Genetic variations in wood properties of third generation *Acacia mangium* Willd. progeny tests from Sumatra, Indonesia

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Abstract. *Acacia mangium* Willd. is a fast-growing tree commonly used in pulp and paper production. Despite extensive planting, there is a need for genetic improvement to enhance wood properties for better pulp output. This study assessed genetic variations in moisture content, pilodyn penetration, specific gravity, fiber length, cell wall thickness, lumen diameter, and cellulose content in a third-generation progeny test of *A. mangium* in South Sumatra, involving 52 families. Averages for 3-year-old *A. mangium* were as follows: pilodyn penetration at 11.22 mm, moisture content at 117.18%, specific gravity at 0.44, fiber length at 1.01 mm, and alpha cellulose at 68.03%. Phenotypic variation of wood properties ranged from 3.53% to 19.62%, while genotypic variation was between 1.83% and 9.91%. There was a strong genetic correlation between pilodyn penetration and wood properties (specific gravity, holocellulose, and alpha cellulose) with individual heritability of wood properties estimates (h^2_i) from 0.09 to 0.37. Significant family differences were found in pilodyn penetration, specific gravity, fiber length, holocellulose, and alpha cellulose, with genetic gains of wood properties between 1.78% and 9.72%.

Keywords: *Acacia mangium*; Genetic improvement; Wood properties; Pulp production; Heritability estimates

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Introduction

Acacia mangium Willd. is a key species in the pulp and paper industry, particularly in tropical regions of Southeast Asia, where it has become a favored plantation species due to its rapid growth, adaptability to varied climates, and valuable wood properties (Hegde et al. 2013). Since the 1990s, Indonesia has widely cultivated *A. mangium* on marginal lands across the country, promoting it as a sustainable resource to meet the rising demand in the pulp and paper sector (Sutedjo and Warsudi 2017; Goreti et al. 2021). This species is distributed in several regions, such as Riau, South Sumatra, West Java, South Kalimantan, East Kalimantan, West Papua, and Maluku province (Figure 1). However, initial plantations were established using unimproved seeds, which limited wood productivity and quality (Suyanto and Soedjoko 2007; Krisnawati et al. 2011; Goreti et al. 2021).

To address these limitations, the Indonesian Ministry of Environment and Forestry (MoEF), in collaboration with the Japan International Cooperation Agency (JICA) and Musi Hutan Persada Company, initiated a breeding program in 1993. This program began with a first-generation progeny test and was later extended to second- and third-generation trials focused on growth enhancement. However, these trials initially did not assess wood property traits critical for pulp production, such as specific gravity, fiber length, lignin, and cellulose content, which directly affect pulp yield and quality (Nisatmanto and Kurinobu 2002; Susanto et al. 2013; Nirsatmanto 2016; Sunarti et al. 2022). Given the industry's need for both high growth rates and quality wood, improving the genetic traits of *A. mangium* relevant to pulp properties has become essential.

The pulp and paper industry requires raw materials characterized by substantial wood increments and superior quality. The quality of wood is indicated by pulp output; thus, investigations into pulp-related wood qualities are essential for tree selection in third-generation progeny tests. Qualities such as specific gravity and fiber length are critical determinants of tree species' utility for pulp manufacturing. The primary chemical constituents of wood that constitute cell walls (cellulose and lignin) and extractive substances, together with their distribution inside the cell walls, influence the characteristics of pulp and paper (Pereira et al. 2003). Fengel and Wegener (1995) indicated that several wood properties affecting pulp production for paper comprise specific gravity, moisture content, fiber dimensions, wood extractives, lignin, and cellulose. The potential for genetic improvement in morphological traits and wood properties has been validated (Harwood et al. 2015).

This study therefore aimed to identify genetic variations in wood properties related to pulp production in third-generation *A. mangium* progeny trials. Key wood characteristics evaluated were pilodyn penetration, moisture content, specific gravity, fiber length, and chemical contents (lignin, holocellulose, alpha cellulose) to determine their impact on pulp output. Estimated genetic parameters, including heritability and genetic gain, were used to assess the potential for genetic improvement of these traits. Genetic correlations between pilodyn penetration and wood properties were used to develop efficient selection criteria for high-quality trees in breeding programs without

