



Among-family variations of chemical and Kraft-pulp properties in the heartwood of the third-generation *Acacia mangium* in Indonesia

Masendra^{1,2,3} · Ikumi Nezu¹ · Fanny Hidayati⁴ · Arif Nirsatmanto⁵ · Sri Sunarti⁵ · Surip⁶ · Dwi Kartikaningtyas⁶ · Jyunichi Ohshima¹ · Shinso Yokota¹ · Futoshi Ishiguri¹

Received: 22 June 2025 / Accepted: 4 November 2025 / Published online: 5 December 2025
© The Author(s) 2025

Abstract

The content of wood chemical components (extractives, ash, Klason lignin, and polysaccharides) and Kraft-pulp properties (yield and kappa number) were directly determined for the inner and outer heartwood of 10-year-old 20 open-pollinated families in the third-generation *Acacia mangium* in Indonesia. The results show that the extractives, Klason lignin, and α -cellulose contents of outer heartwood were higher than those of inner heartwood. Relatively higher variance components of family were observed for polysaccharides and Kraft-pulp yield. Significant positive phenotypic correlations were found between stem diameter and either basic density or α -cellulose content, as well as between Kraft-pulp yield and α -cellulose content. Meanwhile, significant negative correlations were found between Kraft-pulp yield and organic solvent extracts or Klason lignin. Therefore, it is concluded that families with larger stem diameters and higher α -cellulose contents tend to produce higher pulp yield.

✉ Futoshi Ishiguri
ishiguri@cc.utsunomiya-u.ac.jp

- ¹ School of Agriculture, Utsunomiya University, Utsunomiya 321-8505, Japan
- ² United Graduate School of Agricultural Science, Tokyo University of Agriculture and Technology, Fuchu, Tokyo 183-8509, Japan
- ³ Department of Bioresources Technology and Veterinary, Vocational College, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia
- ⁴ Faculty of Forestry, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia
- ⁵ National Research and Innovation Agency, Yogyakarta 55281, Indonesia
- ⁶ Forest Tree Seed Center Regional 3, Indonesian Ministry of Forestry, Yogyakarta 55582, Indonesia

Introduction

Acacia mangium Willd. is a fast-growing species and belongs to Fabaceae (Lemmens et al. 1995). This species is naturally distributed in the Sula Islands, Seram, Aru Islands, Irian Jaya, Western Province of Papua New Guinea, and north-eastern Queensland (Lemmens et al. 1995). The wood of this species is an essential raw material for pulp and paper (Yahya et al. 2010; Haque et al. 2019). By 2014, the total plantation area of *A. mangium* in Southeast Asia was 1.35 million hectares, of which 37% (0.50 million hectares) was located in Indonesia (Nambiar and Harwood 2014). By 2020, 790,150 hectares of *A. mangium* plantations in Sumatra and Kalimantan had been converted to *Eucalyptus* species, primarily due to the impact of *Ceratocystis* infection (Hardiyanto et al. 2024). Nevertheless, due to its considerable pulp and paper production. For example, Brawner et al. (2022) investigated families with resistance to *Ceratocystis*, while Masendra et al. (2024) further examined families resistant to white-rot (*Trametes versicolor*) and brown-rot (*Fomitopsis palustris*) fungi.

In Indonesia, a tree breeding program for *A. mangium* was initiated by the Center for Forest Biotechnology and Tree Improvement (Nirsatmanto and Kurinobu 2002; Nirsatmanto et al. 2003, 2004, 2013, 2015, 2023; Kurinobu 2005; Nirsatmanto 2012; Sunarti et al. 2022; Masendra et al. 2023, 2024; Yokoyama et al. 2025). In this program, a sub-line breeding system has been implemented, in which sub-lines consist of four different seed origins: two provenance sub-lines A and B from Papua New Guinea (PNG) and two provenance sub-lines C and D from Far North Queensland (FNQ), Australia (Nirsatmanto and Kurinobu 2002). The seedling-seed orchards of *A. mangium* have been established at the provenance levels under the sub-line system. The first-generation seedling seed orchards of *A. mangium* were established in 1994 in South Kalimantan and South Sumatra, Indonesia, using about 50 families per sub-line (Nirsatmanto and Kurinobu 2002). The second generation of seedling-seed orchards (approximately 50 families per sub-line) was established in South Kalimantan in 2001, using superior families selected from the first generation and new candidate trees from the same provenance (Kurinobu 2005). Meanwhile, the third generation of seedling-seed orchards was established in Central Java, Indonesia, in 2012, with 10 families per sub-line selected from superior families of the second generation (a total of 789 trees were inventoried in 2022) (Masendra et al. 2023). The advantage of using the sub-line system for *A. mangium* tree breeding programs is to improve tree characteristics while maintaining genetic diversity throughout generations (Nirsatmanto and Kurinobu 2002).

Evaluation of chemical and pulp characteristics of wood from *Acacia* and *Eucalyptus* species in tree breeding programs has been reported using non-destructive methods, such as near-infrared (NIR) spectroscopy (Stackpole et al. 2011; Karlina-sari et al. 2014; Nickolas et al. 2020) because analyzing a large number of wood samples is time-consuming and costly. By NIR spectroscopy, the mean values of pulp yield predicted by NIR spectroscopy for wood from 17-year-old *Eucalyptus globulus* trees planted in Australia ranged from 53.2% to 55.5% (Nickolas et al. 2020). Additionally, the NIR-spectroscopy predicted extractive content, lignin, cellulose, and pulp yield of wood in 16-year-old *E. globulus* planted in Australia were

4.76%, 20.5%, 43.4%, and 53.2%, respectively (Stackpole et al. 2011). Furthermore, NIR-spectroscopy predicted cellulose contents of 5 to 7 years *A. mangium* planted in Indonesia was about 50.0% (Karlinasari et al. 2014). In addition to non-destructive tests, the destructive method, or direct measurement of chemical and pulp characteristics, has also been employed for *Acacia* and *Eucalyptus* species (Martins et al. 2020; Mboumba et al. 2022). For instance, the lignin content, cellulose content, and Kraft-pulp yield of 4-year-old *Acacia crassicaarpa* trees planted in Indonesia were 27.0%, 44.4%, and 53.8%, respectively (Martins et al. 2020). Meanwhile, in 4-year-old *Eucalyptus camaldulensis* planted in Thailand, the mean values of lignin content, holocellulose content, and Kraft-pulp yield were 21.3%, 86.1%, and 44.4%, respectively (Mboumba et al. 2022). In addition to the indirect measurements, direct measurements of chemical components and pulp properties are also necessary to obtain accurate values for key traits such as α -cellulose, γ -cellulose, and Kraft-pulp yield. These measurements are essential not only for reliable evaluation of phenotypic characteristics in *A. mangium* but also for their relevance to the industry.

It was reported that pulp yield was phenotypically correlated positively with cellulose and negatively with extractives (Poke et al. 2006; Stackpole et al. 2011; Martins et al. 2020). These facts suggest that when wood is utilized as a raw material of pulp and paper, the chemical characteristics of wood are important for determinants of processing quality (Poke et al. 2006; Stackpole et al. 2011; Martins et al. 2020). The wood properties were recently evaluated in the third-generation *A. mangium* trees (Masendra et al. 2023, 2024; Yokoyama et al. 2025; Susanto et al. 2025). Since the first and second generations of the *A. mangium* breeding programs in Indonesia emphasized growth traits for the increase of pulp and paper yield (Nirsatmanto and Kurinobu 2002; Nirsatmanto 2012), information on the relationships and phenotypic characteristics for chemical and Kraft-pulp properties becomes particularly important for advanced-generation *A. mangium* produced in the tree breeding program.

Previous studies have investigated the chemical composition and pulp properties of *Acacia* and *Eucalyptus* species using both destructive and non-destructive approaches on wood samples (Martins et al. 2020; Nickolas et al. 2020; Mboumba et al. 2022). In third-generation *A. mangium*, color and methanol extractive content differed between inner and outer heartwood (Masendra et al. 2024), suggesting that pulp and paper quality might differ. Therefore, evaluating the chemical composition and Kraft-pulp properties of both inner and outer heartwood is important not only for clarifying their phenotypic characteristics but also for their influences on pulp yield, bleaching efficiency, and production costs.

