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Original Article

Variation in Tree Growth Characteristics, Pilodyn Penetration, and Stress-wave Velocity in 65 Families of *Acacia mangium* Trees Planted in Indonesia[1]

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ABSTRACT

Growth characteristics [stem diameter (D), tree height (H)] and wood properties [Pilodyn penetration (P) and stress-wave velocity (SWV)] were measured for 65 families of 6-year-old *Acacia mangium* trees planted in Indonesia, in order to characterize their variation in D, H, P, and SWV. Therefore, the correlations between the measured characteristics were also determined, and their significant differences observed. Furthermore, their low to moderate values of narrow-sense heritability was obtained, and the results indicated the characteristics to be genetically controlled in *A. mangium*. In addition, highly significant positive correlations were observed among the growth characteristics, suggesting a close relationship, while there was no significant association between the growth characteristics and P, as well as SWV, indicating their independent. Therefore, these results demonstrate a potential for the improvement of both growth and wood properties of *A. mangium* trees, using the appropriate breeding programs. In addition, 18 families showed good performance in D and SWV, signifying their positive prospect of being considered as plus trees for the next generation breeding cycles.

Keywords: *Acacia mangium*, tree breeding, growth characteristics, pilodyn penetration, stress-wave velocity

1. INTRODUCTION

Some fast-growing tree species have been developed in Indonesia, which includes *Acacia* spp., *Eucalyptus* spp., *Falcataria moluccana*, and *Gmelina arborea*. *Acacia mangium* has been identified to be the most adaptable in the marginal area when compared to 46 other species tested by the government (Arisman, 2002). In addition, it easily acclimatizes to various types of soil with varying pH, grows rapidly, and also tends to produce good quality timber (Fujimoto *et al*., 2002; Kim *et al*., 2009). Hence, it is widely planted in several tropical countries and subtropics, including Malaysia, Vietnam, Bangladesh, and especially in Indonesia (Fujimoto *et al*., 2002; Kim *et al*., 2009), where it is one of the prevalent species developed in the forest of industrial plants, as a raw material for pulp and paper (Marsoem, 2004). Meanwhile, other species (including

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slow-growing types), encompassing three species of styrac wood, *Gmelina arborea,* teak, Moluccan ironwood, linggua, red meranti, gofasa and *Pinus merkusii*, wood properties have been investigated (Iswanto *et al*., 2016; Hidayati *et al*., 2017a; Hidayati *et al*., 2017b; Hidayat *et al*., 2017; Darmawan *et al*., 2018).

Therefore, the increasing need for solid wood both in construction and furniture worldwide provides opportunities for fast-growing species to be applied as construction materials and furniture, e.g., *A. mangium*. This also increases its selling price comparably with being a raw material for pulp and paper. Furthermore, the properties both in density and in strength have been widely studied (Fujimoto *et al*., 2002; Honjo *et al*., 2005; Kim *et al*., 2009; Kojima *et al.,* 2009; Matsumoto *et al*., 2010; Makino *et al*., 2012). Nugroho *et al*. (2011) reported about the wood properties of 5 provenances of *A. mangium* planted in Indonesia, and Hai *et al*. (2015) stated evidence about its growth characteristics and wood properties in second-generation progeny test planted in Vietnam. Meanwhile, studies on this property from tree breeding programs material, where their quality is one of the important aspects in obtaining superior products (Zobel and van Buijtenen, 1989) are limited. However, several fast-growing species have been investigated, including *A. mangium*, *Falcataria moluccana*, *A. auriculiformis*, and *Eucalyptus* (Hai *et al*., 2015; Ishiguri *et al*., 2007; Hai *et al*., 2008; Muneri and Raymond, 2000). Therefore, it is expected that an increase in the quality of *A mangium* wood is improved through these programs.