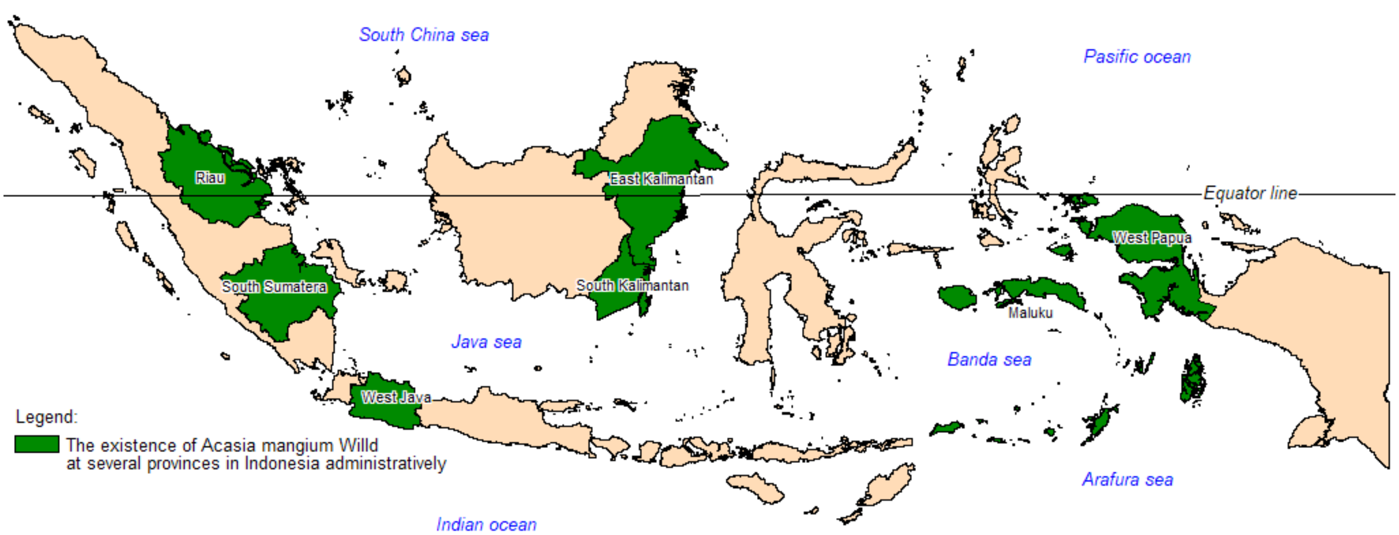

Figure 1. Spatial distribution of *Acacia mangium* Willd. in Indonesia.

causing damage to standing trees. Ultimately, the study aims to provide insights for optimizing *A. mangium* breeding programs focused on enhancing wood properties crucial for the pulp and paper industry in Indonesia.

Materials and Methods

Trial site, genetic material and experimental design

The third-generation progeny test of *A. mangium* was conducted in the Subanjeriji Trial, located at latitude 3.4°S and longitude 103.7°E. The trial was established at an elevation of 110 m above sea level in South Sumatra on podzolic soil. The average minimum temperature of the coldest month was 23°C, while the average maximum temperature of the hottest month was 33°C. Annual precipitation was 2,082 mm, with peak rainfall occurring from December to March and minimal rainfall in June. Humidity levels varied from 29% to 73%.

The progeny test comprised 52 open-pollinated families from the second-generation progeny test of *A. mangium* (Oriomo-Papua New Guinea provenance) during the Subanjeriji Trial. The experimental arrangement comprised 30 replications (blocks) utilizing a row-column pattern (incomplete block design) at group B-3 in Figure 2. Each plot consisted of a single row of four trees, with a spacing of 4 m between rows and 3 m between trees within each row. Only 10 blocks were used for measuring the wood properties (Figure 2).

Wood sample collection and wood properties measurement

A total of 326 trees (52 families with different replications of each family with a range of 3 to 11 trees) of 3-year-old third-generation *A. mangium* progeny were measured. Pilodyn penetration was measured on standing trees using a Pilodyn tester (6 J Forest, Proceq, Switzerland) with three positions were obtained for each tree at 50 cm above the ground after removing the bark (Ishiguri et al. 2008; Hidayati et al. 2013a; Hidayati et al. 2013b). The mean values of pilodyn penetration were calculated for each tree.

The average diameter of the sample trees was 20.85 cm (±3.49 cm). The sample trees were cut and wood discs samples were taken 50 cm above the ground. Wood samples were obtained from 52 families (the same number of the trees as for pilodyn testing) The discs were used to measure green specific gravity, green moisture content, fiber length, cell wall thickness, lumen diameter, lignin content, extractive content, alpha-cellulose content, and holocellulose content. Radial strips (2 cm in width, 2 cm in thickness, and length dependent on tree diameter) were prepared from each disk for measuring moisture content and specific gravity. Green specific gravity was determined from pith to bark. Blocks were obtained from one side with respect to the pith of the disk. Green specific gravity was calculated as the ratio of oven-dry mass to green volume, as determined by the water displacement method.