The objective of this study is to obtain fundamental information on the among-family variation of chemical components and Kraft-pulp properties of the inner and outer heartwood in 99 trees from 20 open-pollinated families of third-generation *A. mangium* selected through the tree breeding programs in Indonesia, with the aim of identifying wood traits that can contribute to improve pulp and paper quality.

Materials and methods

Materials

The *Acacia mangium* sampled trees were 10-year-old and planted in Alas Kethu Special Purpose Forest Area in Wonogiri, Central Java, Indonesia (7°47'S, 110°56'E), using seedling-seed orchard from the third generation. The third-generation *A. mangium* is an open-pollinated family consisting of 40 families from two provenances and four sub-lines (Nirsatmanto et al. 2015; Masendra et al. 2023). At the age of 10 years, the progeny trial was thinned to keep the seedling-seed orchard. A total of 99 thinned individuals were used as the study materials, while the remaining trees formed the seedling-seed orchard. The selected trees represented 20 families (five families from each sub-line) with approximately five trees per family. Table 1 shows the mean and standard deviation of stem diameter at 1.3 m above the ground, tree height, and basic density for all selected trees. A log with a length of 30 cm was collected from the stem at a height of 1.0–1.3 m above the ground in each tree. The logs were then sawn into radial boards with a thickness of 30 mm and air-dried for two months at room temperature without an air-conditioner. The air-dried board was cut in half at the pith position. Due to different concentrations of extractives between inner heartwood (near the pith) and outer heartwood (near the boundary between

Table 1 Growth traits and basic density of family means and standard deviations of the sample trees

Sub-line	Family ID	n	D (cm)		TH (m)		BD (g/cm ³)	
			Mean	SD	Mean	SD	Mean	SD
A	5	5	24.0	4.2	15.8	3.7	0.501	0.037
	6	5	21.3	3.1	12.4	3.4	0.459	0.016
	7	5	20.5	6.1	13.2	2.9	0.490	0.024
	9	5	24.3	4.8	12.8	3.5	0.490	0.022
	10	5	21.6	0.5	15.4	4.4	0.424	0.035
B	12	5	18.2	2.0	15.2	4.8	0.456	0.011
	13	5	20.7	4.6	18.0	3.1	0.445	0.060
	14	5	21.4	4.3	13.2	2.7	0.439	0.038
	17	5	20.7	4.1	19.2	6.3	0.438	0.045
	19	5	17.6	4.5	12.6	4.8	0.449	0.062
C	22	5	17.0	2.6	15.8	6.3	0.440	0.043
	25	4	17.7	3.0	16.3	7.8	0.436	0.060
	27	5	13.9	2.5	12.2	3.5	0.444	0.039
	28	5	17.1	3.7	13.4	3.1	0.426	0.037
	29	5	16.6	6.1	14.6	3.8	0.446	0.048
D	32	5	18.8	1.7	12.0	4.5	0.452	0.034
	33	5	17.5	1.9	13.4	4.0	0.409	0.029
	35	5	19.1	7.4	13.8	2.8	0.465	0.057
	37	5	19.1	4.2	16.0	4.7	0.480	0.045
	38	5	15.8	1.4	12.0	3.4	0.411	0.049
Mean/total		99	19.1	4.5	14.4	4.4	0.450	0.045

n, number of trees; D, stem diameter at 1.3 m above the ground; TH, tree height; BD, basic density; SD, standard deviation

heartwood and sapwood) in hardwood species (Hillis 1987), the heartwood was cut and separated into inner and outer heartwood. The differences in the two parts were investigated visually on the radial surface of the heartwood: the inner heartwood has a light color, and the outer heartwood has a dark color, as shown in Fig. 1 (Masendra et al. 2024).

Wood basic density

Basic density was measured using the water displacement method (Panshin and de Zeeuw 1980). The strip specimens with a thickness of 1 cm from the pith to bark were collected at 1.3 m above the ground from 99 trees. The strip specimens were cut into small block specimens at 1 cm intervals from the pith toward the bark side. As a result, four to 14 block specimens (depending on the stem diameter) were obtained. The mean value of all block specimens from a tree was calculated, and then the calculated value was regarded as the representative value of the tree.

Fig. 1 Differences in the color of inner and outer heartwood for the third-generation *A. mangium*. IHW, inner heartwood; OHW, outer heartwood; SW, sapwood. This radial board was scanned from family ID 33 of sub-line D (Masendra et al. 2024)



Chemical properties

Wood powder (42–82 mesh) was prepared from the inner and outer heartwood sections of the radial boards using a rotary speed mill (P-14, Fritsch, Idar-Oberstein, Germany) to assess the chemical properties. Ash content was measured by heating the wood sample (1.0 g) in a muffle furnace (FO 100, Yamato, Tokyo, Japan) at 600 °C for 1 h, according to the method described by Kuroda (2000). Hot-water extract was determined by boiling 1.0 g of the sample in distilled water in a 200 mL Erlenmeyer flask connected with a Liebig condenser for 3 h. The 1% NaOH extract content was measured by heating a 1.0 g sample in 100 mL of 1% NaOH (Kanto Chemical Co., Tokyo, Japan) aqueous solution for 1 h in a water bath at 80 °C. To determine the content of organic-solvent extracts, a 5.0 g sample was extracted with a 120 mL mixture of 95% ethanol (EtOH) (Kanto Chemical Co., Japan) and toluene (Kanto Chemical Co., Japan) (1 : 2, v : v) for 6 h using a Soxhlet extractor. After extraction, the solvent was evaporated using a rotary evaporator (N-1100, EYELA, Tokyo, Japan). The ash and extractive contents were measured gravimetrically.

The content of Klason lignin was determined according to the modified method described by Kuroda (2000). The organic solvent extract-free wood powder (1.0 g) was reacted with 20 mL of 72% H₂SO₄ (FUJILM Wako Pure Chemical Corporation, Osaka, Japan) for 4 h at room temperature to hydrolyze and solubilize the carbohydrates. The suspension was then diluted with 765 mL of distilled water to reduce the H₂SO₄ concentration to 3% and further boiled for 2 h. Then, the suspension was allowed to settle before filtration. The residue was washed with 500 mL of hot-distilled water until reaching a neutral pH. The obtained insoluble residue was determined as the Klason-lignin content.

Holocellulose content was determined according to the method described by Kuroda (2000). The organic solvent extract-free sample (2.5 g) and distilled water (150 mL) were put in a 300 mL Erlenmeyer flask. A 0.2 mL CH₃COOH (FUJIFILM Wako Pure Chemical Corporation, Osaka, Japan) and 1.0 g NaClO₂ (Kanto Chemical Co., Tokyo, Japan) were added to the flask and heated in a water bath at 70 °C. CH₃COOH and NaClO₂ were added to the flask every hour for 3 h. The mixture was cooled down, and the residue was filtered and washed with 500 mL of distilled water and 50 mL of acetone (FUJIFILM Wako Pure Chemical Corporation, Osaka, Japan). The residue was dried in the oven at 105 ± 3 °C and weighed to determine holocellulose content.

The content of α -cellulose was determined using a holocellulose sample. The 25 mL of 17.5% NaOH-aqueous solution was added to a 1.0 g holocellulose sample in a 50 mL beaker, the sample was left for 4 min, and then homogenized with a glass stick for 5 min. After 21 min, 25 mL of distilled water was added to the suspension and then left for 5 min. The content in a beaker was filtered within 5 min, the residue was washed first with 200 mL of distilled water, and the solution was collected to determine β - and γ -cellulose contents. Then, the residue was washed with 40 mL of 10% CH₃COOH and left for 5 min. After that, the residue was rewashed with 1000 mL of distilled water and dried in the oven at 105 ± 3 °C. The content of α -cellulose was determined gravimetrically (Kuroda 2000).

