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VARIATION OF GROWTH CHARACTERISTICS AND STRESS-WAVE VELOCITY OF THE FIRST GENERATION *MANGLIETIA GLAUCA* FAMILIES PLANTED IN INDONESIA

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ABSTRACT

Growth characteristics, including stem diameter (D), tree height (H), and stem volume (V), and wood property stress-wave velocity (SWV), were measured in 100 families of 7-year-old first-generation *Manglietia glauca* trees planted in Indonesia. Therefore, this study aimed to evaluate the variation in D, H, V, and SWV among the families and their heritability. An analysis of the correlations, principal components and selection index was also conducted. The presence of significant differences in all measured traits among the families indicate a genetic contribution to traits variation. Low to moderate narrow-sense heritability values were observed across all traits, showing that the genetic enhancement of growth and wood properties in *M. glauca* is achievable through selective breeding. Moderate to highly significant positive correlations were observed among the growth traits, highlighting their strong interrelationships. D and SWV showed a low significant positive correlation. H and V showed no significant correlation with SWV. Therefore, SWV should be included as selection criterion in *M. glauca* breeding. PCA and selection index are effectively for identified superior families of growth and strength traits, supporting their selection as candidates for future breeding programs.

KEYWORDS: *Manglietia glauca*, tree breeding, growth characteristics, stress-wave velocity

INTRODUCTION

Manglietia glauca Bl. is an indigenous tree species in Indonesian forests that is becoming increasingly rare (Kalima and Wardhani 2013; Pudjiono et al. 2020). However, it is categorized as a fast-growing tree species with a growth cycle of less than 10 years (Sudomo et al. 2010). This species is naturally distributed across Sumatra, Java, Bali, Lombok, and Sulawesi Islands, inhabiting mixed forests at elevations of 900 to 1700 m above sea level, where conditions are characterized by high humidity and fertile soils (Pudjiono 2016). In general, the wood has a straight stem, cylindrical without buttresses, and clearly visible annual rings. Due to these characteristics, local communities are increasingly interested in cultivating *M. glauca* in community forests to meet their wood needs. On the other hand, its wild availability remains limited. Identifying trees with promising growth potential is vital to support cultivation and conservation. Establishing a nursery will ensure the production of high-quality seedlings for reliable planting material. As *M. glauca* naturally varies genetically, selecting suitable parent trees is important to pass superior traits to future generations. This process is key to developing improved *M. glauca* seedlings that can support both cultivation efforts and species conservation (Pudjiono et al. 2020).

M. glauca tree breeding activities have been carried out by the Ministry of Forestry and Perum Perhutani in Indonesia in order to develop this species outside its native area. The initial stage, *M. glauca* seed exploration activities have been carried out from 3 areas in West Java, namely Tasikmalaya, Sumedang, and Sukabumi (Pudjiono 2016). The exploration results have been planted in three different locations: Sleman, Yogyakarta; Temanggung, Central Java; and Trenggalek, East Java, Indonesia (Pudjiono et al. 2018; 2019). A progeny test with a total of 100 families from three different provenances has been established in those three sites. The families were selected based on growth characteristics. At 42-month-old, the stem diameter and tree height of *M. glauca* trees planted in Temanggung, Central Java, Indonesia ranged between 1.3-28.7cm with an average of 9.4 cm and 106-1083 cm with an average of 577 cm, respectively. The analysis showed that family significantly influenced both total height and stem diameter of the trees (Pudjiono et al. 2020). In another site in Trenggalek, East Java (Indonesia), out of 18-month-old *M. glauca* trees, tree height and stem diameter ranged between 103-195 cm with an average of 155 cm and 0.90-3.53 cm with an average of 1.93 cm, respectively. The analysis results showed that family significantly affected both the total height and stem diameter of the trees (Pudjiono et al. 2019).

On the other hand, the information on the wood properties of *M. glauca* from breeding material is very limited in Indonesia. Meanwhile, the properties of the wood produced will vary due to the influence of internal (genetic) and external factors (Zobel and Jett 1995). The traditional methods of testing require destructive testing, often to the point of failure, using bending tests (Hai et al. 2017). The techniques that are non-destructive in assessing wood properties offer advantages in lowering costs, energy consumption, and time requirements, suitable for use with both solid and engineered wood materials (Jeong et al. 2016; Rofii et al. 2016; Hidayat et al. 2017). One of the non-destructive techniques to assess wood properties, specifically wood mechanical properties, is stress wave velocity (SWV) measurement (Ishiguri et al. 2007). This technique shows a significant positive relationship with the characteristics of standing trees and logs, particularly with the Young's modulus of logs, modulus of elasticity (MOE) and modulus of rupture (MOR) (Ross et al. 1997; Wang et al. 2001; Ishiguri et al. 2007,

2013; Dharmawati et al. 2024; Duong et al. 2025). In other fast-growing species planted in Indonesia (such as *Acacia mangium*, *Neolamarckia cadamba*, and *Neolamarckia macrophylla*), SWV was significantly different among the families (Hidayati et al. 2019; Chaerani et al. 2019; Masendra et al. 2023; Dharmawati et al. 2024). It indicates a genetic contribution to mechanical properties (SWV) variation. Wood properties can be included as an indicator in selecting plus trees in breeding programs to increase wood productivity and quality in fast-growing species. Therefore, this study aimed to evaluate the variation of growth characteristics, wood property (SWV), and their relationships in first-generation *M. glauca* families planted in Indonesia.

