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NOTE

Variation in tree growth characteristics, stress-wave velocity, and Pilodyn penetration of 24-year-old teak (*Tectona grandis*) trees originating in 21 seed provenances planted in Indonesia

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Abstract Growth characteristics [stem diameter (*D*), tree height (*H*), and bole volume (*V*)], stress-wave velocity (SWV), and Pilodyn penetration (*P*) were measured for 21 seed provenances of 24-year-old teak trees planted in Indonesia to characterize variation in tree growth characteristics, SWV, and *P* among seed provenances. Broad-sense heritability and correlations between the measured characteristics were also determined. Significant differences for all measured characteristics were observed among provenances, indicating that these characteristics are genetically controlled. Broad-sense heritabilities of growth characteristics, SWV, and *P* are moderate values. These results indicate potential for improving growth characteristics and wood properties of teak trees with the help of breeding programs. Highly significant positive correlations were observed among the growth characteristics, suggesting that they are closely related. In contrast, no significant correlations were observed between the growth characteristics and SWV, indicating that they are independent. We conclude that mechanical properties are also important criteria for selecting plus trees in tree breeding programs. Principal component analysis revealed that seed provenances from Indonesia (Bangilan, Deling, and Randublatung) and India (Malabar and Central Province) have high scores of growth characteristics and SWV.

Keywords Teak · Seed provenance · Growth characteristics · Stress-wave velocity · Pilodyn penetration

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Introduction

Provenance trials of growth characteristics in teak (*Tectona grandis*) trees have been conducted with the purpose of improving the productivity and rotation period of plantations by selecting seed or sources of cutting. The results have revealed that growth characteristics and stem quality including stem form differ among seed provenances [1, 2]. However, these studies did not include wood quality traits. In our previous research, growth characteristics [stem diameter (*D*), tree height (*H*), and bole volume (*V*)], stress-wave velocity (SWV), and Pilodyn penetration (*P*) were significantly different among 15 clones planted at two different sites in Indonesia [3]. Based on these results, we proposed that the wood properties of teak trees can be improved by implementing appropriate tree breeding programs [3]. However, in the test sites, it is very difficult to get the samples by felling a large number of trees. The stress-wave method is a well-known non-destructive method for evaluating wood quality, especially mechanical properties. There is a significant, positive relationship between the SWV of standing trees and the Young's modulus of logs or lumbers [4–7]. In addition, *P* is also a

Table 1 Mean values of growth characteristics, stress-wave velocity (SWV), and Pilodyn penetration (*P*) in each seed provenance

Code	Seed provenance	Number of trees	*D* (cm)	*H* (m)	*V* (m^3)	SWV (km/s)	*P* (mm)
1	Cepu, Java, Indonesia	7	26.4	19.7	0.728	3.08	23.0
2	Bangilan, Java, Indonesia	8	25.5	18.2	0.688	3.31	22.5
3	Muna, Southeast Sulawesi, Indonesia	7	21.1	15.8	0.473	3.02	24.1
4	Ngliron, Java, Indonesia	8	19.3	15.5	0.403	3.29	23.8
5	Margasari, Java, Indonesia	9	24.7	16.9	0.692	3.16	24.3
6	Ponorogo, Java, Indonesia	9	25.5	18.3	0.699	3.16	24.4
7	Gundih, Java, Indonesia	9	24.1	18.5	0.619	3.10	23.7
8	Deling, Java, Indonesia	6	28.1	21.3	0.895	3.35	23.0
9	Java, Indonesia	5	19.1	14.7	0.389	3.25	23.0
10	Blora, Java, Indonesia	8	25.0	18.0	0.677	3.32	20.4
11	Pati, Java, Indonesia	3	17.2	15.3	0.316	3.39	22.8
12	Randublatung, Java, Indonesia	7	23.0	18.9	0.561	3.31	23.4
13	Soe, Nusa Tenggara, Indonesia	8	19.9	15.3	0.418	3.31	23.5
14	Malabar, India	8	31.5	21.8	1.126	3.26	23.6
15	Central Province, India	11	26.8	20.7	0.798	3.26	25.0
16	Godavari, India	6	26.9	20.4	0.788	3.20	25.9
17	Thailand	10	15.5	15.5	0.256	3.08	21.3
18	Kay, Vietnam	6	14.8	12.8	0.228	3.31	22.1
19	Kouse, Vietnam	7	19.3	15.2	0.401	3.07	23.2
20	Kouai, Vietnam	4	16.7	13.9	0.291	3.29	21.0
21	Myanmar	9	20.9	18.2	0.484	3.19	23.3

Seed provenance of code 9 is unknown

D stem diameter, *H* tree height, *V* bole volume, *SWV* stress-wave velocity, *P* Pilodyn penetration

useful non-destructive test to evaluate basic density [6, 8, 9].