To determine β -cellulose, the sample solution after α -cellulose determination was diluted to a volume of 800 mL. The 40 mL of 30% CH_3COOH was added to the solution and then heated until the color changed. The solution was cooled for 2 h, and filtered through a paper filter (No. 2, Whatman, Toyo Roshi Kaisha Limited, Tokyo, Japan), and dried in the oven at 105 ± 3 °C. The content of β -cellulose was determined gravimetrically. The γ -cellulose proportion was calculated by subtracting α - and β -cellulose from holocellulose (Kuroda 2000).

Kraft-pulp properties

Wood sticks (approximately $1 [\text{T}] \times 1 [\text{R}] \times 20 [\text{L}]$ mm) were cut from the inner and outer heartwood sections of the radial boards to assess Kraft-pulp properties. A 5 g sample of wood sticks was used for Kraft pulping under the following conditions: an active alkali charge of 18% (as NaOH), a sulfidity index of 25%, a liquor-to-wood ratio of 4:1, and a cooking time of 90 min at 170 °C. After cooking, the cooked pulp was defibrillated with a pestle and a mortar. The cooked pulp was filtered through a glass filter (1G1) and then washed with 2 L of distilled water. The washed pulp was dried at 105 °C and then weighed as Kraft-pulp yield (Istikowati et al. 2016).

The kappa number was determined according to the Japanese Industrial Standards (JIS P8211: 2011), applicable for measurements within the range of 5–100. Briefly, 50 mL of sulfuric acid was mixed with 50 mL of 0.02 M potassium permanganate solution (FUJIFILM Wako Pure Chemical Corporation, Osaka, Japan) in a 1 L conical beaker. To the mixture, 1 g of oven-dried Kraft-pulp was added. The sample solution was then diluted to 500 mL with distilled water. The suspension was then mixed with a magnetic stirrer for 10 min. Ten mL of 1 M potassium iodide solution (Kanto Chemical Co., Tokyo, Japan) was added to the sample mixture. The mixture was then titrated using 0.2 M sodium thiosulfate solution (FUJIFILM Wako Chemicals, Osaka, Japan) until the color changed. The kappa number was calculated by the following equations (Eqs. 1 and 2):

$$\text{KN} = p \times f/w \quad (1)$$

$$p = (b - a)C/0.1 \quad (2)$$

where KN is kappa number, p is the volume of 0.02 M potassium permanganate solution (mL) consumed by pulp sample, w is oven-dried Kraft-pulp weight (g), b is the volume of 0.2 M sodium-thiosulfate solution consumed in the blank determination, a is the volume of 0.2 M sodium-thiosulfate solution (mL) consumed by kraft-pulp sample, C is the molar concentration (M) of sodium-thiosulfate solution, and f is a correction factor to 50% (mass/mass) potassium permanganate consumption that depending on the value of p .

Statistical analysis

The R software version 4.3.2 (R Core Team 2023) was used for statistical analysis. The phenotypic variations among families in the measured traits were assessed using

a linear mixed-effects model. The variance components of the measured traits were estimated using the “lmer” function in the “lme4” package (Bates et al. 2015), with family as a random effect (3).

$$Y_{ij} = \mu + Family_j + e_{ij} \quad (3)$$

where Y_{ij} is the trait at the i th tree of the j th family, μ is the grand mean, $Family_j$ is the random effect of the j th family, and e_{ij} is the residual. Furthermore, to categorize the 20 families for optimal wood utilization, principal component analysis (PCA) and cluster analysis were applied. Phenotypic values (the family mean) in each measured trait were used for PCA. The cluster analysis was applied using the Ward hierarchical clustering algorithm, which uses the 1st and 2nd principal component scores from PCA as variables.

To evaluate the relationships between the traits, phenotypic correlation coefficients (r) were calculated using Pearson’s correlation coefficient based on the values of both the inner and outer heartwood samples. Moreover, a t -test was performed to differentiate between the traits in the inner and outer heartwood samples.

Table 2 Sub-line means and standard deviations of inner and outer heartwood extracts and ash contents and t -test results between inner and outer heartwood

Sub-line	n	Trait	IH		OH		t -value	p -value
			Mean	SD	Mean	SD		
A	25	HWE (%)	7.7	1.5	7.8	1.3	−0.224	0.824
		AE (%)	16.1	2.1	16.3	1.6	−0.394	0.696
		OSE (%)	6.3	1.8	8.7	1.6	−4.960	<0.001
		Ash (%)	0.5	0.3	0.5	0.2	0.523	0.604
B	25	HWE (%)	6.4	2.3	7.8	2.1	−2.150	0.037
		AE (%)	15.3	2.1	17.0	2.7	−2.631	0.011
		OSE (%)	5.1	1.3	8.6	2.0	−7.337	<0.001
		Ash (%)	0.5	0.3	0.5	0.3	0.353	0.725
C	24	HWE (%)	6.5	2.0	7.0	1.8	−0.864	0.392
		AE (%)	16.5	2.2	16.2	2.1	0.494	0.624
		OSE (%)	6.2	2.1	8.6	2.0	−3.920	<0.001
		Ash (%)	0.7	0.4	0.6	0.4	0.298	0.767
D	25	HWE (%)	5.9	1.5	7.5	1.7	−3.693	0.001
		AE (%)	14.4	2.4	16.3	2.1	−3.131	0.003
		OSE (%)	6.1	1.5	7.9	1.9	−3.843	<0.001
		Ash (%)	0.7	0.3	0.7	0.3	0.418	0.678

n , number of trees; IH, inner heartwood; OH, outer heartwood; SD, standard deviation; HWE, hot-water extracts; AE, Alkali (1% NaOH) extracts; OSE, organic solvent (EtOH-toluene) extracts

Results and discussion

Contents of wood chemical components

Table 2 shows the extractive and ash contents in the 10-year-old third-generation *A. mangium*. The mean values of inner heartwood in each sub-line ranged from 5.9 to 7.7% for hot-water extracts, 14.4–16.5% for alkali extract contents, 5.1–6.3% for organic-solvent extracts, and 0.5–0.7% for ash content. Meanwhile, the outer heartwood ranged from 7.0 to 7.8% for hot-water extracts, 16.2–17.0% for alkali extracts, 7.9 to 8.7% for organic-solvent extracts, and 0.5–0.7% for ash content. Compared to the previous studies, the third-generation *A. mangium* showed higher hot-water, alkali, and organic-solvent extract contents than those reported for *A. mangium* 3-year-old (Susanto et al. 2025) and *Acacia aulocarpa* 27-year-old (Lukmandaru et al. 2025), respectively.

The results of the *t*-test showed significant differences between the inner and outer heartwood for hot-water and alkali extracts in sub-lines B and D, and organic-solvent extracts for all sub-lines ($p < 0.05$, Table 2). In woody species, the hot-water and alkali extracts contain nonstructural components of low molecular weight, such as simple sugars, degraded hemicellulose (xylans and mannans), polyphenols, fatty acids, and ash-related components, while organic-solvent extracts (EtOH-toluene extracts in the present study) represent fatty acids, steroids, and polyphenols (Hillis 1987). Those components are responsible for wood coloration in the heartwood formation to distinguish the difference between sapwood, outer heartwood, and inner heartwood (Hillis 1987). Previously, it was reported that extractive contents in the outer heartwood were higher than those in the inner heartwood in some hardwood species, such as *Tectona grandis* wood (Haupt et al. 2003; Lukmandaru and Takahashi 2008). Therefore, the higher values of extracts at the outer heartwood in *A. mangium* (Table 2) indicate that those components were deposited as newly formed heartwood substances during heartwood formation. In addition, the lower values of these components in the inner heartwood are also related to polymerization and autoxidation that occur in these substances within the inner heartwood (Masendra et al. 2024). On the other hand, extractives and ash contents are undesirable wood chemical components in the pulping process. These components are not part of wood cell walls that are not converted into cellulosic pulp (Sjöström and Alén 1999). Furthermore, they hinder the penetration of reagents, reduce pulping yield, increase bleaching costs, cause equipment impregnation, and reduce pulp quality (dos Santos et al. 2024; Neiva et al. 2024; Lukmandaru et al. 2025). As the fatty acid in *A. mangium* wood is the main component responsible for pitch deposition in cellulosic pulp (Lange and Hashim 2001; Pieterinen et al. 2004), considering the organic-solvent extracts from the 20 families may be important to understand pulp and paper quality from this species.