Measurements of fiber dimensions (fiber length, lumen diameter, and cell wall thickness) were conducted using a micrometer. Small strip specimens were macerated with Franklin's solution (100% glacial acetic acid [CH_3COOH] and 50% hydrogen peroxide [$H_2O_{2]}$ at a 1:10 ratio) for measuring fiber dimensions. The macerated fibers were stained with 1% safranin, cleared with alcohol, then mounted with Canada balsam. Images were captured using a digital camera attached to a microscope. A total of 50 wood fibers were measured for fiber length. Lumen diameter and cell wall thickness were also measured, using the macerated sample. Three positions of each fiber were measured for lumen diameter and cell wall thickness, then averaged. Ten fibers were measured for every sample, then averaged for each sample.

Wood samples were extracted for the analysis of wood chemistry, according to Technical Association of the Pulp and Paper Industry (TAPPI) standard T 204 cm-97 (1997). Lignin and alpha-cellulose contents were quantified utilizing TAPPI T 222 om-2 (2006) and TAPPI T 203 cm 99 (1999). Holocellulose content in wood samples was analyzed utilizing the acid chlorite method (Browning 1967).

Data Analysis

Common general linear models described by Hocking et al. (1978), Setiadi et al. (2021), Baskorowati et al. (2022), Purwanto et al. (2022), and Susanto et al. (2024) were utilized in this research. An analysis of variance (ANOVA) was carried out in order to investigate differences among families on the basis of the linear model presented below:

$$Y_{ijkl} = \mu + R_i + F_j + e_{ijk} \quad (1)$$

where, Y_{ijkl} = plot mean at j^{th} family and i^{th} replicate; μ = overall mean; R_i = effect of the i^{th} replicate; F_j = effect of the j^{th} family; and E_{ijk} = residual error with a mean of zero.

Individual tree heritabilities (h^2_i) was calculated based on Williams et al. (2002):

$$h^2_i = 1/r * \sigma^2_f/\sigma^2_p \quad (2)$$

where, r = coefficient of relationship; σ^2_f = variance between families; σ^2_p = phenotypic variance = ($\sigma^2_f + \sigma^2_m$); and σ^2_m = variance between plot.