In Indonesia, seedlings for establishing the commercial teak plantations are mostly obtained by sexual propagation. In general, seed sources in seed production areas have been selected from plantations based on growth characteristics and stem quality form. The collected seeds are used for establishing commercial teak plantation in Java, Indonesia. Therefore, it is desirable to genetically improve seed quality to establish more productive teak plantations in Indonesia.

In the present study, to characterize genetic variations in growth characteristics and wood properties in the teak trees, tree growth characteristics (*D*, *H*, and *V*), SWV, and *P* were investigated for trees originating in 21 seed provenances planted in Indonesia.

Materials and methods

The experimental site of this study was located in the Education Forest of Wanagama, Gadjah Mada University, Yogyakarta, Indonesia (07°54′S–110°32′E). The provenance trial site for teak was established in February 1988. The environmental conditions of the provenance trial site were as follows: average temperature, 27.7 °C; annual precipitation, 1954 mm/year; relative humidity, 80–85 %; altitude, 214 m above sea level; soil, Mediterranean; and topography, flat. Seeds were collected from 21 different provenances in Indonesia and foreign countries (Table 1). The seedlings were initially planted at 3 × 3 m spacing. No fertilization or thinning treatments were applied. A total of 155 of 24-year-old trees were used.

D was measured at 1.3 m above the ground using diameter tape (F10-02DM, KDS). *H* was measured using an altimeter (Vertex IV, Haglöf), and *V* was calculated from the equation of Monteuuis et al. [1]. SWV of the stem was measured using a commercial, hand-held stress-wave timer (FAKOPP Microsecond Timer, FAKOPP Enterprise) according to the method previously described [3, 5]. Start and stop sensors were set at 150 and 50 cm from ground level, respectively. The start sensor was hit with a small hammer to create a stress wave. After the stress wave was received by the stop sensor, the stress-wave propagation time between the two sensors was recorded. Eleven measurements of stress-wave propagation time were obtained for each tree, and the mean value was calculated for each tree. SWV was calculated by dividing the distance between sensors (100 cm) by the averaged stress-wave propagation time. *P* was measured using a Pilodyn tester (strength of spring, 6 J; diameter of pin, 2.5 cm, Proceq) at 1.3 m above ground level at three positions for each tree [3, 7, 8]. The bark at the measuring positions was removed before measuring *P*. The mean value of three *P* measurements was recorded for each tree.

Analyses of variance (ANOVA) were performed to evaluate the differences in growth characteristics, SWV, and *P* among seed provenances. The following ANOVA model was used for each character:

$$Y_{ij} = \mu + S_i + C_j + \varepsilon_{ij} \quad (1)$$

where Y_{ij} denotes the response of the *j*th seed provenance in the *i*th replication, μ the overall mean, S_i the site effect at the *i*th replication, C_j the genetic effect of the *j*th seed provenance, and ε_{ij} is the error within Y_{ij}. Broad-sense heritabilities of growth characteristics, SWV, and *P* were estimated using the following formula proposed by Falconer [10] to assess the magnitude of genetic effects:

$$H^2 = \sigma_c^2 / \left[\sigma_c^2 + \sigma_e^2\right] \quad (2)$$

where H^2 denotes the broad-sense heritability, σ_c^2 the variance component of seed provenance, and σ_e^2 denotes the variance component of the environment factor. Principal component analysis (PCA) was performed using R software (http://www.r-project.org) to select seed provenances with good performance for both growth characteristics and wood properties.

Results and discussion

The mean values of *D*, *H*, *V*, SWV, and *P* in each seed provenance were 14.8–31.5 cm, 12.8–21.8 m, 0.228–1.126 m^3, 3.02–3.39 km/s, and 20.4–25.9 mm, respectively (Table 1).