The mean values of inner heartwood in each sub-line ranged from 24.9 to 25.9% for Klason lignin, 77.9–79.7% for holocellulose, 43.8 to 46.1% for α -cellulose, 5.7–6.5% for β -cellulose, and 27.1 to 28.4% for γ -cellulose, respectively (Table 3). The outer heartwood values ranged from 26.0 to 27.9% for Klason lignin, 77.6–78.9% for holocellulose, 46.7 to 48.7% for α -cellulose, 6.1 to 6.7% for β -cellulose, and

Table 3 Sub-line means and standard deviations of Klason lignin and polysaccharides contents in inner and outer heartwood and *t*-test results between inner and outer heartwood

Sub-line	<i>n</i>	Trait	IH		OH		<i>t</i> -value	<i>p</i> -value
			Mean	SD	Mean	SD		
A	25	KL (%)	25.7	1.8	26.0	1.9	−0.625	0.535
		HC (%)	79.7	1.2	78.0	1.8	3.748	<0.001
		α -C (%)	46.0	2.5	48.7	3.5	−3.165	0.003
		β -C (%)	6.5	2.0	6.6	0.6	−0.283	0.778
		γ -C (%)	27.2	3.1	22.7	2.9	5.305	<0.001
B	25	KL (%)	25.0	2.1	26.2	2.5	−1.788	0.080
		HC (%)	79.7	1.4	78.7	2.4	1.838	0.072
		α -C (%)	46.1	2.7	48.3	3.0	−2.739	0.009
		β -C (%)	6.5	1.0	6.7	0.9	−0.829	0.411
		γ -C (%)	27.1	2.8	23.7	2.7	4.423	<0.001
C	24	KL (%)	25.9	2.7	27.4	2.2	−2.017	0.049
		HC (%)	77.9	1.7	78.9	2.6	−1.552	0.127
		α -C (%)	43.8	2.1	46.7	1.6	−5.319	<0.001
		β -C (%)	5.7	1.0	6.1	0.6	−1.796	0.079
		γ -C (%)	28.4	2.0	26.1	3.0	3.153	0.003
D	25	KL (%)	24.9	2.3	27.9	1.8	−5.049	<0.001
		HC (%)	79.4	1.4	77.6	1.8	4.028	<0.001
		α -C (%)	45.9	2.8	46.8	1.8	−1.392	0.170
		β -C (%)	5.9	1.1	6.2	0.5	−1.409	0.165
		γ -C (%)	27.6	2.3	24.5	2.3	4.801	<0.001

n, number of trees; IH, inner heartwood; OH, outer heartwood; SD, standard deviation; KL, Klason lignin; HC, holocellulose; α -C, α -cellulose; β -C, β -cellulose; γ -C, γ -cellulose

22.7 to 26.1% for γ -cellulose, respectively. The Klason lignin content in the present study was lower than that of 4-year-old *A. crassicarpa* (Martins et al. 2020) and 27-year-old *A. aulocarpa* (Lukmandaru et al. 2025), but higher than that of 3-year-old *A. mangium* (Susanto et al. 2025). Furthermore, the α -cellulose content in this study was comparable to that reported for other *Acacia* species (Martins et al. 2020; Lukmandaru et al. 2025) but lower than that of *A. mangium* 3-year-old reported by Susanto et al. (2025).

The significant differences ($p < 0.05$) in Klason-lignin content between inner and outer heartwood samples were found in sub-lines C and D (Table 3). The holocellulose content differed in the inner and outer heartwood of sub-lines A and D. The α - and γ -celluloses were different between the inner and outer heartwood in all sub-lines, except for α -cellulose in sub-line D ($p = 0.170$). Hardwood lignin is composed of both guaiacyl and syringyl units derived from trans-coniferyl and trans-sinapyl alcohols (Sakakibara and Sano 2001). The radial distribution of lignin in the hardwood species has been reported in the previous studies (Yokoi et al. 1999; Lhate et al. 2010; Feng et al. 2025); lignin content varies among species and either increases from the inner to the outer heartwood or follows the opposite trend. For example, in *T. grandis*, the decrease in lignin in the inner heartwood may be due to a higher syringyl-to-guaiacyl ratio (S/G ratio) (Feng et al. 2025). In *E. camaldulensis*, the S/G ratio was also higher on the pith side and decreased gradually towards the bark (Yokoi et al. 1999). In addition, the S/G ratio was strongly positively correlated with acid-soluble lignin

Table 4 Sub-line means and standard deviations of Kraft-pulp yield and kappa number in inner and outer heartwood and *t*-test results between inner and outer heartwood

Sub-line	<i>n</i>	Trait	IH		OH		<i>t</i> -value	<i>p</i> -value
			Mean	SD	Mean	SD		
A	25	KP (%)	52.0	1.8	49.6	1.4	5.055	<0.001
		KN	18.0	2.6	21.9	4.3	−3.920	<0.001
B	25	KP (%)	52.7	1.8	51.3	1.6	2.846	0.006
		KN	19.7	4.5	24.7	3.5	−4.409	<0.001
C	24	KP (%)	51.7	2.0	49.6	1.4	4.225	<0.001
		KN	20.1	3.4	23.4	2.5	−3.745	0.001
D	25	KP (%)	51.3	1.7	49.6	1.5	3.660	0.001
		KN	19.9	4.5	22.2	3.3	−2.070	0.044

n, number of trees; IH, inner heartwood; OH, outer heartwood; SD, standard deviation; KP, Kraft-pulp yield; KN, kappa number

content but weakly negatively correlated with Klason lignin in *E. globulus* (Alves and Rodrigues 2022). These findings suggest that syringyl units contribute to the solubilization of lignin under acidic conditions, resulting in lower Klason lignin content. Therefore, the lower Klason lignin content in the inner heartwood than that in the outer heartwood for all sub-lines (Table 3) might be due to its higher S/G ratio, which enhances lignin solubilization under acidic conditions. Furthermore, the lower lignin content of inner heartwood corresponded with the lower kappa number (Table 4), as described in Kraft-pulp properties section. On the other hand, α -cellulose generally indicates undegraded, high-molecular-weight cellulose; β - and γ -cellulose represent degraded cellulose and hemicelluloses, respectively (Baeza and Freer 2001). The distribution of polysaccharide content has been reported in broad-leaved species (Lhate et al. 2010; Lukmandaru 2018; Feng et al. 2025). For example, the contents of hemicellulose and cellulose decreased from the outer heartwood to the middle and outer heartwood in 18-year-old *T. grandis* (Feng et al. 2025). *Eucalyptus pellita* showed a higher cellulose content in the inner heartwood than in the outer heartwood, while hemicellulose had the opposite result (Lukmandaru 2018). However, in *Icuria dunensis* and *Pterocarpus angolensis*, the cellulose of outer heartwood was higher than inner heartwood, while the hemicellulose was conversely (Lhate et al. 2010). Thus, the present results corresponded to those of the broad-leaved species reported by Lhate et al. (2010). In addition, the degree of polymerization and crystallinity of cellulose increased with tree age in the species of *Trema orientalis* (Jahan and Mun 2005). Therefore, due to the outer heartwood produced lastly, the higher content of cellulose was accompanied by lower hemicellulose contents in the outer heartwood of the third-generation *A. mangium* of the present study (Table 3), indicating that the degree of polymerization and crystallinity of cellulose in this outer heartwood part is high. Lower lignin contents are desirable for pulping because they must be removed to increase cellulosic pulp yield (dos Santos et al. 2024). In contrast, since cellulose is the primary source of pulpwood, especially the dissolving pulp component, the α -cellulose content is crucial for pulp quantity. The higher the cellulose content in the pulp, the better the yield and quality of the final product (Lourenço et al. 2008; Martins et al. 2020). In addition, as γ -cellulose is similar to hemicellulose, the presence of this component may be responsible for the high consumption of alkali during the

Kraft-cooking process. Furthermore, producing hexenuronic acid from glucuronoxylan (hemicellulose) during cooking is also undesirable in the pulp-bleaching process (Haque et al. 2019; Neiva et al. 2024).