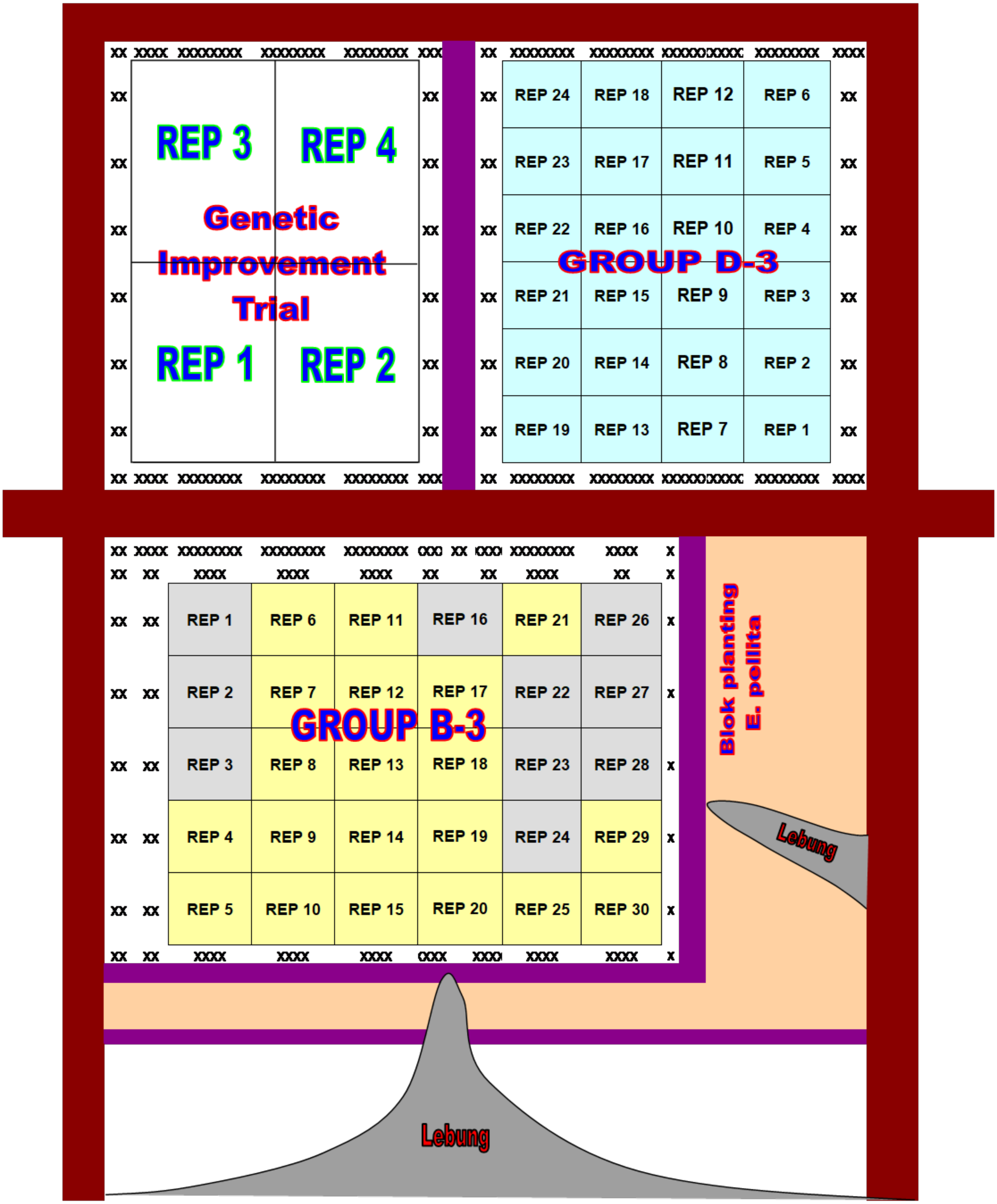

Figure 2. Layout of research plot at the Subanjeriji Trial.

Phenotypic coefficient of variation (PCV) (%) and genotypic coefficient of variation (GCV) were estimated according to Burton and DeVane (1953).

$$PCV = \frac{\sqrt{\sigma^2 p}}{\bar{x}} \times 100 \quad (3)$$

$$GCV = \frac{\sqrt{\sigma^2 g}}{\bar{x}} \times 100 \quad (4)$$

where, σ^2 g = variance component of genotypic = σ^2A; σ^2A = variance component of additive = 1/r * σ^2_f; σ^2p = variance component of phenotypic; and $\bar{x}$ = mean of value of wood properties.

Genetic correlations (denoted r_g) were calculated according methodologies described by Williams et al. (2002):

$$r_g = \frac{Cov_f(X,Y)}{[\sigma^2_f(x) \cdot \sigma^2_f(y)]^{1/2}} \quad (5)$$

where, $Cov_f(X,Y)$ = covariance of the two traits at family level; σ^2_f (x) = family-level variance components of trait (x); and σ^2_f (y) = family-level variance components of trait (y).

Expected genetic gain (denoted ΔG) in the trial was estimated based on Shelbourne (1992):

$$\Delta G = i \cdot \sigma^2_p \cdot h^2_i \quad (6)$$

where, I = selection intensity; σ^2_p = phenotypic variance; and h^2_i = individual heritability for the trait of interest.

Results

Measurements and analyses of wood properties in 3-year-old *A. mangium* progeny trials at Subanjeriji in South Sumatra are shown in Tables 1–4. The mean and range of wood qualities evaluated, together with the genetic and phenotypic variety are presented in Table 1.

The range of phenotypic coefficients of variation of wood properties in the progeny trials ranged from 3.53% to 19.62% (Table 1), indicating that the phenotypic variance of wood properties was relatively small. The genotypic coefficient of variance in the progeny test was from 1.83% to 9.91%. This indicated that the genetic variation was also low. Individual heritability estimates for wood properties in the study ranged from low to high (h^2_i = 0.09 to 0.37), indicating that not all wood properties were strongly controlled by genetics.

Pilodyn penetration, moisture content, specific gravity, fiber length, holocellulose content, and alpha cellulose content all differed significantly amongst families (Table 2). Cell wall thickness, lumen diameter, extractive content, and lignin content did not differ significantly between families.

The genetic and phenotypic correlations between wood properties in the third-generation *A. mangium* progeny test at Subanjeriji are displayed in Table 3. Several wood properties exhibited significant genetic and phenotypic relationships among themselves (Table 3). Strong negative and positive genetic correlations are essential in tree selection activities based on wood characteristics.

The evaluation of genetic gain for wood properties of 3-year-old *A. mangium* in the third-generation progeny test in the Subanjeriji Trial is shown in Table 4. Estimated genetic gains for wood qualities from 3-year-old *A. mangium* in the third-generation progeny test in the Subanjeriji Trial are presented in Table 4. Genetic gain ranged from 1.78% to 9.72%, contingent upon a selection intensity of 10% for identifying the superior trees within the progeny test population.

Table 1. Mean, phenotypic coefficient of variation (PCV), genotypic coefficient of variation (GCV) and individual heritability (h^2_i) of *Acacia mangium* wood properties.