MATERIAL AND METHODS

A first-generation progeny trial of *M. glauca* was established in April 2016 in Temanggung, Central Java, Indonesia. This trial consists of 100 families originating from three provenances in West Java Province (Tasikmalaya, Sukabumi, and Sumedang) Indonesia. Geographically, the site is located at 04°01'043" S and 92°13'579" E, at an altitude of 469 m above sea level. The trial site features a flat to moderately steep topography, and the soil type is latosol with a sandy soil texture. The annual rainfall is 2403 mm/year. The mean annual temperature is 25^{o}C. This study used a randomized complete block design with seven replications and four-tree plots, arranged with a spacing of 4 m × 3 m. However, many trees died during the trial period due to the prolonged dry season in the region. At 6.7-year-old thinning (75%) was performed. The average survival rate was 77.1%. The survival rate of the Tasikmalaya, Sukabumi, and Sumedang provenances were 79.3%, 76.5% and 78%, respectively.

A total of 371 seven-year-old trees were evaluated for growth traits (stem diameter/D, tree height/H, and stem volume/V) and wood property (stress-wave velocity/SWV). Stem diameter was measured at 1.3 m with a diameter tape (F10-02DM, KDS, Japan), height with an altimeter (Haga, Germany), and volume using West's (2009) formula. SWV was determined with a FAKKOP Microsecond Timer with an accuracy of ± 1 μs, expressed as the standard deviation (FAKKOP Enterprise, Hungary) following Ishiguri et al. (2007). Start and stop sensors (High sensitivity SD02 vibration sensors) were positioned at 150 cm and 50 cm above ground level. A hammer strike on the start sensor created a stress wave detected by the stop sensor. Eight propagation time readings per tree were averaged. Stress wave velocity (SWV) was then calculated by dividing the test span between start and stop sensors by the measured stress wave transmission time (Wang et al. 2001).

Analysis of variance (ANOVA) was conducted to assess the differences in stem diameter (D), height (H), volume (V), and SWV among the tested families. The ANOVA model used for each trait is outlined below:

$$y_{jkl} = \mu + B_j + F_k + \varepsilon_{jkl} \quad (1)$$

where: yjkl is the observation on the *lth* tree from the kth family in the *jth* block. Narrow-sense heritability for growth traits, SWV, and P were estimated according to Gailis et al. (2020) to determine the genetic effects:

$$h^2 = \frac{4 \times \sigma_f^2}{\sigma_f^2 + \sigma_\varepsilon^2} \quad (2)$$

While h^2 is the narrow-sense heritability, σ_f^2 and σ_ε^2 are the estimated variance components of family and residual, respectively. In addition, simple correlation was used to investigate the relationship among characteristics. Principal component analysis (PCA) was conducted using family best linear unbiased predictors (BLUPs) for stem diameter (D), stem volume (V), and stress-wave velocity (SWV). Before PCA, family BLUPs for each trait were mean-cantered and standardized to unit variance to eliminate differences in measurement scale among traits. PCA was conducted using the prompt function in R, with the option scale. = TRUE. Eigenvalues, trait loadings, the proportion of variance explained by each principal component, and cumulative explained variance were calculated. Superior families were identified using a quantitative multi-trait selection index. Family BLUPs for D, V, and SWV were standardized to z-scores, and the selection index for each family was calculated as:

$$Si_i = \frac{ZD_i + ZV_i + Zswv_i}{3} \quad (4)$$

where: Si_i is the selection index of family (i), and ZD_i, ZV_i, and $Zswv_i$ are the standardized BLUPs for diameter, volume, and SWV, respectively.

Higher index values indicated better overall performance across the three traits. Families were ranked in descending order of the selection index. The 24 highest-ranked families, representing the top 24% of the 100 tested families, were classified as superior and recommended for further breeding. The quantitative selection threshold was a selection-index value of ≥0.6072591, corresponding to the 24th-ranked family.

RESULTS AND DISCUSSION

Tab. 1 shows the mean values of D, H, V, and SWV from the first-generation progeny trial of *M. glauca*. The mean value of D, H, V, and SWV across families were 21.37 cm, 15.58 m, 0.236 m^3, and 3.37 km/s, respectively. SWV is an indirect or surrogate indicator of wood mechanical performance, particularly stiffness-related properties. In this study, validation of the relationship between SWV and wood mechanical properties testing was not conducted. However, this approach has been reported to have a strong positive association with the characteristics of standing trees and logs, especially in relation to the Young's modulus of logs in other species (Ross et al. 1997; Wang et al. 2001; Ishiguri et al. 2007,2013; Dharmawati et al. 2024). Pudjiono et al. (2020) reported that in the same stand of 3.5-year-old trees, the average values of D and H were 9.4 cm and 5.77 m, respectively. The result of ANOVA and narrow-sense individual heritability of D, H, V, and SWV of the *M. glauca* are shown in Tab. 2.

