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NOTE

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

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Abstract Tree improvement programs for teak (*Tectona grandis*) have mainly focused on breeding of trees with superior growth characteristics. However, improvement in wood quality should be included in breeding programs for high yield and high quality timber. In the present study, growth characteristics [stem diameter (*D*), tree height (*H*), and bole volume (*V*)], stress-wave velocity (SWV), and Pilodyn penetration (Py) were measured for 15 clones of 12-year-old teak trees planted at two different sites in Indonesia to clarify the variations in tree growth characteristics, SWV, and Py among clones, their repeatability, interaction between genotype and environment, and correlations between measured characteristics. Significant differences of all measured characteristics were found among 15 clones at both sites. Their repeatability showed relatively moderate to high values in both sites. These results indicate that these characteristics are closely related to genetic factors. Significant interaction between genotype and environment was found in all measured characteristics. In addition, SWV and Py showed lower interaction between genotype and environment than growth characteristics. No significant correlation was found between growth characteristics and SWV. These results suggest that wood properties and growth characteristics of teak trees can be improved by application of an appropriate tree breeding program.

Keywords Teak clone · Site effects · Growth characteristics · Stress-wave velocity · Pilodyn penetration

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Introduction

Teak (*Tectona grandis*) is one of the most important tropical hardwood species because its wood has high natural durability and high dimensional stability [1, 2]. It is native to the Indian Peninsula, Burma, Laos, Thailand, and the Philippines [3]. Wood of this species has been extensively used in furniture, construction, building boats, and other uses [3].

Tree breeding programs for teak have been established in Southeast Asian countries with the aim of developing more productive teak forests [3]. Tree breeding programs for teak have primarily targeted breeding of trees with superior growth characteristics such as diameter, height, stem form, and pest resistance [3–5]. Zobel and van Buijtenen [6] pointed out that wood quality improvement should be included as an integral part of the breeding programs. Thus, to date, there has been a focus on improving teak wood properties by tree breeding [7–9].

Teak is an important commercial plantation species in Indonesia. Approximately 90 % of the total teak forest area in Indonesia is found on the island of Java [10]. To date, some clones with superior growth characteristics have been selected by the breeding programs in Indonesia. However, the demand for teak wood is increasing in Indonesia because total wood production is decreasing by the depletion of teak wood resource, and by low productivity due to the relatively long rotation age of 60 or more years [11]. However, only limited information is available concerning the wood properties of teak.

In the present study, growth characteristics [stem diameter (*D*), tree height (*H*), and bole volume (*V*)], stress-wave velocity (SWV), and Pilodyn penetration (Py) were measured for the same 15 clones of 12-year-old teak trees planted at two different sites on the island of Java, Indonesia. From the results obtained, the variations in growth characteristics, stress-wave velocity, and Pilodyn penetration among clones, the repeatability (broad-sense heritability), interaction between genotype and environment, and correlations between growth characteristics, stress-wave velocity, and Pilodyn penetration were clarified.

Materials and methods

Two hundred superior parent trees of teak (*Tectona grandis*) were selected from several plantations in East and Central Java, Indonesia. Of these, 65 clones were chosen for the study. The study plantation was established in February 1999 at four different locations (Cepu, Ngawi, Bojonegoro, and Ciamis) on the island of Java, Indonesia [12]. According to the best growth performance of the trees, in the present study used the same 15 clone trees planted at two different sites, Cepu (7°01′S–111°32′E) and Ciamis (7°19′S–108°32′E). Environmental conditions at the two clonal test sites are shown in Table 1. The distance between two sites is approximately 600 km. Although latitudes of two sites were almost the same, precipitation in Ciamis (2740 mm/year) is two times higher than in Cepu (1436 mm/year). In addition, dry season in Cepu is longer than Ciamis [13]. Therefore, we selected these two sites for the present study. Trees were initially planted with 3 × 3-m spacing. After planting, fertilization was not applied but 50 % thinning was performed in 2007.

In July 2011, stem diameter (*D*), tree height (*H*), and bole volume (*V*), stress-wave velocity (SWV), and Pilodyn penetration (Py) were measured for total 90 trees from the 15 clones at the two sites with 3 replicates for each clone. *D* was measured at 1.3 m above the ground using calipers (Type, Haglöf). *H* was measured using a Haga altimeter. *V* was calculated using the equation proposed by Monteuuis et al. [4]. The stress-wave velocity (SWV) of the stem was measured using a commercial, hand-held stress-wave timer (FAKOPP Microsecond Timer, FAKOPP Enterprise) [14]. 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 the stress wave. After the stop sensor received the stress wave, 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 using the averaged stress-wave propagation time divided by the distance between sensors (100 cm). Pilodyn penetration (Py) was measured using a Pilodyn tester (strength of spring, 6 J; diameter of pin, 2.5 cm, Proceq) according to the previously described method [15, 16]. Py was measured at 1.3 m above ground level at three positions for each tree, without removing the bark, and the mean value of Py was calculated for each tree.