Wood property	Variation ranges	$\bar{x}$±SD	PCV (%)	GCV (%)	h^2_i
Pilodyn penetration	7.50–15.75 (mm)	11.22 (±1.42) mm	11.69	6.36	0.30
Moisture content	51.50–330.18 (%)	117.18 (±32.90) %	10.15	5.77	0.15
Specific gravity	0.22–0.72	0.44 (±0.07)	16.70	9.91	0.37
Fiber length	0.76–1.20 (mm)	1.01 (±0.06) mm	5.77	3.13	0.35
Cell wall thickness	2.41–5.00 (µm)	3.05 (±0.41) µm	13.56	4.27	0.09
Lumen diameter	7.59–19.44 (µm)	12.32 (±2.13) µm	17.33	6.34	0.13
Extractive content	1.60–7.14 (%)	3.64 (±1.15) %	19.62	9.11	0.24
Lignin content	19.35–39.45 (%)	24.10 (±5.57) %	11.85	5.46	0.21
Holocellulose content	63.63–83.95 (%)	74.83 (±3.93) %	3.53	1.83	0.27
Alpha cellulose content	53.08–68.82 (%)	68.03 (±3.86) %	9.99	6.09	0.37

Notes: $\bar{x}$±SD = Mean and standard deviation.

Table 2. Analysis of variance (ANOVA) of *Acacia mangium* wood properties.

Wood properties / Variance Sources	Df	MS	Pr>F
Pilodyn penetration			
Replications	9	7.633	<0.0001**
Families	51	3.683	<0.0001**
Error	740	1.236	
Moisture content			
Replications	9	0.004	<0.2171**
Families	51	0.004	<0.0491*
Error	740	0.002	
Specific gravity			
Replications	9	0.061	<0.0001**
Families	51	0.007	<0.0001**
Error	262	0.003	
Fiber length			
Replications	9	0.006	0.0525
Families	51	0.005	0.0038**
Error	267	0.002	
Cell wall thickness			
Replications	9	0.358	0.0200*
Families	51	0.137	0.7390
Error	267	0.160	
Lumen diameter			
Replications	9	2.455	0.8410
Families	51	5.272	0.2152
Error	267	4.505	
Extractive content			
Replications	9	0.923	0.0428
Families	51	0.650	0.0529
Error	264	0.468	
Lignin content			
Replications	9	12.702	0.0948
Family	51	10.122	0.0768
Error	264	7.579	
Holocellulose content			
Replications	9	15.976	0.0074**
Family	51	9.271	0.0235*
Error	264	6.202	
Alpha cellulose content			
Replication	9	470.365	< 0.0001**
Family	51	61.353	< 0.0001**
Error	269	26.973	

Notes: ns = not significant; * = significant at level of 0.05; ** = significant at level of 0.01.

Discussion

Significant differences among families were observed for pilodyn penetration, specific gravity, fiber length, holocellulose content, and alpha cellulose content. The findings indicated that pilodyn penetration, moisture content, specific gravity, fiber length, holocellulose content, and alpha cellulose content were influenced by family variation, suggesting genetic control. These wood properties must be considered in forestry breeding programs to meet the seedling needs for wood quality suitable for pulp production. Specific gravity, fiber length, holocellulose content, and alpha cellulose concentration are essential for pulp production (Arisman 1996; Lestari 2012).

Wood properties revealed that the third-generation *A. mangium* progeny test showed significant variances among individual trees (Table 1). This signifies that wood properties must be acknowledged as genetic variables in the breeding of *A. mangium* and establishes a basis for choosing the most suitable trees with superior wood quality. The selection of trees for wood qualities is based on individual heredity. Fiber length, specific gravity, extractives content, lignin content, alpha cellulose content, and holocellulose content demonstrate significant heritability; hence, these wood qualities need meticulous attention in tree selection to obtain superior wood quality.

Alpha-cellulose is essential for assessing cellulose purity. The presence of lignin and extractives adversely affects pulp quality. Nonetheless, there was no substantial difference between families in the progeny test regarding lignin and extractive content; so, these two factors may be excluded from consideration in tree selection, since they do not influence the quality of the resultant pulp. This study revealed significant variability in wood properties among 3-year-old third-generation *A. mangium* (Table 1). Thus, wood characteristics must be considered within the genetic criteria for the breeding of *A. mangium.*

Average specific gravity of the third generation of *A. mangium* at the age of 3 years was 0.44, with a variation range that extended from 0.22 to 0.72. This indicates that the trees possess qualities that are suitable for pulp production. Other research indicates that the ideal specific gravity range of *A. mangium* for pulp production is 0.37 to 0.46 (Arisman 1996). Susanto et al. (2013) examined the specific gravity of 17 provenances in the first generation of 5-year-old *A. mangium* progeny tests in Wonogiri, Central Java, and found that variances in specific gravity between provenances ranged from 0.40 to 0.47. Specific gravity of the trees from both the first and third generations provided promising potential for pulp manufacturing.