Tab. 1: Growth characteristics and stress-wave velocity of each family in the 7-year-old first-generation progeny trial of Manglietia glauca.

Family code	Number of trees	D (cm)		H (m)		V (m^3)		SWV (km/s)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	3	19.63	2.89	15.33	2.31	0.183	0.028	3.50	0.40
2	3	23.53	2.70	16.20	0.75	0.286	0.076	3.45	0.15
3	3	21.43	2.98	15.67	0.58	0.228	0.057	3.43	0.39
4	4	23.80	3.81	15.98	3.89	0.296	0.147	3.63	0.23
5	5	21.04	4.44	15.10	3.93	0.230	0.146	3.27	0.36
6	3	24.37	1.10	14.50	3.50	0.274	0.084	3.38	0.28
7	2	24.35	0.92	17.50	4.95	0.330	0.117	3.72	0.33
8	2	23.65	2.19	14.75	2.47	0.256	0.004	3.05	0.19
9	2	23.40	2.83	17.75	3.18	0.301	0.019	3.40	0.12
10	4	21.88	3.74	16.35	0.72	0.251	0.078	3.47	0.34
11	6	21.23	6.34	13.77	5.16	0.225	0.133	3.34	0.25
12	1	18.10	0.00	14.70	0.00	0.151	0.000	3.22	0.00
13	4	23.98	3.96	12.88	0.63	0.239	0.092	3.51	0.10
14	6	20.50	3.73	14.07	3.74	0.203	0.112	3.47	0.38
15	5	19.32	4.20	14.56	5.52	0.190	0.143	3.45	0.36
16	5	21.98	3.58	13.16	3.28	0.208	0.091	3.46	0.25
17	3	22.13	3.09	15.33	2.02	0.237	0.064	3.33	0.16
18	2	22.75	1.48	16.50	1.41	0.267	0.012	3.50	0.06
19	4	21.93	5.96	14.63	3.16	0.245	0.172	3.17	0.41
20	6	21.18	2.92	15.23	4.29	0.222	0.090	3.52	0.32
21	3	22.63	3.27	13.40	1.64	0.215	0.043	3.20	0.35
22	2	20.45	5.02	15.25	1.06	0.203	0.084	3.77	0.32
23	4	20.45	1.80	15.83	3.83	0.210	0.065	3.51	0.41
24	7	22.63	2.84	16.64	1.57	0.271	0.071	3.39	0.22
25	2	22.35	3.75	17.75	1.06	0.280	0.077	3.76	0.15
26	4	20.03	3.38	14.88	2.59	0.193	0.078	3.32	0.48
27	1	26.10	0.00	21.30	0.00	0.456	0.000	3.05	0.00
28	4	20.60	3.98	15.35	3.14	0.211	0.081	3.46	0.17
29	4	17.98	2.76	16.93	3.70	0.177	0.069	3.11	0.36
30	6	18.30	3.88	14.65	2.76	0.165	0.092	3.06	0.33
31	3	26.03	3.86	19.97	1.96	0.432	0.136	3.36	0.27
32	4	23.88	1.73	17.23	3.55	0.309	0.075	3.31	0.29
33	3	23.27	1.16	18.13	3.15	0.305	0.024	3.37	0.32
34	3	19.60	4.95	15.80	4.46	0.206	0.113	3.32	0.24
35	2	20.55	5.73	16.50	2.83	0.217	0.083	3.29	0.04
36	5	18.16	3.63	13.70	2.83	0.153	0.085	3.31	0.28
37	3	24.80	4.68	18.37	2.80	0.375	0.170	3.30	0.16
38	2	25.35	0.78	16.75	3.18	0.340	0.085	3.59	0.11
39	3	20.13	2.69	11.73	4.14	0.156	0.078	3.45	0.26
40	6	22.43	2.84	16.23	3.08	0.262	0.091	3.37	0.37
41	2	22.15	2.76	14.00	2.83	0.223	0.098	3.64	0.23
42	3	21.17	6.13	14.67	1.15	0.221	0.116	3.55	0.14
43	2	21.95	2.05	16.75	1.77	0.252	0.021	3.41	0.03
44	5	21.76	1.79	18.06	2.47	0.275	0.080	3.52	0.24
45	4	22.58	3.13	18.05	3.50	0.291	0.090	3.59	0.21
46	5	22.42	4.52	16.08	3.24	0.267	0.145	3.53	0.27
47	4	23.75	2.04	17.45	2.97	0.316	0.099	3.23	0.22
48	6	22.63	1.28	16.02	3.59	0.260	0.069	3.39	0.21
49	7	23.09	2.92	14.77	4.82	0.255	0.109	3.31	0.26
50	4	19.83	2.12	17.55	0.71	0.219	0.046	3.63	0.33
51	1	24.80	0.00	15.00	0.00	0.290	0.000	3.61	0.00
52	2	21.65	0.35	11.00	4.24	0.161	0.057	3.48	0.31
53	4	26.15	2.19	17.13	1.93	0.367	0.054	3.46	0.18
54	3	20.30	1.77	15.67	2.57	0.200	0.011	3.40	0.35
55	5	20.62	2.80	17.64	3.17	0.241	0.080	3.51	0.24