Kraft-pulp properties

The results of Kraft-pulp yield and kappa number are shown in Table 4. The mean values of inner heartwood in each sub-line ranged from 51.3 to 52.7% for Kraft-pulp yield and 18.0 to 20.1 for kappa number, respectively. The outer heartwood ranged from 49.6 to 51.3% for Kraft-pulp yield and 21.9–24.7 for kappa number. In comparison, the pulp yield in the present study was within the range reported for *Acacia* and *Eucalyptus* species in the previous studies (Stackpole et al. 2011; Martins et al. 2020), indicating that the third-generation *A. mangium* exhibits comparable pulping performance and fiber quality to other major pulpwood species.

The *t*-test results found significant differences between the inner and outer heartwood in the Kraft-pulp yield and kappa number for all sub-lines ($p < 0.05$, Table 4). According to the results in Table 4, inner heartwood generally might provide a higher Kraft-pulp yield, possibly due to its lower lignin content and higher cellulose fraction. Lower kappa numbers in the inner heartwood suggest better delignification efficiency during the pulping process, requiring less bleaching effort and chemical usage. In contrast, the higher kappa number and lower Kraft-pulp yield of outer heartwood imply better lignin retention, which could lead to increased chemical and energy consumption during Kraft pulping. However, the outer heartwood also contains a higher α -cellulose fraction, making it more suitable for dissolving pulp applications than Kraft-pulp (dos Santos et al. 2024). These differences highlight a challenge for the pulp industry, as maintaining uniform chip quality is critical for efficient and consistent pulping operations, yet they also provide an opportunity for product diversification.

Regarding pulp bleaching, the preferred kappa number for bleachable pulp of *Acacia* species is 15 to 25 (Malinen et al. 2006; Haque et al. 2019). Therefore, the present results indicate that the Kraft-pulp yield of the third-generation *A. mangium* is bleachable pulp, with a kappa number ranging from 18.0 to 24.7 (Table 4). Furthermore, due to the high concentration of organic-solvent extracts and γ -cellulose (Tables 2 and 3) in the heartwood of these families, besides bleaching, dispersing and washing pulp also might be needed to remove the fatty acids and hexenuronic acid compounds that cause low-quality for cellulosic pulp (Pieterinen et al. 2004; Haque et al. 2019; Lukmandaru et al. 2025).

It was reported that fast-growing tree species, such as *E. globulus*, *E. camaldulensis*, and *A. crasscarpa*, have high potential for pulp and paper production (Stackpole et al. 2011; Martins et al. 2020, 2024; Mboumba et al. 2022). In comparison, the present study is the first to examine the chemical and Kraft-pulp properties of inner and outer heartwood third-generation *A. mangium*, highlighting their potential for promoting product diversity and improved utilization of pulp and paper using this species in Indonesia.

Table 5 Phenotypic-correlation coefficients between measured traits

	<i>D</i>	TH	BD	OSE	KL	HC	α -C	KP	KN
<i>D</i>		0.306	0.371	-0.104	-0.007	-0.269	0.250	-0.121	0.178
TH	0.306		-0.053	0.040	0.149	-0.098	0.113	-0.122	0.215
BD	0.371	-0.053		0.174	0.017	-0.054	0.245	-0.068	0.109
OSE	-0.423	-0.205	0.148		-0.076	0.160	0.116	-0.067	0.123
KL	0.001	0.075	0.093	0.021		-0.352	-0.215	-0.326	0.220
HC	0.142	0.033	0.114	0.037	-0.319		0.411	0.347	-0.029
α -C	0.049	-0.200	0.171	0.074	-0.129	0.483		0.315	-0.100
KP	0.144	0.171	-0.144	-0.441	-0.058	0.263	0.358		0.090
KN	-0.196	0.074	-0.171	0.055	-0.053	-0.133	-0.385	-0.164	

Number of samples=99 trees. *D*, stem diameter at 1.3 m above the ground; TH, tree height; BD, basic density; OSE, organic-solvent (EtOH-toluene) extracts; KL, Klason lignin; HC, holocellulose; α -C, α -cellulose; KP, Kraft-pulp yield; KN, kappa number. Values in the lower and upper diagonals indicate correlation coefficients of inner and outer heartwood, respectively. The values with bold style indicate the phenotypic correlation coefficients with *p*-values of less than 0.05

Relationships between measured traits

Table 5 represents the phenotypic correlations (*r*). Significant positive correlations were found between stem diameter and tree height ($r=0.306$) or basic density ($r=0.371$). In the inner heartwood, negative correlations were observed between organic solvent extracts and stem diameter ($r=-0.423$) or tree height ($r=-0.205$). In the outer heartwood, α -cellulose content was positively correlated with stem diameter ($r=0.250$) or basic density ($r=0.245$). Positive correlations were found between Kraft-pulp yield and holocellulose or α -cellulose contents of 0.263 and 0.358 in the inner heartwood. Meanwhile, the correlation coefficients in the outer heartwood were 0.347 and 0.315. In addition, a negative correlation was found between Klason lignin and holocellulose contents in the inner heartwood ($r=-0.319$) and outer heartwood ($r=-0.352$), respectively. Furthermore, a negative correlation between Kraft-pulp yield and organic-solvent extracts was only found in the inner heartwood sample ($r=-0.441$).

Relationships between growth and wood traits have been investigated in previous works on hardwood species (Quang et al. 2010; Istikowati et al. 2016; Sunarti et al. 2022). For example, a significant positive correlation was found between stem diameter and basic density in 4.5-year-old *A. mangium* second-generation planted in Indonesia ($r=0.400$, $p<0.05$) (Sunarti et al. 2022) or cellulose content in 10-year-old *Eucalyptus europhylla* planted in Vietnam (Quang et al. 2010). Basic density was positively correlated with kappa number in fast-growing tree species, namely, *Artocarpus elasticus*, *Neolitsea latifolia*, and *Alphitonia excelsa* from the secondary forest in Indonesia (Istikowati et al. 2016). In the present study, significant phenotypic correlations were found between growth and wood traits (Table 5), suggesting that wood traits related to pulp and paper quantity depend on growth traits. This positive pheno-

typic association in *A. mangium* suggests that trees with superior growth could also enhance pulp production.

Under nearly the same pulp cooking conditions as those of the present study, correlations between chemical components and Kraft-pulp properties have been reported in previous studies (Ona et al. 1995; Istikowati et al. 2016; Mboumba et al. 2022). Significant positive correlations of Kraft-pulp yield and holocellulose were found in *E. camaldulensis* ($r=0.820$, $p<0.001$) (Ona et al. 1995), and in *A. elasticus*, *N. latifolia*, and *A. excelsa* ($r=0.667$, $p<0.05$) (Istikowati et al. 2016). The Kraft-pulp yield also was positively correlated with α -cellulose content ($r=0.799$, $p<0.001$), but negatively correlated with extractive contents in *E. camaldulensis* ($r=-0.896$, $p<0.001$) (Ona et al. 1995), or Klason lignin in *A. elasticus*, *N. latifolia*, and *A. excelsa* ($r=-0.657$, $p<0.001$) (Istikowati et al. 2016). In *E. camaldulensis* 4-year-old planted in Thailand, the correlations between chemical components and Kraft-pulp properties were found, but not significant (Mboumba et al. 2022). In the present

Table 6 Variance components of linear mixed-effect model for explaining family differences in measured properties