Table 3. Genetic (above the cross) and phenotypic correlation (under the cross) between wood properties of *Acacia mangium.*

	PP	SG	Ext	HC	Lig	AC	FL	LD	CW	MC
PP		-0.67	-0.98	-0.22	0.58	-0.96	0.00	-0.48	0.55	0.46
SG	-0.68		0.16	0.03	-0.24	0.53	-0.32	0.00	0.00	0.61
Ext	0.01	0.06		0.34	0.60	-0.57	-0.43	0.00	0.00	0.00
HC	0.16	0.25	0.08		-0.92	-0.08	-0.43	0.72	-0.54	0.00
Lig	-0.13	0.17	0.23	-0.90		-0.11	0.45	-0.65	0.37	0.00
AC	-0.12	0.25	-0.04	0.06	0.01		-0.01	0.00	0.44	0.00
FL	0.32	0.12	-0.02	0.10	-0.10	-0.03		0.00	0.00	-0.50
LD	0.13	0.08	0.06	-0.04	-0.06	0.04	0.00		-0.82	0.00
CW	0.11	0.06	-0.02	-0.05	0.04	-0.13	0.14	-0.03		0.00
MC	0.35	-0.49	0.00	0.00	0.00	0.00	0.19	0.00	0.00	

Notes: PP = Pilodyn penetration; SG = Specific gravity; Ext = Extractive content;
HC = Holocellulose content; Lig = Lignin content; AC = Alpha cellulose;
FL = Fiber length; LD = Lumen diameter; CW= Cell wall thickness; MC = moisture content

This study revealed that the average cell wall thickness was 3.05 µm, with a range from 2.41 to 5.00 µm. Average lumen diameter was 12.27 µm, with a range from 7.59 to 19.44 µm. Average fiber length was 1.01 mm, with a range from 0.76 to 1.2 mm. Variability in cell wall thickness, lumen diameter, and fiber length in progeny tests are of fundamental importance in breeding trials. Although the average fiber length in the third-generation progeny test was greater than that for the first generation of *A. mangium* in Pelaihari, South Kalimantan, at 22 months of age, at 0.89 mm (Susanto et al. 2012), it was shorter than the fiber length of the first generation at the Wonogiri Trial at the age of 5 years, which was 1.04 mm (Susanto et al. 2013). The generational differences, geographic variations, and age when fiber length was measured are factors that contribute to the variations in fiber length in *A. mangium*. Variations in fiber length of *A. mangium* trees have also been studied in Central Java (Hasegawa et al. 2009).

Average extractive content of 3-year-old third-generation *A. mangium* was 3.64%, lignin content was 24.10%, holocellulose content was 74.83%, and alpha cellulose content was 68.03%. The lower alpha cellulose content demonstrated that it is appropriate for use as a raw material in the paper industry (Lestari 2012). In contrast to the findings of other investigations on *Eucalyptus pellita*, the results of this specific inquiry are presented in Table 5.

Extractive content of *A. mangium* was lower than that of *E. globulus*, which was reported at 6% in West Ridgley, Tasmania (Poke et al. 2005), and lower than the extractive content of *Acacia melanoxylon* in Portugal (Lourenço et al. 2008). Lignin level was lower than that of *E. globulus*, which was 28.48%. Holocellulose and alpha cellulose content were superior to those of other species: *E. globulus* has a holocellulose content of 42.40% (Poke et al. 2005); *Antocephalus* spp. a holocellulose content of 39.20%; and *Falcataria moluccana* exhibited holocellulose and alpha cellulose contents of 63.39% and 40.43%, respectively (Indrawan et al. 2015). The reduced extractives

Table 4. Genetic gain estimation of *Acacia mangium* wood properties.

Traits	$\sigma^2 p$	i	h^2_i	ΔG %
Pilodyn penetration (mm)	1.32	1.75	0.30	6.16
Moisture content (%)	5.74	1.75	0.15	1.51
Specific gravity	0.07	1.75	0.37	9.72
Fiber length (mm)	0.06	1.75	0.35	3.57
Cell wall thickness (µ)	0.41	1.75	0.09	1.78
Lumen diameter (µ)	2.13	1.75	0.13	4.01
Extractive content (%)	0.71	1.75	0.24	6.95
Lignin content (%)	2.85	1.75	0.21	4.22
Holocellulose content (%)	2.64	1.75	0.27	1.77
Alpha cellulose content (%)	6.80	1.75	0.37	6.53

Notes: $\sigma^2 p$ = variance component of phenotypic; i = selection intensity; h^2_i = individual heritability; ΔG % = % genetic gain of population mean in progeny test.
Selection proportion was 10%.