Family code	Number of trees	D (cm)		H (m)		V (m^3)		SWV (km/s)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
56	6	22.25	4.84	15.30	4.30	0.266	0.147	3.24	0.24
57	5	22.54	7.83	13.70	7.12	0.290	0.233	3.41	0.10
58	4	19.28	2.54	13.63	1.93	0.162	0.047	3.35	0.35
59	1	21.70	0.00	15.50	0.00	0.229	0.000	3.62	0.00
60	6	21.02	4.11	14.00	4.23	0.213	0.123	3.08	0.27
61	2	19.80	0.71	11.25	6.01	0.141	0.084	3.69	0.53
62	4	22.40	4.96	16.45	4.13	0.278	0.156	3.43	0.34
63	6	19.23	3.42	16.08	2.96	0.192	0.072	3.05	0.21
64	6	23.42	2.33	16.08	2.14	0.281	0.068	3.47	0.30
65	5	18.32	2.55	14.64	3.40	0.160	0.076	3.50	0.36
66	3	20.60	0.40	12.67	1.15	0.169	0.017	3.32	0.29
67	3	19.13	6.31	15.43	4.39	0.214	0.201	3.03	0.31
68	5	18.70	4.25	13.86	3.71	0.168	0.114	3.07	0.15
69	5	21.14	3.88	14.50	2.81	0.210	0.090	3.26	0.15
70	6	16.30	1.43	13.88	4.01	0.119	0.046	2.99	0.22
71	3	19.87	4.04	16.27	4.20	0.216	0.115	3.04	0.32
72	4	23.03	3.83	19.23	2.14	0.320	0.083	3.47	0.38
73	3	20.63	1.27	15.63	2.95	0.213	0.065	3.59	0.40
74	4	22.50	3.14	18.00	4.14	0.299	0.121	3.46	0.19
75	5	21.50	1.97	14.86	1.86	0.216	0.041	3.33	0.36
76	5	23.34	1.36	18.10	2.72	0.310	0.052	3.55	0.28
77	2	18.25	0.21	13.00	0.00	0.136	0.003	3.38	0.71
78	3	20.67	0.71	15.67	4.31	0.209	0.052	3.66	0.06
79	2	17.75	1.20	14.00	4.24	0.142	0.061	3.51	0.39
80	1	24.50	0.00	16.50	0.00	0.311	0.000	3.62	0.00
81	4	20.88	1.41	12.88	3.68	0.177	0.059	3.25	0.42
82	4	22.25	2.30	16.40	4.09	0.252	0.068	3.20	0.23
83	4	19.68	2.17	15.23	1.50	0.190	0.055	3.52	0.31
84	2	25.30	3.11	13.00	0.71	0.262	0.050	3.22	0.45
85	2	20.95	0.92	14.25	1.77	0.198	0.042	3.11	0.09
86	2	20.20	2.55	16.60	1.98	0.211	0.028	3.52	0.15
87	5	20.64	4.09	13.60	4.44	0.197	0.090	3.30	0.18
88	4	19.13	3.36	16.88	2.95	0.204	0.101	3.52	0.40
89	4	22.35	0.31	17.30	3.85	0.272	0.063	3.32	0.26
90	2	20.35	1.77	15.50	2.12	0.200	0.007	3.15	0.03
91	8	18.70	5.24	14.66	4.51	0.187	0.125	3.22	0.30
92	4	21.40	3.61	17.58	3.36	0.264	0.131	3.47	0.36
93	4	19.38	3.02	15.78	4.88	0.200	0.124	3.34	0.34
94	2	20.10	2.12	16.50	0.71	0.212	0.053	3.86	0.14
95	2	20.65	0.49	14.30	0.71	0.191	0.000	3.25	0.19
96	1	28.20	0.00	22.20	0.00	0.555	0.000	3.45	0.00
97	2	20.85	4.17	14.75	1.77	0.201	0.056	3.30	0.08
98	6	21.65	2.99	15.85	3.51	0.237	0.085	3.33	0.37
99	5	21.94	4.64	15.12	4.30	0.245	0.158	3.29	0.37
100	4	23.08	5.07	19.70	2.34	0.351	0.203	3.27	0.44

Note: D- stem diameter; H- tree height; V- tree volume; SWV- stress-wave velocity.

Tab. 2: Results of analysis of variance (ANOVA) and narrow-sense individual heritability of measured characteristics in first generation progeny trial of Manglietia glauca.

Characteristic	Mean	SD	Significance among families	Variance of families	Variance of block	Variance of error	Narrow-sense heritability
D (cm)	21.37	3.625	0.000157**	0.645	1.990	11.02	0.221
H (m)	15.58	3.428	0.027201*	0.003	4.378	8.418	0.001
V (m^3)	0.236	0.105	0.000824**	0.0003	0.002	0.009	0.142
SWV (km/s)	3.37	0.305	0.000000**	0.008	0.034	0.160	0.464

Note: D, stem diameter; H, tree height; V, tree volume; SWV, stress-wave velocity; SD, standard deviation, **significance at the 1% level, *significance at 5% level.