Trait	Heart-wood type	Fixed-effect parameter			Variance component		
		Estimate	SE	p-value	σ^2_f	σ^2_e	σ^2_f (%)
Stem diameter	–	19.143	0.598	<0.001	3.853	16.264	19.2
Tree height	–	14.345	0.457	<0.001	0.398	18.662	2.1
Basic density	–	0.450	0.006	<0.001	0.289×10^{-3}	0.174×10^{-2}	14.3
Hot-water extracts	IH	6.629	0.264	<0.001	0.799	2.962	21.2
	OH	7.519	0.213	<0.001	0.345	2.778	11.1
Alkali extracts	IH	15.565	0.297	<0.001	0.838	4.554	15.5
	OH	16.488	0.224	<0.001	0.091	4.498	2.0
Organic solvent extracts	IH	5.946	0.190	<0.001	0.148	2.840	4.9
	OH	8.451	0.189	<0.001	0.000	3.519	<0.1
Ash	IH	0.602	0.049	<0.001	0.028	0.096	22.5
	OH	0.567	0.043	<0.001	0.019	0.087	18.2
Klason lignin	IH	25.363	0.235	<0.001	0.087	5.039	1.7
	OH	26.846	0.261	<0.001	0.439	4.580	8.8
Holocellulose	IH	79.175	0.220	<0.001	0.570	1.978	22.4
	OH	78.292	0.236	<0.001	0.173	4.673	3.6
α -Cellulose	IH	45.432	0.311	<0.001	0.606	6.538	8.5
	OH	47.617	0.369	<0.001	1.505	5.996	20.1
β -Cellulose	IH	6.157	0.189	<0.001	0.419	1.459	22.3
	OH	6.442	0.099	<0.001	0.115	0.404	22.2
γ -Cellulose	IH	27.581	0.262	<0.001	0.000	6.791	<0.1
	OH	24.231	0.369	<0.001	1.193	7.531	13.7
Kraft-pulp yield	IH	51.894	0.233	<0.001	0.477	3.028	13.6
	OH	50.053	0.224	<0.001	0.606	1.978	23.5
Kappa number	IH	19.414	0.429	<0.001	0.827	14.155	5.5
	OH	23.040	0.436	<0.001	1.472	11.493	11.4

SE, standard error; σ^2_f , variance of family; σ^2_e , residual variance; σ^2_f (%), proportion of family variance to total variance; IH, inner heartwood; OH, outer heartwood; –, not available. Variance component of stem diameter and tree height were recalculated for 99 trees from 20 families used in the present study from the data of 766 trees from 40 families published on a previous study (Masendra et al. 2023)

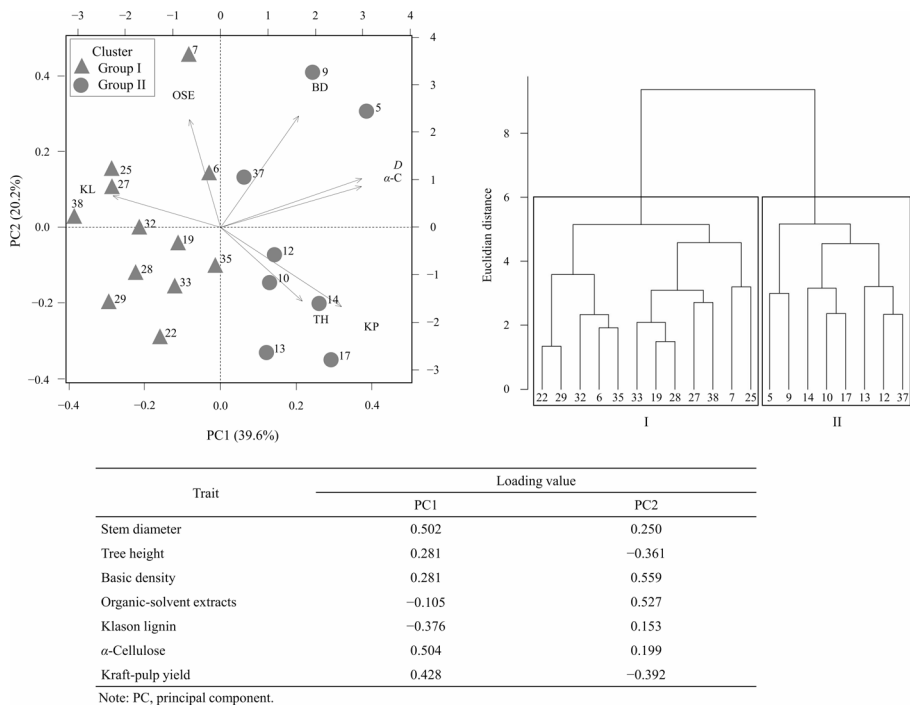


Fig. 2 Principal component (PC) analysis scores of measured traits in 20 families, dendrogram based on the PC score, and loading values. *D*, stem diameter; *TH*, tree height; *BD*, basic density; *OSE*, organic solvent (EtOH-toluene) extracts; *KL*, Klason lignin; α -C, α -cellulose; *KP*, Kraft-pulp yield. The mean values of chemical and Kraft-pulp properties were recalculated from the mean values of the inner and outer heartwood data measurements

study, the relationships between chemical components and Kraft pulp properties corresponded to those of previous studies (Ona et al. 1995; Istikowati et al. 2016). These findings suggest that families with higher Kraft-pulp yield or α -cellulose content might result in a reduction in Klason lignin and organic solvent extracts, which are favorable responses for improving pulp and paper quality.

Variance components and characterization of families

Table 6 summarizes the variance components of the family in measured properties based on mixed-effects model with the random effect of family. Organic solvent extracts of the outer heartwood and γ -cellulose of the inner heartwood showed nearly zero family variance, indicating negligible differences among families. For the remaining traits, the family variance component ratios ranged from 1.7% (Klason lignin of the inner heartwood) to 23.5% (Kraft-pulp yield of the outer heartwood). Relatively large variance component ratios were observed in ash (inner heartwood, 22.5%), holocellulose (inner heartwood, 22.4%), β -cellulose (inner and outer heartwood, 22.3 and 22.2%), hot-water extracts (inner heartwood, 21.2%), α -cellulose (outer heartwood, 20.1%), and stem diameter (19.2%). By contrast, Klason lignin

exhibited relatively smaller family variance component ratios (1.7–8.8%), and the ratio in the organic-solvent extracts of inner heartwood was also low (4.9%). All fixed-effect parameters were statistically significant ($p < 0.001$). These results indicate that phenotypic differences among families were more pronounced for traits associated with polysaccharides and pulp yield, possibly reflecting differences in seed origin.

Figure 2 shows the PCA scores of breeding values for measured traits, a dendrogram based on the principal component (PC) scores, and loading values. The cumulative proportion of variance in PC1 and PC2 was 59.8% (Fig. 2). PC1 had high loading values for stem diameter, tree height, Klason lignin, α -cellulose, and Kraft-pulp yield, whereas basic density and organic-solvent extracts showed high loading values on PC2 (Fig. 2). The cluster analysis using obtained loading values revealed that 20 families were divided into two groups (Fig. 2). The eight families in group II showed superior radial growth, high Kraft-pulp yield, and low Klason lignin contents. The opposite trend was found in the 12 families in group I (Fig. 2). Therefore, the wood from the families of group II might be suitable for pulp and paper production. In addition, group II was dominated by almost all the families from sub-lines A and B, originating from PNG provenance. The growth characteristics and wood properties related to pulp and paper qualities may be due to differences in seed origin. In conclusion, families with superior growth tended to show higher pulp yield and favorable chemical composition, suggesting potential for improving pulp properties in the third-generation *A. mangium*.

Conclusion

Among-family variations in the contents of wood chemical components and Kraft-pulp properties were investigated for the inner and outer heartwood of 10-year-old third-generation *Acacia mangium*. The variance component analysis revealed that the magnitude of among family variations in measured properties with greater variations was observed for those associated with polysaccharides and pulp yield. Significant and positive phenotypic correlations were observed between several growth characteristics and wood properties, suggesting that the content of wood chemical components and Kraft-pulp properties depend on growth characteristics. Although lower in Kraft-pulp yield and higher in Klason lignin, outer heartwood contains a relatively high α -cellulose fraction, making it suitable for dissolving pulp production, which emphasizes cellulose purity rather than yield. The PCA and cluster analysis results, using multiple measured traits, showed that the 20 families could be categorized into two distinct groups. One group consisted of almost all the families from the sub-lines A and B and was characterized by the following: superior radial growth, high Kraft-pulp yield, and low Klason lignin contents of heartwood, which can reduce bleaching costs and improve processing efficiency. Therefore, pulp and paper quality can be enhanced by utilizing wood from group II families originating from PNG provenance. In conclusion, the findings from this study provide phenotypic information that can support future improvement and utilization of *A. mangium* for pulp and paper production.