Table 5. Alpha cellulose, lignin, and extractive contents of *Eucalyptus pellita* in three locations.

Alpha cellulose (%)	Lignin (%)	Extractive (%)	Location
49.02	29.49	—	South Kalimantan (Lukmandaru et al. 2016)
48.45	29.82	5.87	Central Java (Fatimah et al. 2015)
—	29.90	10.11	East Kalimantan (Taufiqhaqiqi et al. 2022)

and lignin contents, along with elevated holocellulose and alpha cellulose levels in the *A. mangium* progeny test at Subanjeriji, are crucial for breeding initiatives aimed at enhancing seed quality for the pulp and paper sector.

The third-generation *A. mangium* progeny test revealed medium to high individual heritability for pilodyn penetration, holocellulose content, lignin content, extractive content, specific gravity, fiber length, and alpha-cellulose content (Table 2). Moderate to high individual heritability was seen in first-generation *A. magium* progeny tests in Peleihari, South Kalimantan, and Wonogiri, Central Java, as well as in *E. urophylla* progeny tests in Vietnam and *E. niten*s progeny tests in East Victoria, Australia. The individual heritability values for pilodyn penetration were 0.62 in *A. mangium* in Peleihari and 0.30 in Wonogiri, 0.42 in *E. urophylla,* and 0.60 in *E. nitens*. The individual heritabilities for specific gravity were 0.35 in *A. mangium* in Pelaihari and 0.57 in Wonogiri, 0.60 in *E. urophylla*, and 0.73 in *E. nitens* (Greaves et al. 1996; Kien et al. 2008; Susanto et al. 2012; Susanto et al. 2013).

Despite exhibiting moderate to high heritability, these wood properties do not inherently possess a large genetic coefficient of variation (GCV) (Table 2). The genetic variation of wood properties is low, as evidenced by their GCV and PCV being less than 20%. However, values with GCV or PCV over 5% included pilodyn penetration, moisture content, specific gravity, lumen diameter, extractives, lignin, and alpha cellulose. These wood properties exhibited more additive genetic variance; hence, these should be factored into tree selection. Research on genetic coefficient of variation and heritability concerning tree selection based on wood density and growth in forest trees has been conducted by Cornelius (1994).

The wood properties studied showed low genetic variation (Table 2). Low genetic variation in wood properties means that the tree selection will yield genetic gains in accordance with genetic diversity (Table 4). Decreased additive variance of wood properties resulted from the *A. mangium* tree population being a third-generation progeny test, which had undergone a selection process for genetic value, hence reducing genetic diversity. Investigations on the reduction of additive variance across succeeding generations indicated that additive variance diminished during several selection cycles, leading to decreased genetic variation relative to the initial generation (van der Werf and de Boer 1990).

The substantial negative genetic correlation between pilodyn penetration and specific gravity, extractive content, and alpha cellulose indicated that pilodyn penetration may be effective in tree selection (Table 3). Minimal damage to the tree makes it much simpler to choose trees based on the characteristics of the wood in the standing tree. An increase in holocellulose content will result in a reduction in lignin and extractive content, while an increase in wood density may also reduce lignin content. This negative correlation between these wood properties is highly advantageous for pulp and paper production. The strong correlation between pilodyn penetration and other wood properties is advantageous for the selection of trees in *A. mangium* progeny assays to optimize pulp and paper production. Rapid tree selection has the potential to enhance alpha cellulose, while simultaneously reducing the amounts of lignin and extractive content. Cown and Hutchison (1983) found a strong correlation between pilodyn penetration and basic density in *Pinus radiata* in New Zealand and suggested that this device could have an application for rapid non-destructive measurement of wood properties. The pilodyn has a long history of use as a non-destructive method for evaluating density in tree breeding programs (Sprague et al. 1983; Woods et al. 1995; Hansen 2000). Wood density and pilodyn pin penetration were significantly negatively correlated (Wei and Borralho 1997; Wu et al. 2010, 2011; Hidayati et al. 2019). Research on the pilodyn for assessing genetic improvements of wood density and selecting *Cryptomeria japonica* trees has been conducted in Japan (Fukatsu et al. 2011).