In this study, there was a significant difference across all measured traits among the 100 families. In the same tree samples at a younger age of 3.5-year-old, D and H were significantly different among families (Pudjiono et al. 2020). In other fast-growing species of Acacia, Hai et al. (2015) reported significant differences in stem diameter (D) and height (H) among 112 families of 4-year-old *A. mangium* planted in Ba Vi, Vietnam. They also found significant variation in the dynamic modulus of elasticity (MOEd) among 100 families of 3-year-old *A. mangium* in Bau Bang, Vietnam. In Indonesia, D, H, and SWV were significantly different among 65 families of *A. mangium* planted in Central Java, Indonesia (Hidayati et al. 2019). Masendra et al. (2023) also reported that D, H, and SWV varied among 40 families of 4 sublines (origins) of 10-year-old third-generation *A. mangium* planted in Central Java, Indonesia. In other acacia species, H was significantly different among 110 families of *A. mearnsii* planted in South Africa (Chan and Isik, 2021). In eucalyptus species, Pelletier et al. (2008) found significant differences in D and H among 308 families of 104-month-old *Eucalyptus pilularis* in Australia. Wu et al. (2011) reported significant differences in D, H, and SWV among 19 clones of Eucalyptus hybrids in China. In Indonesia, D, H, and V were significantly different among 50 clones of 3.5-year-old *E. pellita* planted in East Kalimantan, Indonesia (Fadwati et al. 2023). Furthermore, Chaerani et al. (2019) reported that D and H were varied among 105 families of white jabon (*N. cadamba*) planted in West Java, Indonesia. In addition, D, H, V, and SWV were varied among 15 and 17 families of *Ficus variegata* planted in Yogyakarta, Indonesia (Haryjanto et al. 2024). Our results are consistent with those obtained in previous studies (Pudjiono et al. 2020; Hidayati et al. 2019; Masendra et al. 2023; Pelletier et al. 2008; Wu et al. 2011; Fadwati et al. 2023; Chaerani et al. 2019; Haryjanto et al. 2024). The results suggest, the observed family differences indicate a genetic contribution to trait variation in *M. glauca*.

In other fast-growing species, the narrow-sense heritability of D, H, and SWV was 0.41, 0.37, and 0.27 for *A. mangium* planted in Indonesia (Hidayati et al. 2019). Masendra et al. (2023) reported that the broad-sense heritability of D, H, and SWV were 0.014-0.444, 0.000-0.208, 0.261-0.715, respectively, of four sublines (origins) of *A. mangium* planted in Indonesia. In 3.5-year-old *E pellita* clones planted in South Kalimantan, Indonesia, the broad-sense heritability of D, H, and V was 0.82, 0.82, and 0.83 (Fadwati et al. 2023). Narrow-sense heritability of stem diameter, tree height, volume, and SWV were 0.46 and 0.81, 0.26 and 0.86, 0.49 and 0.85, 0.39-0.37, respectively, of *F. variegata* from two provenances planted in Yogyakarta, Indonesia (Haryjanto et al. 2024). Dharmawati et al. (2024) reported that the broad-sense heritability of stem diameter, tree height, and SWV were 0.412, 0.365, and 0.101 of 11-year-old red jabon (*N. macrophylla*) grown in Central Java, Indonesia. Hai et al. (2015) reported narrow-sense heritability estimates of 0.26 for stem diameter (D), 0.22 for

height (H), and 0.25 for tree volume in 4-year-old *A. mangium* planted in Ba Vi. In Tuyen Quang, the narrow-sense heritability values for D, H, and dynamic modulus of elasticity (MOEd) in 3-year-old *A. mangium* were 0.27, 0.24, and 0.15, respectively. Furthermore, in Bau Bang, they found heritability estimates of 0.14 for D and 0.30 for H in 3-year-old *A. mangium*. Pelletier et al. (2008) reported narrow-sense heritability values of 0.20 for D and 0.27 for H in 104-month-old *E. pilularis* planted in Australia.

In the present study, the narrow sense heritability estimates for D, H, V, and SWV were 0.221, 0.001, 0.142, and 0.464, respectively (Tab. 2), indicating that the relative contribution of additive genetic variation differed among traits. The relatively high heritability of SWV (h^2 = 0.464) compared with the growth traits suggests that genetic differences in stem mechanical characteristics may have been expressed more consistently among families under the conditions of this progeny trial. Most wood properties have a sufficiently strong genetic control, combine with large variation, inherited independently of growth, form, and adaptability (Zobel and Jett, 1995). In contrast, growth traits such as D, H, and V represent cumulative responses to genetic potential and environmental conditions throughout the growing period and may therefore be more affected by microsite variation and other environmental factors. Growth traits integrate genetic effects with cumulative environmental influences over time, whereas SWV reflects the dynamic mechanical response of the stem and is more directly related to intrinsic wood structural characteristics. Therefore, genetic differences affecting stem mechanical properties may be expressed more consistently among families than differences in cumulative growth under the environmental heterogeneity of the trial site. Therefore, the higher heritability of SWV suggests that it may be a useful trait for selecting families with desirable wood mechanical characteristics. The very low heritability of H (h^2 = 0.001), despite its significant family effect, requires careful interpretation. The family variance component for H was very small (0.003) relative to the residual variance (8.418), indicating that only a very small proportion of the observed phenotypic variation in height was captured by the estimated additive genetic component. Thus, a statistically significant family effect does not necessarily indicate strong additive genetic control, and H may be less reliable as a sole selection criterion for additive genetic improvement in this population. Overall, these results indicate potential for improving growth characteristics and wood properties in *M. glauca* through breeding, while SWV may provide an additional and potentially informative selection criterion for wood mechanical characteristics.

