-old *A. mangium* planted in Indonesia (Table 5). The results obtained in the present study (Table 5 and Figure 3) were relatively far from the pith compared to those of the previous studies (Makino et al., 2012; Nugroho et al., 2012; Ngadianto et al., 2023). On the other hand, the variance component ratio of the family ranged from 0.0 (MOR) to 81.1 (wood fiber length) in the selected radial variation models of wood properties (Table 3). This result indicates that the radial variation patterns in wood properties varied among families, depending on the properties. However, as shown in Table 5, the boundary positions between core and outer wood were similar among the families. Based on these results, it is considered that the timing of xylem maturation might have a species-specific value regardless of the differences in families.

Effective family selection in relation to wood properties

Based on the results obtained in the present study, effective family selection in relation to wood properties was considered for *A. mangium*. The properties should be evaluated in two steps for effective family selection. First, the properties showing different intercepts among families, such as air-dry density and MOE, should be evaluated at the initial growth stage. Second, the properties showing different asymptotic values in each family, such as cell length and compressive strength, should be evaluated when the tree reaches a certain diameter (for example, the timing after reaching the size sufficient to be used as solid wood), because the among-family variations of

these properties might become large with radial growth. Therefore, the timing for the family selection in the *A. mangium* should be decided for each wood property considering the among-family variations for the radial variation of wood properties.

Conclusion

Radial variations of wood fiber length, vessel element length, air-dry density, MOE, MOR, and compressive strength were investigated for 100 trees of 10-year-old *A. mangium* from the 20 third-generation families planted in Wonogiri, Central Java, Indonesia. The model based on the Michaelis-Menten equation was selected as the best one explaining the radial variations of all wood properties, suggesting that these wood properties increased near the pith and then stabilized towards the bark. The random-effect parameters of the family in the selected model differed between properties: the asymptotic parameter for wood fiber length, vessel element length, and compressive strength, while the intercept parameter for air-dry density and MOE. On the other hand, the position of the boundary between core and outer wood estimated by radial variation models of multiple wood properties was similar among families (6.6 to 7.0 cm from the pith), indicating that the boundary value might be species-specific. Therefore, the timing of xylem maturation should not be included as a criterion in tree breeding for wood quality in *A. mangium*. Based on the results, the next generation *A. mangium* with superior growth characteristics and wood properties can be produced from the third-generation families in Indonesia.

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