Non-destruction and semi-destructive techniques for evaluating wood properties are capable of decreasing cost, energy, and time, and these are applied in solid and non-solid wood products (Jeong *et al*., 2016; Rofii *et al*., 2016; Hidayat *et al*., 2017). Moreover, Pilodyn was introduced as a non-destructive assessment method for density within the breeding program (Sprague, 1983; Woods *et al*., 1995; Hansen, 2000), as its penetration confers a significantly negative correlation (Taylor, 1981; Wei and Borralho, 1997; Wu *et al*., 2010; 2011b). In addition, the stress-wave velocity (SWV) method is a non-destructive method for evaluating quality, especially based on mechanical properties (Ishiguri *et al*., 2007), and a significant, positive association exists with standing trees or log and Young's modulus of logs (Ross *et al*., 1997; Wang *et al*., 2001; Ishiguri *et al*., 2007; 2013; Wu *et al*., 2011b).

This study is, therefore, aimed at characterizing variations in growth parameters [stem diameter (D) and tree height (H)], and wood properties [Pilodyn penetration (P) and stress-wave velocity (SWV)] in 65 families of *A. mangium,* planted in a third-generation progeny trial. Furthermore, the relationships prevailing amongst each were also investigated.

2. MATERIALS and METHODS

The third-generation progeny trial of *A. mangium* was established in the Forest Research of Alas Ketu, Wonogiri, Central Java province, Indonesia (07°32· S - 110°41·E). This consisted of 65 families, which originated from 8 provenances in Papua New Guinea, and Australia (Table 1), and the set up was established in February 2012. Meanwhile, information on environmental conditions are as follows: the average temperature was 27.22°C, rainfall (1,878 mm/year), the elevation of 141 m above sea level, climate type C (Schmidt and Ferguson), and soil type was vertisol. In addition, the plantation trial was established using randomized complete block design, with six blocks as replications, and four tree-plots for each family, with a spacing of 4 × 2 meters. Furthermore, fertilization was applied two times per year, using NPK up to the point where they were 2-year-old. This process was thinned thrice in the following years: 2015, 2016, and 2017 for retaining one of the best varieties within each tree-plot.

Table 1. Information on the family origin of third-generation progeny trial of *Acacia mangium* (Sunarti et al., 2012)

Provenance	Total number of family	Family code	Number of trees
Oriomo, PNG	11	1,2,3,4,5,6,45,46,47,48,49	46
Kini, WP	32	7,8,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35, 36,37,38,39,40,41,42,43,44,53,54,56,57	137
Wipim, WP	16	9,10,11,12,13,14,15,16,17,18,19,50,51,52,58,59	68
Bimade, PNG	1	60	4
Gubam, PNG	1	61	3
135K N, AUS	1	62	5
Claudi, AUS	1	63	5
Claudie river, AUS	2	64,65	10

Note: PNG, Papua New Guinea; WP, West Province Papua New Guinea; AUS, Australia.

This study involved measuring a total of 278 trees, encompassing the magnitude of growth characteristics (D and H) and wood properties (P and SWV) at 6-year-old. In addition, D was measured at 1.3 m above the ground level, with the aid of a diameter tape (F10-02DM, KDS, Japan), while H was determined using an altimeter (Haga, Germany). Furthermore, P was assessed with a Pilodyn tester (6 J Forest, Proceq, Switzerland) at 1.3 m above ground level, where three replicates were obtained for each tree (Ishiguri *et al*., 2008; Hidayati *et al*., 2013a;b), and their barks were not peeled. Meanwhile, within this progeny test site, nine specimens were felled for other studies (anatomical, physical, and mechanical properties), where the mean value of the bark thickness was 5.15 mm (four points of the bark were measured for each tree), and P was, further, assessed. Fig. 1 shows a negative relationship between P and basic density, which is, therefore, a good indicator for predicting the basic density values *of A. mangium*. Conversely, the SWV of the stem were measured using a commercial hand-held stress wave timer (FAKKOP Microsecond Timer, FAKKOP Enterprise, Hungary), applying the method of Ishiguri *et al*. (2007), where start sensors set at 150 cm from ground level was hit with a small hammer, in an attempt to create the stress wave, which the stop sensor, placed at 50 cm, receives, and the propagation time between the two was recorded. In addition, eight measurements were obtained, and their mean value was calculated for each tree, therefore, SWV was computed by dividing the value obtained with the distance between (100 cm).