A low to moderate but statistically significant correlation positive correlations were observed between D and H in the current study (Fig. 1). D and H have a high positive correlation with V (Fig. 1). Moderate to high positive correlation of D and H was found for other fast-growing hardwood species by other researchers (Kha et al. 2012; Hidayati et al. 2019; Fadwati et al. 2023; Haryjanto et al. 2024; Dharmawati et al. 2024). The results show that the growth characteristics of *M. glauca* trees are strongly interrelated. The implication is that selection based on a single growth trait, such as stem diameter or tree height, could enhance overall tree volume (yield).

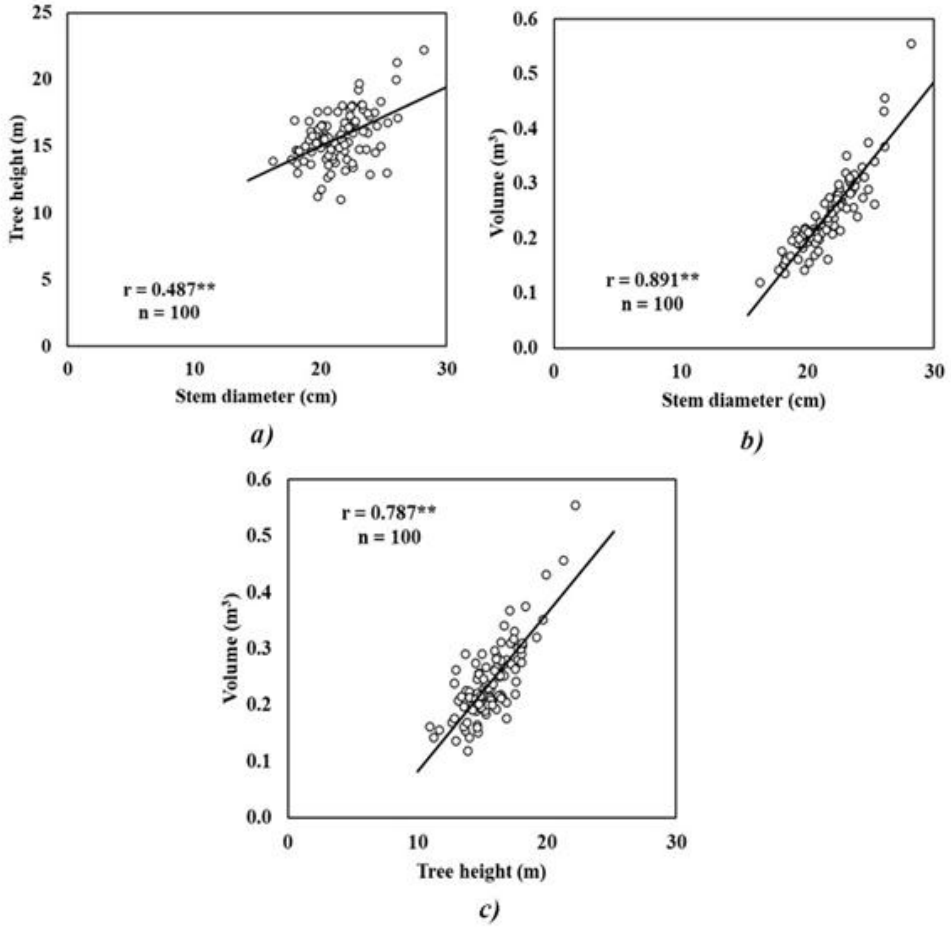

*Fig. 1: Relationship between stem diameter and tree height (a) stem diameter and tree volume (b) tree height and tree volume (c) of the first-generation progeny trial of Manglietia glauca. **Significance at 1% level.*

Fig. 2 shows the relationships between growth characteristics and SWV. Stem diameter has a low positive significant correlation with SWV. A positive significant correlation between stem diameter and SWV was also found in other fast-growing species planted in Indonesia (Prasetyo et al. 2017; Hidayati et al. 2017). SWV has a significant positive correlation of standing trees and the dynamic modulus of elasticity (DMOE) in *Eucalyptus camaldulensis* planted in Thailand (Ishiguri et al. 2013). In addition, SWV of standing trees and the DMOE of logs in *N. macrophylla* (Dharmawati et al. 2024). This result suggests that increasing stem diameter results in better mechanical properties in *M. glauca*. Furthermore, tree height and stem volume were not significantly correlated with SWV. These results are consistent with results observed in other fast-growing species in Indonesia (Makino et al. 2012; Hidayati et al. 2019; Masendra et al. 2023; Haryjanto et al. 2024; Dharmawati et al. 2024). The low positive significant correlation between stem diameter and SWV may be associated with the different biological processes represented by radial and longitudinal growth. Stem diameter reflects radial growth and the accumulation of secondary xylem, which contributes to stem structure and mechanical performance, whereas tree height primarily reflects longitudinal growth and is more strongly influenced by crown development, light availability, competition, and other site related factors. These results suggest that superior growth performance does not necessarily

reduce the mechanical properties such as SWV. Therefore, selection based on growth traits alone may not fully capture variation in wood mechanical properties, and SWV should also be considered as a selection criterion in *M. glauca* breeding programs.