Table 2 shows the result of ANOVA and broad-sense heritability of the teak trees from 21 seed provenances. Danarto and Hardiyanto [11] reported that 142 teak families originating in Java and East Nusa Tenggara, Indonesia, and planted in East Java indicated significant differences in *D*. Chaix et al. [2] reported that *D*, *H*, and mortality rate demonstrated significant differences among 41 different seed origins planted in Taliwas, Malaysia. Significant differences in growth characteristics (*D*, *H*, *V*, mortality rate, and fork height) were also observed among teak trees originating from 42 different genetic sources comprising 26 open-pollinated families from seedlings planted in Sabah, Malaysia [1]. In addition, we previously observed significant differences in *D*, *H*, and *V* among 15 clones of teak trees planted at two different sites in Indonesia [3]. The dynamic Young's modulus of teak trees planted in Costa Rica significantly differed among 20 clones [12]. Furthermore, SWV and *P* significantly differed among 15 clones of teak trees planted in Indonesia [3]. In the present study, the results for growth characteristics, SWV, and *P* obtained from trees originating in 21 different seed provenances were consistent with those obtained in previous studies. Therefore, it is considered that growth characteristics, SWV, and *P* are genetically controlled in teak.

Danarto and Hardiyanto [11] reported the narrow-sense heritability of 0.23 for *D* in 142 families of 12-year-old teak trees planted in East Java, Indonesia. Monteuuis et al. [1] reported narrow-sense heritabilities of 0.24, 0.51, and 0.34 for *D*, *H*, and *V*, respectively, in 8.8-year-old trees from 42 different genetic sources comprising 26 open-pollinated families from seedlings planted in Sabah, Malaysia. In addition, the narrow-sense heritabilities of *D*, *H*, and *V* in 3.5-year-old teak trees from 61 different families planted in Australia were 0.31, 0.22, and 0.29, respectively [13]. Chaix et al. [2] reported narrow-sense heritabilities of 0.46 and 0.76 for *D* and *H*, respectively, in 8.7-year-old teak trees from 26 clonal seed orchard families planted in Taliwas, Malaysia. In our previous study, the broad-sense heritabilities of *D*, *H*, *V*, SWV, and *P* in 15 clones of 12-year-old teak trees planted at two different sites in Indonesia were 0.50–0.76, 0.39–0.44, 0.51–0.77, 0.27–0.30, and 0.60–0.65, respectively [3]. Moya and Marín [12] reported the broad-sense heritability of the dynamic modulus of 0.34 in 10-year-old teak trees planted in Costa Rica. Moderate values for the broad-sense heritability of the measured characteristics in the present study indicate potential for improving growth characteristics and wood properties in teak with the help of breeding programs.

Highly positive significant correlations were observed among *D*, *H*, and *V* in the present study (Table 3). Highly positive correlation coefficients of *D* and *H* have also been previously reported for teak trees [1–3, 13]. In addition,

Table 2 Results of analysis of variance (ANOVA) and broad-sense heritability of measured characteristics

Characteristic	Mean	SD	Significance among seed provenances	Variance of seed provenances	Variance of environment	Heritability
D (cm)	22.4	4.5	a	15.26	40.83	0.27
H (m)	17.4	2.6	a	4.67	12.63	0.27
V (m^3)	0.568	0.233	a	0.036	0.145	0.20
SWV (km/s)	3.22	0.11	a	0.008	0.025	0.24
P (mm)	23.2	1.3	a	1.22	4.05	0.23

SD standard deviation, *D* stem diameter, *H* tree height, *V* bole volume, *SWV* stress-wave velocity, *P* Pilodyn penetration

[a] Significance at the 1 % level

Table 3 Correlation coefficients between growth characteristics, SWV, and *P*

Characteristics	*D*	*H*	*V*	SWV	*P*
D					
H	0.929[b]				
V	0.989[b]	0.925[b]			
SWV	−0.011 ns	0.002 ns	0.026 ns		
P	0.454[a]	0.430 ns	0.426 ns	−0.239 ns	

Correlation coefficients were determined using mean values of each provenance

D stem diameter, *H* tree height, *V* bole volume, *SWV* stress-wave velocity, *P* Pilodyn penetration, *ns* no significance

[a] Significance at the 5 % level

[b] Significance at the 1 % level

Table 4 Loading values from principal component analysis (PCA) of stem diameter (*D*), tree height (*H*), SWV, and *P*

Characteristics	PC 1	PC 2
D	−0.942	0.202
H	−0.935	0.219
SWV	0.136	0.927
P	−0.686	−0.391

D stem diameter, *H* tree height, *SWV* stress-wave velocity, *P* Pilodyn penetration, *PC* principal component

D and *H* have been reported to be positively correlated with *V* [1, 3]. These results indicate that growth characteristics are closely related to one another in teak trees. Furthermore, *D* is among the suitable criteria in teak breeding programs for selecting plus trees with high wood yield.