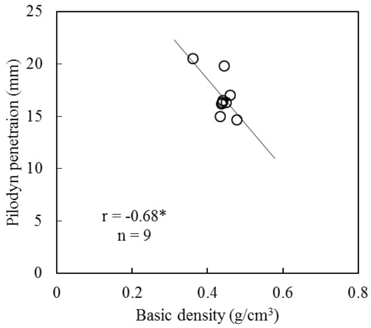

Fig. 1. Relationship between Pilodyn penetration and the basic density of *Acacia mangium*. * indicates significance at the 5% level.

Analyses of variance (ANOVA) were performed to evaluate the differences in D, H, P, and SWV among the tested families, and the following model was used for each character:

$$Y_{ij} = \mu + F_j + \varepsilon_{ij} \quad \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

where Y_{ij} denotes the response of the j-th family in the i-th replication, μ depicts the overall mean, F_j the genetic effect of the j-th family, ε_{ij} was the error associated with Y_{ij}. Furthermore, the narrow-sense family heritability of growth characteristics and wood properties estimated using the following formula, which assesses the magnitude of genetic effects:

$$h_f^2 = \sigma_f^2 / [\sigma_f^2 + (\sigma_e^2/R)] \quad (2)$$

where h_f^2 signifies the narrow-sense family heritability, σ_f^2 denotes their variance component, σ_e^2 was the variance component of the error, and R symbolizes block. Moreover, due to the fact that the tested families are half sib, the narrow-sense value obtained was applied in the calculation of heritability.

3. RESULTS and DISCUSSION

Table 2 shows the mean values of stem diameter (D), tree height (H), Pilodyn penetration (P), and stress-wave velocity (SWV) observed at the third-generation progeny trial of *A. mangium*, where the mean values in each family were 12.7-22.5 cm, 13.7-23.1 m, 15.7-18.9 mm, and 3,238 – 3,627 m/s, respectively.

The results of ANOVA and narrow-sense family heritability are shown in Table 3, and significant differences were observed in all measured characteristics, amongst the 65 families. Hai *et al.* (2015) reported that D and H showed significant differences between 112 families of 4-year-old *A. mangium,* planted in Ba Vi, and P were substantially different amid 112 of 4-year-old, 70 families 3-year-old in Tuyen, and 100 families 3-year-old in Bau Bang, Vietnam. Furthermore, it was also reported that dynamic modulus elasticity (MOE_d) exhibited a significant difference amongst the 100 families of 3-year-old *A. mangium* planted in Bau Bang, while Pelletier *et al.* (2008) stated the D and H of 104-month-old *Eucalyptus pilularis* planted in Australia to be significantly different amongst 308 families. In addition, D, H, P, and SWV were considerably dissimilar between 19 clones of *Eucalyptus* hybrid planted in China (Wu *et al.*, 2011a), 21 seed provenances of 24-year-old teak planted in Indonesia (Hidayati *et al.*, 2013a), and also among 15 clones of 12-year-old teak planted and two distinctive sites (Hidayati *et al.*, 2013b). Furthermore, the results obtained were consistent with those in previous studies (Hai *et al.*, 2015; Pelletier *et al.*, 2008; Wu *et al.*, 2011a; Hidayati *et al.*, 2013a,b), hence, it is considered that growth characteristics and wood properties are genetically controlled in *A. mangium*.