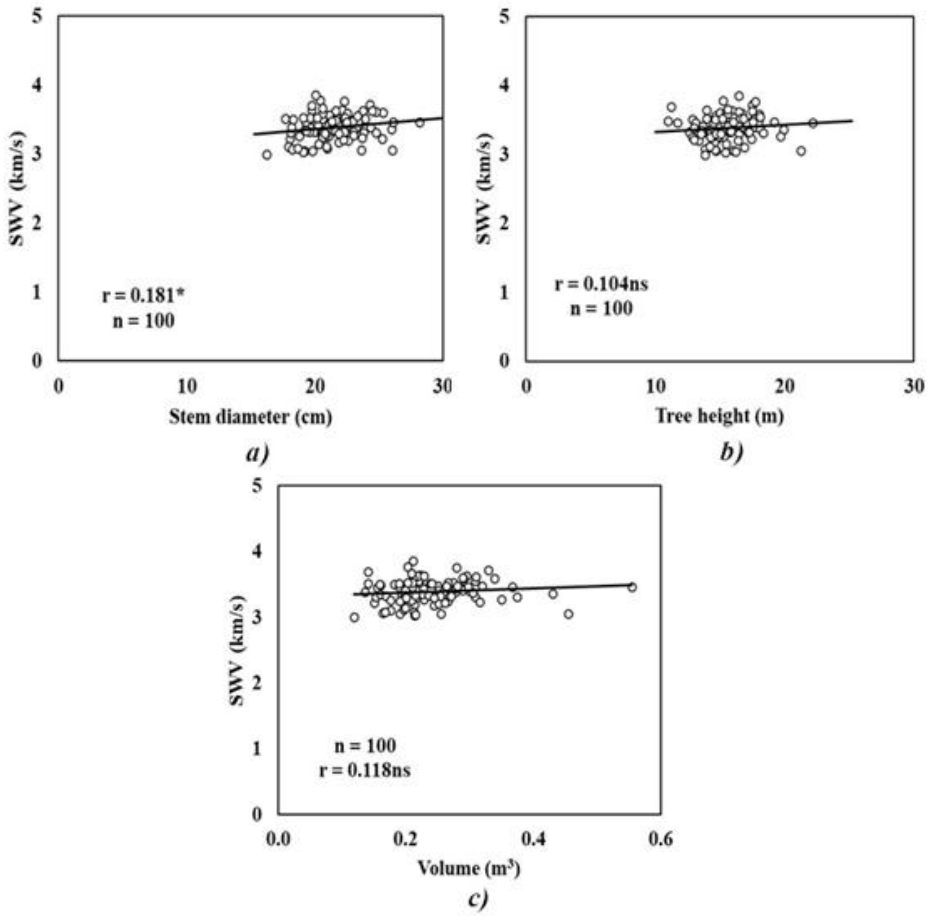

*Fig. 2: Relationship between stem diameter and SWV (a) tree height and SWV (b) tree volume and SWV (c) of the first-generation progeny trial of Manglietia glauca. *Significance at 5% level, ns - no significance.*

Tab. 3 shows that the absolute values of loading values for PC 1 were high in D and V; however, loading value for PC 2 was high in SWV (PC1 primarily represents variation in growth traits (D and V)), whereas PC2 reflects variation associated with wood mechanical property (SWV). These results suggest that growth characteristics and SWV contribute to PC 1 and PC 2.

Tab. 3: Loading values from PCA of stem diameter (D), stem volume (V), and stress-wave velocity (SWV).

Characteristics	PC 1	PC 2
D	0.657	0.246
V	0.649	0.298
SWV	0.384	-0.922

Note: D- stem diameter, V- stem volume, and SWV- stress-wave velocity SWV, PC- principal component.

Families were distributed into distinct groups in the PCA plot (Fig. 3), indicating variation in the combined performance of diameter, volume, and stress-wave velocity (SWV) among

families. PCA was used to visualize multivariate relationships among families rather than as the sole criterion for family selection. PCA of standardized family BLUPs showed that PC1 had an eigenvalue of 2.089 and explained 69.62% of the total variation, whereas PC2 had an eigenvalue of 0.812 and explained 27.08% of the variation. Together, PC1 and PC2 accounted for 96.70% of the total variation. PC3 had an eigenvalue of 0.099 and explained the remaining 3.30% of the variation (Tab. 4). Similar grouping of families based on growth traits and wood properties has been reported in *Tectona grandis*, *Acacia mangium*, and *Neolamarckia macrophylla* (Hidayati et al. 2013; Masendra et al. 2023; Darmawati et al. 2024).