No significant correlations were observed between growth characteristics and SWV in teak trees (Table 3), suggesting that SWV in teak is independent of growth characteristics. There is a significant, positive relationship between the SWV of standing trees and the Young's modulus of logs or lumbers [4–7]. Therefore, we concluded that mechanical properties such as Young's modulus are also important criteria for selecting the plus trees in teak breeding programs. In our previous study, we observed relatively high positive significant correlation between growth characteristics and *P* in teak trees planted at two different sites in Indonesia [3]. In the present study, a moderately significant positive correlation was observed between *D* and *P* (Table 3). It is well known that *P* is negatively correlated with wood density [6, 8, 9]. Therefore, it is considered that trees with good *D* may have lower wood density. Rao and Shashikala [14] reported that a negative significant correlation was found between growth rate (*D*) and basic density of Thithimathi clones of teak planted in India. However, further studies are required to clarify the relationship between *D* and *P* in teak tree.

PCA is a multivariate technique that analyzes a data table in which observations are described by several intercorrelated quantitative dependent variables. Its goal is to extract the important information from the table, to represent it as a set of new orthogonal variables called principal components (PCs), and to display the pattern of similarity of the observations and of the variables as points in map. The correlation between a component and a variable estimates the information they share. In the PCA framework,

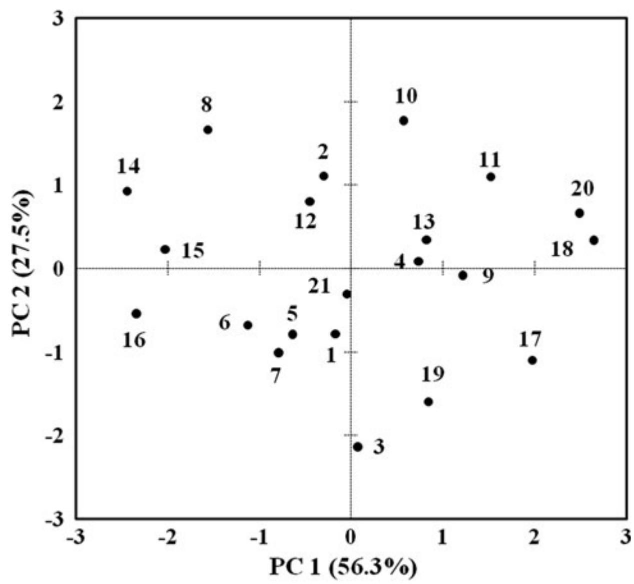

Fig. 1 Principal component analysis (PCA) scores for 21 seed provenances of *Tectona grandis*. *Closed circles* and *numbers* indicate seed provenances. *PC* principal component

this correlation is called a loading value [15]. As shown in Table 4, the absolute values of loading values for PC 1 were high in *D* and *H*, and loading values for PC 2 were high in SWV, indicating that growth characteristics and SWV contribute to PC 1 and PC 2, respectively. SWV of stems has been reported to be positively correlated with the Young's modulus of wood [4–7]. Thus, the Young's modulus contributes to PC 2. The seed provenances were well separated as shown in Fig. 1, indicating that PCA is a suitable analysis method for selecting the seed provenances with good performance in both growth characteristics and wood properties. In the present study, as per the results of PCA, some seed provenances demonstrated high scores for growth characteristics and Young's modulus, such as those from Indonesia [Bangilan (No. 2), Deling (No. 8), and Randublatung (No. 12)] and India [Malabar (No. 14) and Central Province (No. 15)]. Relatively high absolute value of loading value in PC 2 was observed for *P*, indicating that *P* also contributes to PC 2. *P* is closely related to the wood density of stem [6, 8, 9]. Thus, seed provenances from Bangilan (No. 2) and Blora (No. 10) demonstrated good values for *D* and *H*, high values for SWV which are positively correlated with Young's modulus of wood, and low values for *P* (high basic density).