Hai *et al.* (2015) reported the narrow-sense heritability of D, H, and P to be 0.26, 0.22, and 0.25, respectively for the 4-year-old planted tree in Ba Vi. Meanwhile, in Tuyen Quang, their values including that of MOE_d were 0.27, 0.24, 0.21, and 0.15, respectively for the 3-year-old specimen. Furthermore, it was also reported to be 0.14, 0.30, and 0.22, for D, H, and P respectively in 3-year-olds at Bau Bang (Hai *et al.*, 2015). In addition, the values obtained for 104-month-old *E. pilularis* planted in Australia were 0.20 and 0.27 for D and H, respectively (Pelletier *et al.*, 2008), while broad-sense heritability of D, H, P, and SWV were 0.27, 0.27, 0.23, and 0.24, respectively of 24-year-old teak provenances in Indonesia (Hidayati *et al.*, 2013a). Furthermore, this was also estimated for 12-year-old teak clones, planted at two different sites in Cepu to be 0.50, 0.39, 0.65, and 0.30 respectively for D, H, P, and SWV, while those planted in Ciamis were 0.76, 0.44, 0.60, and 0.27, respectively (Hidayati *et al.*, 2013b). Furthermore, low to moderate values were obtained in the present study (Table 3), indicating a potential for improving growth characteristics and wood properties in *A. mangium,* through breeding programs. Moreover, the heritability of SWV was observed to be slightly higher than Pilodyn penetration (h_i^2 = 0.27), suggesting it to be the most important criteria in selecting trees for construction and furniture purpose. Furthermore, the heritability values obtained were higher than what was recorded in prior research (Hai *et al.*, 2015), suggesting its ability to increase with tree age.

Table 2. Mean values of growth characteristics, pilodyn penetration, and stress-wave velocity of each family in 6-year-old of third-generation progeny trial of *Acacia mangium*

Family code	Number of trees	D (cm)		H (m)		P (mm)		SWV (m/s)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	4	19.1	1.42	18.5	2.67	16.0	1.42	3,227	223
2	5	21.7	3.03	19.9	2.12	18.2	3.03	3,342	85
3	4	18.6	1.83	19.9	2.29	17.1	1.83	3,456	278
4	3	15.7	1.84	13.7	3.92	16.9	1.84	3,340	142
5	5	20.1	3.01	19.4	2.58	16.5	3.01	3,583	164
6	4	21.1	2.14	20.6	3.21	18.0	2.14	3,497	170
7	5	18.9	3.04	19.9	0.74	17.6	3.04	3,525	158
8	4	15.7	1.00	15.0	2.84	18.7	1.00	3,238	77
9	5	18.9	3.30	18.5	2.92	17.8	3.30	3,466	220
10	4	16.0	2.29	17.6	1.17	18.0	2.29	3,404	63
11	3	17.0	3.34	20.3	2.27	16.7	3.34	3,445	328
12	5	19.5	1.90	20.1	3.19	17.1	1.90	3,291	260
13	3	19.3	1.79	18.8	1.08	16.8	1.79	3,411	109
14	3	16.6	3.89	19.7	2.97	17.3	3.89	3,318	224
15	5	19.2	3.33	16.9	3.59	16.4	3.33	3,604	119
16	5	22.1	1.92	20.6	2.09	18.0	1.92	3,241	163
17	4	21.9	1.88	20.5	3.78	18.5	1.88	3,358	159
18	4	18.0	2.03	19.6	2.50	18.0	2.03	3,459	306
19	4	20.7	1.16	21.0	3.42	16.6	1.16	3,287	163
20	4	20.9	2.75	23.1	0.76	17.6	2.75	3,627	157
21	3	12.7	1.59	11.0	1.30	18.3	1.59	3,170	157
22	3	18.3	3.25	18.3	2.97	17.6	3.25	3,433	354
23	5	19.3	2.77	18.2	3.82	18.0	2.77	3,432	205
24	4	19.2	1.00	23.0	4.86	17.3	1.00	3,366	30
25	5	20.6	2.88	18.5	3.41	18.6	2.88	3,267	148
26	5	19.3	4.27	19.2	3.40	17.5	4.27	3,365	129
27	4	19.8	3.16	20.6	3.42	17.3	3.16	3,514	90
28	4	19.3	2.00	20.8	2.51	16.4	2.00	3,489	195
29	5	18.4	1.81	20.0	1.04	17.0	1.81	3,521	93
30	5	19.1	3.07	19.6	2.29	16.0	3.07	3,571	96
31	3	17.3	2.95	17.8	3.91	18.4	2.95	3,365	199
32	5	21.0	1.55	20.0	2.47	16.4	1.55	3,482	105
33	4	22.3	2.13	21.5	1.65	17.5	2.13	3,386	110
34	5	18.9	2.86	19.7	1.53	17.2	2.86	3,584	76
35	4	19.9	2.82	19.5	3.84	17.3	2.82	3,581	280
36	5	17.7	3.08	18.3	2.50	17.1	3.08	3,515	118
37	4	17.5	2.49	16.8	4.25	18.0	2.49	3,357	171
38	4	18.1	2.23	18.8	1.85	17.3	2.23	3,359	104
39	5	16.9	1.22	18.5	4.03	18.2	1.22	3,541	176
40	5	17.4	1.04	18.0	4.02	16.5	1.04	3,504	214
41	4	20.3	2.06	18.0	1.39	16.3	2.06	3,397	344