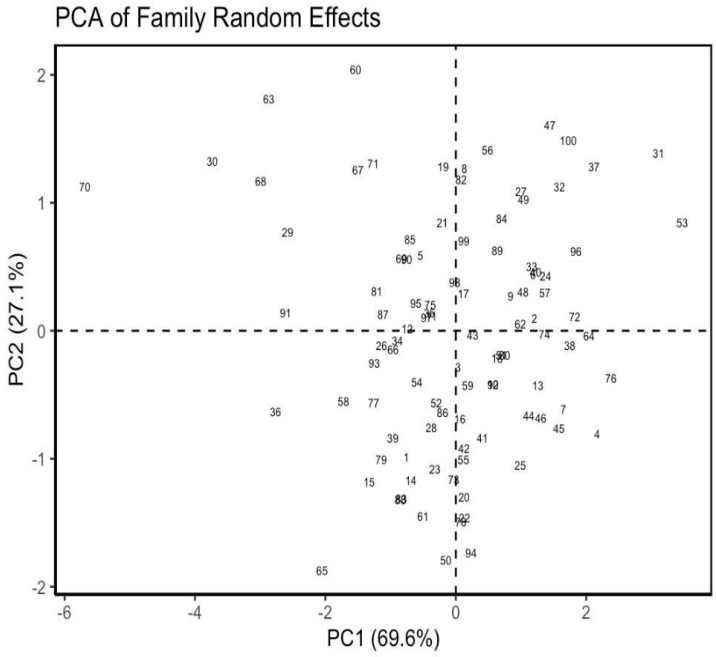

Fig. 3: Principal component analysis (PCA) scores for 100 families of Manglietia glauca. Closed circles and numbers show families. PC, principal component.

Tab. 4: Eigenvalues and explained variance of principal component analysis for family BLUPs of diameter, volume, and SWV.

Principal component	Eigenvalue	Variance explained (%)	Cumulative variance (%)
PC1	2.089	69.62	69.62
PC2	0.812	27.08	96.7
PC3	0.099	3.3	100

Note: PC- principal component.

Superior families were determined using the multi-trait selection index, rather than by visual inspection of PCA position or cluster membership. Families with a selection index of ≥0.6072591 were classified as superior (Tab. 5). Based on this objective threshold, 24 families were selected: 53, 31, 76, 4, 64, 37, 72, 7, 38, 45, 96, 46, 100, 74, 13, 32, 57, 24, 44, 25, 2, 40, 47, and 6. These families showed the highest overall standardized performance for diameter, volume, and SWV and are recommended as candidates for further breeding and solid-wood product development.

Tab. 5: Family BLUPs, multi-trait selection index, and ranking of the 24 recommended families.

Rank	Family	Diameter BLUP	Volume BLUP	SWV BLUP	Selection Index	Superior
1	53	0.8996	0.019612	0.019773	1.8487	Yes
2	31	0.6908	0.022806	-0.002297	1.5802	Yes
3	76	0.439	0.013271	0.045566	1.3895	Yes
4	4	0.4549	0.008892	0.056531	1.3237	Yes
5	64	0.5239	0.009364	0.029178	1.1548	Yes
6	37	0.5071	0.016192	-0.012672	1.0352	Yes
7	72	0.3082	0.012499	0.022086	1.0162	Yes
8	7	0.3087	0.007554	0.043192	1.0064	Yes
9	38	0.4132	0.008414	0.027741	0.9975	Yes
10	45	0.223	0.008131	0.047521	0.9898	Yes
11	96	0.3751	0.013449	0.005306	0.9633	Yes
12	46	0.2312	0.005418	0.040677	0.821	Yes
13	100	0.3177	0.01721	-0.024501	0.7893	Yes
14	74	0.2089	0.009336	0.020089	0.7722	Yes
15	13	0.488	0.00035	0.030279	0.7555	Yes
16	32	0.4691	0.010878	-0.015487	0.7519	Yes
17	57	0.2583	0.009674	0.009408	0.7338	Yes
18	24	0.3574	0.008178	0.004741	0.7216	Yes
19	44	0.0821	0.006906	0.03813	0.7188	Yes
20	25	0.0997	0.003496	0.048685	0.6912	Yes
21	2	0.3184	0.005805	0.013316	0.6655	Yes
22	40	0.3125	0.007737	0.001753	0.6333	Yes
23	47	0.4454	0.011974	-0.033186	0.611	Yes
24	6	0.4425	0.004318	0.001089	0.6073	Yes

CONCLUSIONS

In conclusion, growth characteristics (D, H, and V) along with wood property (SWV) were assessed in a first-generation trial of *M. glauca* in Indonesia. Significant variation was observed among families for all measured traits, indicating the presence of genetic variation in growth and wood property (SWV) in *M. glauca.* The narrow-sense individual heritability estimates for these traits ranged from low to moderate. The high positive correlations were found among the growth traits (D, H, and V), while correlations between stem diameter and wood property (SWV) were low significantly positive, but tree height and stem volume were not significant. These results suggest that incorporating wood properties as a selection criterion could enhance the effectiveness of breeding programs for *M. glauca*. In addition, PCA results and selection index are clearly selected superior families on growth and strength parameters that could be selected as superior trees for the next breeding program.

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