Conclusion

Tree growth characteristics (*D*, *H*, and *V*), SWV, and *P* were investigated in teak trees originating in 21 seed provenances planted in Indonesia, with the aim of characterizing the genetic variation in growth characteristics and wood properties. Growth characteristics (*D*, *H*, and *V*), SWV, and *P* varied among the seed provenances. The broad-sense heritabilities of the measured characteristics were moderate. Highly positive correlations were observed between the growth characteristics, but no significant correlations were observed between growth characteristics and SWV. Based on these results, we conclude that the growth characteristics and wood properties of teak plantations can be improved by implementing appropriate tree breeding programs in seed production areas. PCA results revealed that seed provenances from Indonesia (Bangilan, Deling, and Randublatung) and India (Malabar and Central Province) have high scores of growth characteristics and SWV.

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References

1. Monteuuis O, Goh DKS, Garcia C, Alloysius D, Gidiman J, Bacilieri R, Chaix G (2011) Genetic variation of growth and tree quality traits among 42 diverse genetic origins of *Tectona grandis* planted under humid tropical conditions in Sabah, East Malaysia. Tree Genet Genomes 7:1263–1275
2. Chaix G, Monteuuis O, Garcia C, Alloysius D, Gidiman J, Bacilieri R, Goh DKS (2011) Genetic variation in major phenotypic traits among diverse genetic origins of teak (*Tectona grandis* L. f) planted in Taliwas, Sabah, East Malaysia. Ann For Sci 68:1015–1026
3. Hidayati F, Ishiguri F, Iizuka K, Makino K, Tanabe J, Marsoem SN, Na'iem M, Yokota S, Yoshizawa N (2013) Growth characteristics, stress-wave velocity, and Pilodyn penetration of 15 clones of 12-year-old *Tectona grandis* trees planted at two different sites in Indonesia. J Wood Sci 59:249–254
4. Wang X, Ross RJ, McClellan M, Barbour RJ, Erickson JR, Forsman JW, McGinnis GD (2001) Nondestructive evaluation of standing trees with a stress wave method. Wood Fiber Sci 33:522–533
5. Ishiguri F, Eizawa J, Saito Y, Iizuka K, Yokota S, Priadi D, Sumiasri N, Yoshizawa N (2007) Variation in the wood properties of *Paraserianthes falcataria* planted in Indonesia. IAWA J 28:339–348
6. Wu SJ, Xu JM, Li GY, Risto V, Lu ZH, Li BQ, Wang W (2011) Estimation on basic density and modulus of elasticity of eucalypt clones in Southern China using non-destructive methods. J Trop For Sci 23:51–56
7. Ishiguri F, Matsui R, Iizuka K, Yokota S, Yoshizawa N (2008) Prediction of the mechanical properties of lumber by stress-wave velocity and Pilodyn penetration of 36-year-old Japanese larch trees. Holz Roh Werkst 66:275–280
8. Wu SJ, Xu JM, Li GY, Risto V, Lu ZH, Li BQ, Wang W (2010) Use of the Pilodyn for assessing wood properties in standing trees of *Eucalyptus* clones. J For Res 21:68–72
9. Raymond CA, MacDonald AC (1998) Where to shoot your Pilodyn: within tree variation in basic density in plantation *Eucalyptus globulus* and *E. nitens* in Tasmania. New For 15:205–221
10. Falconer DS (1989) Introduction to quantitative genetics, 3rd edn. Wiley, New York
11. Danarto S, Hardiyanto EB (2000) Results of the progeny test of teak at 12 years of age at Jember, East Java. In: Proceeding of third regional seminar on teak. Potentials and opportunities in marketing and trade of plantation teak: challenge for the new millennium. Yogyakarta, pp 249–253
12. Moya R, Marín JD (2011) Grouping of *Tectona grandis* (L. f.) clones using wood color and stiffness. New For 42:329–345
13. Callister AN, Collins SL (2008) Genetic parameter estimates in a clonally replicated progeny test of teak (*Tectona grandis* Linn. f.). Tree Genet Genomes 4:237–245
14. Rao RV, Shashikala S (2005) Assessment of growth rate, basic density and heartwood content in selected teak clones of CSO, Thithimathi, Karnataka. In: Proceeding of the international conference on quality timber products of teak from sustainable forest management. Peechi, pp 511–515
15. Abdi H, Williams LJ (2010) Principal component analysis. Wires Comput Stat 2:433–459