Table 2. (Continued)

Family code	Number of trees	D (cm)		H (m)		P (mm)		SWV (m/s)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
42	5	22.5	1.87	21.6	4.73	17.0	1.87	3,497	170
43	5	19.2	1.13	16.5	3.72	18.9	1.13	3,406	147
44	4	17.2	3.11	17.8	2.00	18.0	3.11	3,402	315
45	3	17.6	2.18	18.3	2.02	15.7	2.18	3,456	129
46	5	18.9	0.99	19.2	2.97	16.6	0.99	3,473	311
47	4	18.7	3.63	17.6	3.76	16.4	3.63	3,454	197
48	4	18.7	3.21	18.4	2.75	17.8	3.21	3,323	218
49	5	19.7	2.37	19.5	2.22	17.8	2.37	3,513	79
50	5	20.0	1.82	21.1	1.38	16.8	1.82	3,449	229
51	3	17.9	1.39	21.3	2.87	16.7	1.39	3,572	118
52	5	20.7	1.89	20.6	2.92	17.4	1.89	3,540	172
53	4	19.0	2.13	18.4	1.85	16.4	2.13	3,598	127
54	4	18.4	2.46	19.9	1.82	16.2	2.46	3,567	152
55	3	17.6	2.44	20.0	3.07	16.7	2.44	3,312	104
56	4	20.2	2.81	18.4	3.23	17.6	2.81	3,331	177
57	4	20.0	2.93	22.4	3.18	17.6	2.93	3,377	121
58	5	18.8	3.30	19.8	3.88	16.8	3.30	3,536	122
59	5	18.6	0.45	19.5	2.53	16.1	0.45	3,396	76
60	4	18.6	1.71	19.3	3.95	18.3	1.71	3,435	187
61	3	16.2	1.35	14.5	3.80	18.6	1.35	3,526	65
62	5	19.9	0.68	21.4	0.50	17.5	0.68	3,449	50
63	5	19.1	1.80	18.5	1.26	18.2	1.80	3,375	138
64	5	18.4	4.28	20.5	1.50	16.2	4.28	3,497	110
65	5	18.5	2.52	19.0	3.32	18.2	2.52	3,300	122

Note: D, stem diameter; H, tree height; P, Pilodyn penetration; SWV, stress-wave velocity; SD, Standard deviation

Table 3. Results of analysis of variance (ANOVA) and narrow-sense heritability of the measured characteristics in third-generation progeny trial of *Acacia mangium*