Analysis of variance (ANOVA) was applied to examine the differences among clones and the interactions between genotype and environment of growth characteristics, SWV, and Py. The following model of ANOVA was used for each growth characteristic, SWV, and Py at each site:

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

where Y_{ij} is the parameter of the *j*th clone in *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 clone, and ε_{ij} is the error with Y_{ij}. Clonal repeatability of growth characteristics, SWV, and Py at each site were estimated using the following formula proposed by Falconer [17] 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 is the clonal repeatability/broad-sense heritability, σ_c^2 the variance component for clone, and σ_e^2 is the variance component of environmental factor. In addition, mean values of the measured properties were also compared between the two sites by paired *t* test. Furthermore, to asses the interactions between genotype and environment, the following model of ANOVA was used for each growth characteristic, SWV, and Py:

$$Y_{ijk} = \mu + S_i + C_j + (SC)_{ij} + \varepsilon_{ijk} \quad (3)$$

where Y_{ijk} is the parameter of the *k*th tree of the *j*th clone in the *i*th site, μ the overall mean, S_i the environmental effect

Table 1 Environmental conditions at the two clonal test sites

	Cepu	Ciamis
Province	Central Java	West Java
Latitude (S)	7°01′	7°19′
Longitude (E)	111°32′	108°32′
Altitude (m)	50	300
Precipitation (mm/year)	1436	2740
Mean temperature (°C)	27.5	25.0
Soil type	Vertisol	Inceptisol
Topography	Flat	Flat

of ith site, C_j the genetic effect of jth clone, $(SC)_{ij}$, interaction between jth clone and ith site, ε_{ijk} is the random error.

Results and discussion

Among clone variations

The mean values for *D*, *H*, *V*, SWV, and Py of the 15 teak clones planted in Cepu were 11.3–25.2 cm, 7.7–15.7 m, 0.136–0.658 m^3, 3.37–3.78 km/s, and 18.7–27.6 mm, respectively (Table 2). The mean values of these characteristics of teak clones planted in Ciamis were 17.0–37.7 cm, 12.3–23.7 m, 0.295–1.472 m^3, 3.23-3.77 km/s, and 21.0–26.9 mm, respectively (Table 3). Monteuuis et al. [4] reported that significant differences in growth characteristics (mortality rate, *D*, *H*, *V*, and fork height) were observed among teak trees originating from 42 different genetic sources comprising 26 open-pollinated families from seedlings planted in Malaysia. In addition, the dynamic Young's modulus of elasticity of teak planted in Costa Rica significantly differed among 20 clones [9]. In the present study, significant differences were found among the 15 clones for all measured characteristics at both sites (Tables 2, 3). Our results of *D*, *H*, *V*, SWV, and Py are consistent with those obtained by previous researchers [4, 9]. Therefore, it can be said that, in teak, SWV and Py are also controlled by genetic factors.

Table 2 Growth characteristics, SWV, Py and their repeatabilities in 45 teak trees from 15 clones planted at Cepu, Indonesia

Clone code	*D* (cm)	*H* (m)	*V* (m^3)	SWV (km/s)	Py (mm)
A	17.2	13.8	0.318	3.45	22.9
B	16.7	13.2	0.295	3.37	22.2
C	17.1	14.8	0.298	3.61	20.5
D	11.6	7.7	0.139	3.54	20.4
E	16.9	13.2	0.296	3.59	21.5
F	21.3	14.8	0.474	3.71	24.3
G	14.5	13.8	0.214	3.78	21.9
H	14.6	12.8	0.223	3.55	21.6
I	17.0	13.7	0.305	3.72	21.4
J	11.3	10.3	0.136	3.44	20.9
K	17.6	15.7	0.330	3.57	23.4
L	14.3	12.3	0.212	3.68	18.7
M	12.7	9.2	0.172	3.62	19.9
N	17.2	14.7	0.304	3.39	23.2
O	25.2	15.0	0.658	3.54	27.6
Significance among clones	**	**	**	*	**
Variance of clones	9.59	3.42	0.013	0.008	3.79
Variance of environment	9.69	5.44	0.012	0.019	2.07
Repeatability	0.50	0.39	0.51	0.30	0.65

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

* Significance at the 5 % level

** Significance at the 1 % level

Table 3 Growth characteristics, SWV, Py, and their repeatabilities in 45 teak trees from 15 clones planted at Ciamis, Indonesia