Acknowledgements The authors thank the students of the Department of Bioresources Technology and Veterinary, Vocational College, Universitas Gadjah Mada, Indonesia, as well as the staff of the Forest Tree Seed Center Regional 3, Yogyakarta, Indonesia, for their help in fieldwork.

Author contributions Conceptualization: M., A.N., S.S., F.I, Methodology: M., I.N., F.H., A.N., S.S., F.I, Data collection: M., I.N., F.H., A.N., S.S., S., D.K., F.I, Data analysis: M., I.N., F.I, Writing—original draft: M., I.N., F.I, Writing—reviewing and editing: F.H., A.N., S.S., S., D.K., J.O., S.Y, Visualization: M., I.N., F.I. All authors reviewed the manuscript.

Data availability The raw data can be obtained at the request of the corresponding author.

Declarations

Conflict of interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Alves A, Rodrigues JC (2022) Correlation between lignin content and syringyl-to-guaiacyl (S/G) ratio of *Eucalyptus globulus* wood. *Holzforschung* 76:791–798. <https://doi.org/10.1515/hf-2021-0119>
- Baeza J, Freer J (2001) Chemical characterization of wood and its components. In: Hon DNS, Shiraishi N (eds) *Wood and cellulosic chemistry*, 2nd edn. Marcel Dekker Inc, New York, pp. 275–384
- Bates D, Mächler M, Bolker BM, Walker SC (2015) Fitting linear mixed-effects models using lme4. *J Stat Softw* 67:1–48. <https://doi.org/10.18637/jss.v067.i01>
- Brawner JT, Sunarti S, Nirsatmanto A, Indrayadi H, Tarigan M, Yulianto M, Rahayu S, Hardiyanto EB, Glen M, Mohammed C, Rimbawanto A (2022) Screening clonally replicated *Acacia mangium* breeding populations for tolerance to *Ceratocystis* canker and wilt disease. *Tree Genet Genomes* 18:17. <https://doi.org/10.1007/s11295-022-01548-9>
- dos Santos VB, da Conceição GJ, Rodrigues PD, Cirilo NRM, Almeida MNF, Rocha MFV, Guimarães JFR, Carvalho AMML, Gomes FJB, Marcelino PRC, de Paula Barbosa VO, Neto TCC, Moulin JC, Pedrazzi C, Vidaurre GB (2024) Impact of age and genotype on the quality of *Eucalyptus* wood for dissolving pulp. *Ind Crops Prod* 218:118930. <https://doi.org/10.1016/j.indcrop.2024.118930>
- Feng Q, Yan L, Huang G, Ren S, Appelt J, Radtke S, Koch G, Cao J, Zhao R (2025) Variation in anatomical characteristics and chemical compositions during the sapwood to heartwood transformation of cultivated teak and their relationships to color formation. *Wood Sci Technol* 59:38. <https://doi.org/10.1007/s00226-025-01642-w>
- Haque M, Nanjiba M, Jahan MS, Quaiyyum MA, Alam MZ, Nayeem J (2019) Pre-bleaching of kraft acacia pulp. *Nordic Pulp Paper Res J* 34:165–172. <https://doi.org/10.1515/npprj-2018-0082>
- Hardiyanto EB, Inail MA, Nambiar S, Mendham DS (2024) Sustaining plantation forest productivity in Sumatra over three decades: from acacias to eucalypts. *For Ecol Manage* 553:121613. <https://doi.org/10.1016/j.foreco.2023.121613>
- Haupt M, Leithoff H, Meier D, Puls J, Richter HG, Faix O (2003) Heartwood extractives and natural durability of plantation-grown Teakwood (*Tectona grandis* L.): a case study. *Holz Roh- Werkst* 61:473–474. <https://doi.org/10.1007/s00107-003-0428-z>
- Hillis WE (1987) *Heartwood and tree exudates*. Springer, Berlin, Heidelberg

- Istikowati WT, Aiso H, Sunardi, Sutiya B, Ishiguri F, Ohshima J, Iizuka K, Yokota S (2016) Wood, chemical, and pulp properties of woods from less-utilized fast-growing tree species found in naturally regenerated secondary forest in South Kalimantan, Indonesia. *J Wood Chem Technol* 36:250–258. <https://doi.org/10.1080/02773813.2015.1124121>
- Jahan MS, Mun SP (2005) Effect of tree age on the cellulose structure of Nalita wood (*Trema orientalis*). *Wood Sci Technol* 39:367–373. <https://doi.org/10.1007/s00226-005-0291-7>
- JIS P821 (2011) Pulp-determination of Kappa Number, Japanese Industrial Standards, 2011
- Karlinasari L, Sabed M, Wistara INJ, Purwanto YA (2014) Near infrared (NIR) spectroscopy for estimating the chemical composition of (*Acacia mangium* Willd.) wood. *J Indian Acad Wood Sci* 11:162–167. <https://doi.org/10.1007/s13196-014-0133-z>
- Kurinobu S (2005) Overseas forest tree breeding and genetic resources (4): genetic gains achieved by the two generations of breeding for *Acacia mangium* in Indonesia. *Trop For* 64:66–71. https://doi.org/10.32205/ttf.64.0_66
- Kuroda K (2000) Wood analysis. In: Japan Wood Research Society (ed) Manual for wood science experiments. Buneido, Tokyo, pp 88–97
- Lange W, Hashim R (2001) The composition of the extractives from unaffected and heartrot affected heartwood of *Acacia mangium* Willd. *Holz Roh- Werkst* 59:61–66. <https://doi.org/10.1007/s001070050475>
- Lemmens RHMJ, Soerianegara I, Wong WC (1995) Plant resources of South-east Asia No5(2) timber trees: minor commercial timbers. Prosea Foundation, Bogor
- Lhate I, Cuvilas C, Terziev N, Jirjis R (2010) Chemical composition of traditionally and lesser used wood species from Mozambique. *Wood Mater Sci Eng* 5:143–150. <https://doi.org/10.1080/17480272.2010.484867>
- Lourenço A, Baptista I, Gominho J, Pereira H (2008) The influence of heartwood on the pulping properties of *Acacia melanoxylon* heartwood. *J Wood Sci* 54:464–469. <https://doi.org/10.1007/s10086-008-0972-6>
- Lukmandaru G (2018) Chemical characteristics of *Eucalyptus pellita* with heart rot. *Wood Res* 63:193–202
- Lukmandaru G, Takahashi K (2008) Variation in the natural termite resistance of Teak (*Tectona grandis* Linn. fil.) wood as a function of tree age. *Ann For Sci* 65:708. <https://doi.org/10.1051/forest:2008047>
- Lukmandaru G, Warahapsari FA, Sunarta S (2025) Effect of extractive removal on kraft pulp properties of *Acacia aulocarpa* wood. *J Trop Sci* 37:108–111. <https://doi.org/10.26525/jtfs2025.37.3.374>
- Malinen RO, Pisuttipiched S, Kolehmainen H, Kusima FN (2006) Potential of *Acacia* species as pulpwood in Thailand. *Appl J* 59:190–196. <https://doi.org/10.3316/INFORMIT.531523545324578>
- Martins GS, Yuliarto M, Antes R, Sabki, Prasetyo A, Unda F, Mansfield SD, Hodge GR, Acosta JJ (2020) Wood And pulping properties variation of *Acacia crassicaarpa* A. Cunn. Ex Benth. and sampling strategies for accurate phenotyping. *Forests* 11:1043. <https://doi.org/10.3390/f11101043>
- Martins GS, Yuliarto M, Yong WC, Melia T, Maretha MV, Sharma M, Lakey N, Ordway J, Acosta JJ, Hodge G (2024) Estimation of additive and dominance effects in an *Acacia crassicaarpa* multi-environment progeny trial using genomic pedigree reconstruction. *For Sci* 70:113–122. <https://doi.org/10.1093/forsci/fxae004>
- Masendra, Nezu I, Ishiguri F, Hidayati F, Nirsatmanto A, Sunarti S, Surip, Kartikaningtyas D, Takashima Y, Takahashi Y, Ohshima J, Yokota S (2023) Variations of growth and wood traits in standing trees of the third-generation *Acacia mangium* families in Indonesia. *Silvae Gen* 72:150–162. <https://doi.org/10.2478/sg-2023-0016>
- Masendra, Nezu I, Ishiguri F, Hidayati F, Nirsatmanto A, Sunarti S, Surip, Kartikaningtyas D, Ohshima J, Yokota S (2024) Among-family variations of wood-color parameters, decay resistance, total phenol, and total flavanol content in the heartwood of the third-generation *Acacia mangium* in Indonesia. *Holzforchung* 78:587–598. <https://doi.org/10.1515/hf-2024-0063>
- Mbomba UCM, Tanaka Y, Nezu I, Ishiguri F, Diloksumpun S, Tanabe J, Ohshima J, Iizuka K, Yokota S (2022) Among-family variations of direct measurement values for chemical and pulp properties in 4-year-old *Eucalyptus camaldulensis* half-sib families in Thailand. *Nord Pulp Pap Res J* 37:405–412. <https://doi.org/10.1515/npprj-2022-0014>
- Nambiar EKS, Harwood CE (2014) Productivity of acacia and eucalypt plantations in Southeast Asia. 1. Bio-physical determinants of production: opportunities and challenges. *Int Forestry Rev* 16:225–248. <https://doi.org/10.1505/146554814811724757>
- Neiva DM, Godinho MC, Simões RMS, Gominho J (2024) Encouraging invasive *Acacia* control strategies by repurposing their wood biomass waste for pulp and paper production. *Forests* 15:822. <https://doi.org/10.3390/f15050822>