Characteristic	Mean	SD	Significance among families	Variance of families	Variance of environment	Heritability
D (cm)	18.9	1.74	0.0002*	1.395	5.929	0.41
H (m)	19.1	2.03	0.0008*	1.641	8.328	0.37
P (mm)	17.3	0.79	0.0272*	0.197	1.839	0.25
SWV (m/s)	3,432	105	0.0144*	4,205	33,640	0.27

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

Meanwhile, it was reported in teak that narrow-sense heritability of D and H gradually increased at an exponent of age (Monteuuis *et al*., 2011).

Highly positive significant correlations were established between D and H in the present study (Fig. 2), and also for other hardwood species observed in

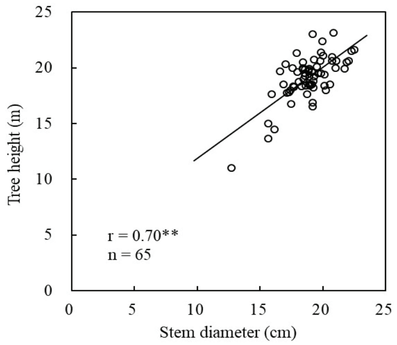

Fig. 2. Relationship between stem diameter and tree height in third-generation progeny trial of *Acacia mangium*. ** indicate significance at the 1% level.

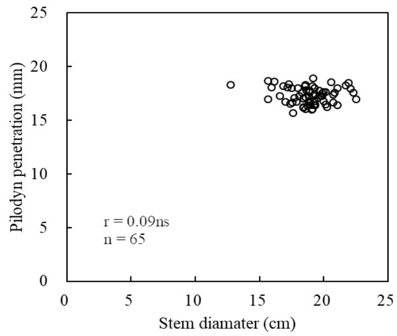

Fig. 3. Relationship between stem diameter and Pilodyn penetration in third-generation progeny trial of *Acacia mangium*. ns indicates non-significance.

previous research (Kha *et al*., 2012; Callister and Collins, 2008; Monteuuis *et al*., 2011; Chaix *et al*., 2011; Hidayati *et al*., 2013a, b; Hidayati *et al*., 2017). This result suggests growth characteristics to be closely related to one another in *A. mangium* trees.

Generally, a substantial negative association was discovered between P and wood density (Moura *et al*., 1987; Wei and Borralho, 1997; Wu *et al*., 2010, 2011b). Kojima *et al*. (2009) reported no correlation concerning xylem density and lateral growth rate in *A. mangium* planted in Malaysia. In addition, minimal positive correlations were observed amongst growth characteristics (D and H) and P in *E. urophylla* planted in China (Wei and Boralho, 1997), while moderate to high levels were found in other hardwood species (Wu *et al*., 2011b; Hidayati *et al*., 2013a, b), and the present study showed no significant correlations (Fig. 3 & 4). These results are consistent with previous outcomes (Kojima *et al*., 2009; Wei and Boralho, 1997), suggest that P is independent of growth characteristics in *A. mangium*.

Fig. 5 and 6 illustrate the relationships between growth characteristics and SWV. Stress-wave velocity of standing trees was to be significantly positive correlation to DMOE (dynamic modulus of elasticity) of logs or MOE of small clear specimens (Wang *et*

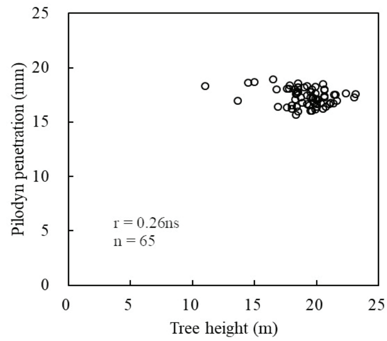

Fig. 4. Relationship between tree height and Pilodyn penetration in third-generation progeny trial of *Acacia mangium*. ns indicates non-significance.