Genetic or phenotypic correlations between moisture content and other wood properties, such as extractives, holocellulose, lignin, alpha cellulose, lumen diameter, and cell wall thickness were weak. Moisture content was poorly correlated with pilodyn penetration, specific gravity, and fiber length, suggesting that moisture content does not impact other wood qualities relevant to the selection process. A significant negative genetic correlation was found between pilodyn penetration and specific gravity in the first-generation *A. mangium* progeny test in Pelaihari, South Kalimantan, with $r_g = -0.83$, and in Wonogiri, Central Java, with $r_g = -0.91$ (Susanto et al. 2012, 2013). Strong negative correlations between pilodyn pin penetration and basic density were also found in *P. radiata* with $r = -0.80$ (Cown and Hutchison 1983). Other progeny tests have revealed strong negative phenotypic and genetic correlations between pilodyn pin penetration and specific gravity in various species, including *E. urophyla* in Guangxi Zhuang Autonomous Region, with $r_g = -1.00$ and $r_p = -0.80$ (Wei and Borralho 1997); *C. japonica* in Japan, with $r_p = -0.92$ (Yamashita et al. 2007); and *E. urophyla* in Vietnam, with $r_g = -0.86$ (Kien et al. 2008), as well as *E. nitens* in eastern Victoria, Australia, with $r_g = -0.92$ and $r_p = -0.59$ (Greaves et al. 1996).

Our research suggests that the negative genetic and phenotypic correlations between fiber length and other wood properties were weak. As a result, it is useful to select trees with high alpha cellulose or holocellulose contents without diminishing fiber length. A study on *E. globulus* in Northwestern Tasmania revealed a weak genetic correlation ($r_g = 0.21$) between the fiber length and specific gravity (Apiolaza et al. 2005). A weak genetic correlation was observed in the *A. mangium* progeny test between specific gravity and fiber length, extractive content and holocellulose content, lignin content and specific gravity, and lignin content and cell thickness. A weak or moderate correlation between these wood properties implied that they were insufficient for estimating wood properties.

Specific gravity, fiber length, holocellulose content, and alpha cellulose were anticipated to improve by 9.72%, 3.57%, 1.77%, and 6.53%, respectively, following selection at 3 years of age (Table 4). The projections in wood properties may be considered cautious, due to the exclusion of some factors from these computations. Concurrently, extractive content and lignin content may decrease by 6.95% and 4.22%, respectively (Table 4). However, it is important to note that for the families in Subanjeriji, this degree of improvement is necessary to align the selected population's wood properties with those of the *A. mangium* plantation in Indonesia. This study's results demonstrate significant improvements in the commercial wood quality of *A. mangium* by selection and breeding. A program is now in progress in South Sumatra involving the progeny test of *A. mangium* at the Subanjeriji trial, aimed at converting it into a seedling seed orchard. The anticipated result of utilizing improved *A. mangium* seeds is a more efficient pulp and paper industry in Indonesia, yielding higher profits for companies and thus providing a stronger incentive to replace declining plantations with superior germplasm. An anticipated substantial advantage from a more efficient *A. mangium* is expected for several pulp and paper facilities in Indonesia.

Conclusions

Analysis of wood properties and genetic parameters in the third-generation offspring test of *A. mangium* indicated that genetic variations in wood properties were relatively low; however, there were moderate to high heritability values for attributes such as pilodyn penetration, holocellulose content, lignin content, extractive content, specific gravity, fiber length, and alpha-cellulose content. Consequently, these wood properties can serve as a basis for tree selection to enhance wood quality. Pilodyn penetration, which was strongly genetically correlated with wood properties, can be employed for tree selection to improve wood quality without causing damage to the tree stem. Concurrently, specific gravity, fiber length, holocellulose content, and alpha cellulose can be enhanced, while diminishing extractive content and lignin, thus improving the quality of the resultant wood for pulp production.

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Authors' contributions

Mudji Susanto: Conceptualization, methodology, investigation, wood chemical analysis, parameter genetic analysis, writing original draft, and editing. Masumi Hasegawa: Review on article and supervision on lab. for wood analysis. Ganis Lukmandaru: Review on chemical analysis. Setiyo Budi: Fiber dimension analysis. Mashudi: Wood sample preparation. Liliana Baskorowati: Review on article and editing. ILG Nurtjahjaningsih: Review on genetic. Rina Laksmi H: Review on method. Sugeng Pudjiono: Data curation. Dedi Setiadi: Checking data for analysis. Sumardi: Data preparation of wood chemical properties. Ratih Damayanti: Review on wood properties. Budiman Achmad: Data analysis. Andy Bhermana: Writing for spatial distribution of *Acacia mangium* and visualization; Yusuf Sigit Ahmad Fauzan: Data preparation of wood physical properties. Fanny Hidayati: Review on wood physical properties analysis and editing.

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