- Nickolas H, Williams D, Downes G, Tilyard P, Harrison PA, Vaillancourt RE, Potts B (2020) Genetic correlations among pulpwood and solid-wood selection traits in *Eucalyptus globulus*. *New Forests* 51(1):137–158. <https://doi.org/10.1007/s11056-019-09721-0>
- Nirsatmanto A (2012) Genetic variation observed in composite seedling seed orchard of *Acacia mangium* Willd. at central Java, Indonesia: implications for increasing genetic gain and seed production. *J Forestry Res* 9:91–100. <https://doi.org/10.20886/ijfr.2012.9.2.91-99>
- Nirsatmanto A, Kurinobu S (2002) Trend of within-plot selection practiced in two seedling seed orchards of *Acacia mangium* in Indonesia. *J Forest Res* 7:49–52. <https://doi.org/10.1007/BF02762598>
- Nirsatmanto A, Kurinobu S, Hardiyanto EB (2003) A projected increase in stand volume of introduced provenances of *Acacia mangium* in seedling seed orchards in South Sumatra, Indonesia. *J Forest Res* 8:127–131. <https://doi.org/10.1007/s103100300016>
- Nirsatmanto A, Leksono B, Kurinobu S, Shiraishi S (2004) Realized genetic gain observed in second-generation seedling seed orchards of *Acacia mangium* in South Kalimantan, Indonesia. *J For Res* 9:265–269. <https://doi.org/10.1007/s10310-004-0081-3>
- Nirsatmanto A, Setyaji T, Surip (2013) Trend of realized genetic gain observed in second-generation seedling seed orchards of *Acacia mangium* in South Kalimantan. *Indonesian J Res* 10:57–65. <https://doi.org/10.20886/ijfr.2013.10.1.57-64>
- Nirsatmanto A, Setyaji T, Sunarti S, Kartikaningtyas D (2015) Genetic gain and projected increase in stand volume from two cycles breeding program of *Acacia mangium*. *Indonesian J Res* 2:71–79. <https://doi.org/10.20886/ijfr.2015.2.2.71-79>
- Nirsatmanto A, Sunarti S, Putri AI, Haryjanto L, Kartikawati NK, Herawan T, Lestari F, Pudjiono S, Rim-bawanto A (2023) Genetic stability observed in third-generation progeny trial of *Acacia mangium*: the importance of genotype by environment interaction assessment in advance generation breeding strategy. *For Sci Technol* 19:285–295. <https://doi.org/10.1080/21580103.2023.2264887>
- Ona T, Sonoda T, Ito K, Shibata M (1995) Studies on decision of selection indexes for quality breeding eucalypt pulpwood (VI): relationship between wood and pulp properties brought by their within-tree variations on *E. camaldulensis*. *Jpn Tappi J* 49:1347–1356
- Panshin AJ, de Zeeuw C (1980) Text book of wood technology, 4th edn. McGraw-Hill, New York
- Pieterinen S, Willför S, Holmbom B (2004) Wood resin in *Acacia mangium* and *Acacia crassiparpa* wood and knots. *Appita J* 57:146–150
- Poke FS, Potts BM, Vaillancourt RE, Raymond CA (2006) Genetic parameters for lignin, extractives and decay resistance in *Eucalyptus globulus*. *Ann Sci* 63:813–821. <https://doi.org/10.1051/forest:2006080>
- Quang TH, Kien ND, von Arnold S, Jansson G, Thinh HH, Clapham D (2010) Relationship of wood composition to growth traits of selected open-pollinated families of *Eucalyptus urophylla* from a progeny trial in Vietnam. *New Forests* 39:301–312. <https://doi.org/10.1007/s11056-009-9172-5>
- R Core Team (2023) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>. Accessed on 1 May 2024
- Sakakibara A, Sano Y (2001) Chemistry of lignin. In: Hon DNS, Shiraishi N (eds) *Wood and cellulosic chemistry*, 2nd edn. Marcel Dekker Inc, New York, pp. 109–174
- Sjöström E, Alén R (1999) *Analytical methods in wood chemistry, pulping, and papermaking*. Springer, Berlin, Heidelberg
- Stackpole DJ, Vaillancourt RE, Alves A, Rodrigues J, Potts BM (2011) Genetic variation in the chemical components of *Eucalyptus globulus* wood. *G3 Genes|Genomes|Genetics* 1:151–159. <https://doi.org/10.1534/g3.111.000372>
- Sunarti S, Nirsatmanto A, Brawner J, Setyaji T, Kartikaningtyas D, Handayani BR, Surip, Hidayati F (2022) Effect of genetic gain in diameter and wood density on advanced generation breeding strategy of *Acacia mangium* in Indonesia. *J Trop Sci* 34:92–102. <https://doi.org/10.26525/jtfs2022.34.1.92>
- Susanto M, Hasegawa M, Lukmandaru G, Budi S, Baskorowati L, Nurtjahjaningsih ILG, Hendrati RL, Pudjiono S, Setiadi D, Sumardi, Damayanti R, Achmad B, Bhermana A, Fauzan YSA, Hidyati F (2025) Genetic variations in wood properties of third generation *Acacia mangium* Willd. progeny tests from Sumatra, Indonesia. *Wood Fiber Sci* 57:111–121. <https://doi.org/10.2238/wfs-2025-10>
- Yahya R, Sugiyama J, Silsia D, Gril J (2010) Some anatomical features of an *Acacia* hybrid, *A. mangium* and *A. auriculiformis* grown in Indonesia with regard to pulp yield and paper strength. *J Trop Sci* 22:343–351
- Yokoi H, Ishida Y, Ohtani H, Tsuge S, Sonoda T, Ona T (1999) Characterization of within-tree variation of lignin components in *Eucalyptus camaldulensis* by pyrolysis–gas chromatography. *Analyst* 124:669–674. <https://doi.org/10.1039/a809217f>

Yokoyama H, Masendra, Nezu I, Hidayati F, Irawati D, Ngadianto N, Nirsatmanto A, Sunarti S, Surip, Kartikaningtyas D, Ohshima J, Yokota S, Ishiguri F (2025) Evaluation of differences in radial variations of wood properties among families for producing the next-generation *Acacia mangium* in Indonesia. *Silvae Genet* 74:20–30. <https://doi.org/10.2478/sg-2025-0003>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.