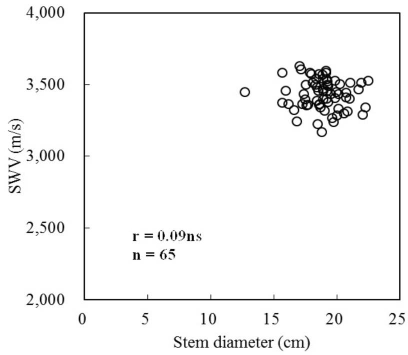

Fig. 5. Relationship between stem diameter and SWV in third-generation progeny trial of Acacia mangium. ns indicates non-significance.

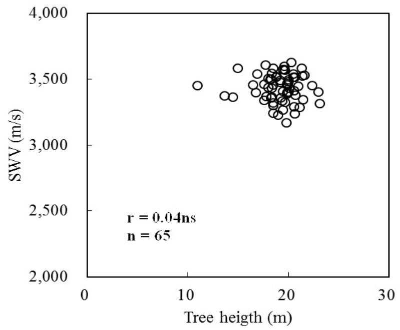

Fig. 6. Relationship between tree height and SWV in third-generation progeny trial of *Acacia mangium*. ns indicates non-significance.

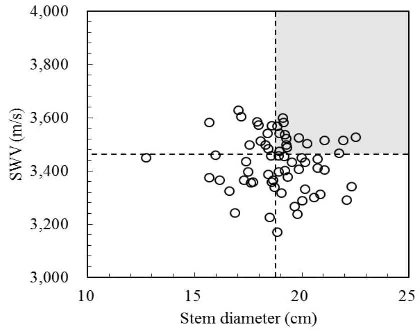

Fig. 7. Family grouping according to the mean value of stem diameter and SWV, indicated by the dotted line, while the grey color area shows a high value.

al., 2001; Ishiguri *et al*., 2013). Furthermore, D negatively correlates, though slightly, with DMOE (Hai *et al*., 2015), while Makino *et al*. (2012) reported no significant correlation to occur in those planted within Indonesia. In addition, other hardwood species showed no sgnificant correlation between growth characteristics (D and H) and SWV, which was also attested by other reports (Dickson *et al*., 2003; Ishiguri *et al*., 2011; Hidayati *et al*., 2013a, b; Hidayati *et al*., 2017). Moreover, these study outcomes are consistent with previous results (Hai *et al*., 2015; Makino *et al*., 2012; Dickson *et al*., 2003; Ishiguri *et al*., 2011; Hidayati *et al*., 2013a, b; Hidayati *et al*., 2017). Therefore, it can be concluded that physical and mechanical properties are also important characters for the selection criteria within breeding programs, and SWV (which is mechanical) seems to be the most important.

D and SWV showed higher values for heritability, in comparison with H and P (Table 3), therefore, a group of the family was made in accordance with these two characteristics (Fig. 7), where 18 showed high performance (above the mean values), including Family 3, 6, 7, 9, 11, 27, 28, 29, 35, 36, 39, 40, 46, 47, 50, 53, 58, and 61. These could be considered as plus trees for the next generation breeding cycles for improving growth and wood properties of *A. mangium*.

4. CONCLUSION

Characterization of variations in tree growth (D and H) and wood properties (P and SWV) were conducted in third-generation progeny trials of *A. mangium* in Indonesia, which were observed to vary among families. Furthermore, narrow-sense heritability of these evaluated characteristics was low to moderate, which is suggestive of genetic control. Meanwhile, highly positive correlations were observed between the growth characteristics, but no significant correlations were established with wood properties (P and SWV). Therefore, it is possible to improve breeding programs for *A. mangium* through the involvement of the analyzed parameters, independently, as the important criteria for selection. In addition, 18 families showed the high performance of D and SWV, suggesting them to be considered as a plus tree for the next generation breeding cycles.

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