Clone code	*D* (cm)	*H* (m)	*V* (m^3)	SWV (km/s)	Py (mm)
A	20.2	15.7	0.422	3.54	22.3
B	17.6	14.2	0.316	3.48	21.9
C	21.5	19.0	0.476	3.56	21.8
D	24.8	16.0	0.634	3.63	23.2
E	24.8	19.2	0.633	3.51	22.3
F	19.3	15.8	0.387	3.23	21.7
G	22.1	16.5	0.504	3.69	23.0
H	21.7	17.0	0.481	3.39	22.0
I	23.5	17.3	0.573	3.51	22.1
J	17.0	12.3	0.298	3.38	22.2
K	18.2	16.0	0.340	3.40	22.1
L	17.0	16.3	0.295	3.50	21.0
M	17.8	15.2	0.324	3.77	22.0
N	22.1	14.7	0.505	3.51	22.9
O	37.7	23.7	1.472	3.65	26.9
Significance among clones	**	**	**	*	**
Variance of clones	24.36	4.78	0.076	0.010	1.47
Variance of environment	7.85	6.04	0.023	0.026	0.97
Repeatability	0.76	0.44	0.77	0.27	0.60

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

* Significance at the 5 % level

** Significance at the 1 % level

Repeatability

Callister and Collin [5] reported repeatability of *D*, *H*, and *V* in 61 clones of 3.5-year-old teak trees at 0.37, 0.28, and 0.35, respectively. Moya and Marín [9] reported that the repeatability of the dynamic modulus of elasticity was 0.34 in 10-year-old teak trees planted in Costa Rica. In the present study, repeatability of measured characteristics showed relatively moderate to high values (Tables 2, 3) compared to the results obtained by previous researchers [5, 9]. Our results of repeatability suggest that these characteristics are closely related to genetic factors. On the other hand, Monteuuis et al. [4] reported that values for the narrow-sense heritability of *D*, *H*, and *V* in teak gradually

Table 4 Comparison of mean values for growth characteristics, SWV, and Py between the two clonal test sites

Property	Site				Significance between two sites
	Cepu		Ciamis		
	Mean	SD	Mean	SD	
D (cm)	16.3	3.6	21.7	5.2	**
H (m)	13.0	2.3	16.6	2.6	**
V (m^3)	0.29	0.13	0.51	0.29	**
SWV (km/s)	3.57	0.12	3.52	0.14	ns
Py (mm)	22.0	2.1	22.5	1.3	ns

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

** Significance at the 1 % level

increased with tree age. This is also true for other tropical fast-growing clonal tree species, such as *Acacia auriculiformis* [18]. These findings suggest that values for repeatability are related to tree age. Therefore, repeatability values of *D*, *H*, and *V* obtained in the present study showed relatively higher values than those obtained by other researchers [5, 18]. However, further researches are needed to clarify the relationship between the repeatability of growth characteristics and tree age.

Effects of environmental factors on growth and other characteristics

Table 4 shows the differences in growth characteristics, SWV, and Py between the two sites. *D*, *H*, and *V* differed significantly (1 % level) between the two sites. This is also true for the results of ANOVA test that significant difference on site effect was observed for growth characteristics (Table 5). For all growth characteristics, the mean values were higher in Ciamis than in Cepu. Monteuuis et al. [4] examined growth characteristics, such as *D*, *H*, and increment of *V*, in teak trees planted in East Malaysia. They pointed out that the wet tropical conditions positively influenced the growth characteristics of teak. In the present study, as shown in Table 1, the mean temperature was almost the same in both sites, whereas precipitation was approximately two times higher in Ciamis than in Cepu. The higher level of precipitation in Ciamis may have effects on the growth characteristics. On the other hand, Cordero and Kanninen [19] reported no significant difference in the oven-dry density of wood between the trees growing in different climatic zones in Costa Rica. Furthermore, Moya and Perez [20] reported that the physical and chemical characteristics of the soil had almost no impact on the wood properties (specific gravity, normal volumetric shrinkage, and heartwood percentage) of teak trees planted in Costa Rica. In the present study, SWV and Py did not differ significantly between the two sites. Therefore, these results suggest that SWV and Py of teak tree are not largely affected by environmental factors.

In the present study, significant interaction between genotype and environment was found in all measured characteristics (Table 5). In addition, SWV and Py showed lower interaction between genotype and environment than growth characteristics. Na'iem [12] reported that significant interaction between clone and site was found in *D* and *H* of 16-month teak trees planted at four sites in Indonesia. On the other hand, Indira and Bhat [21] reported that no significant interaction between clone and site was found in basic density of 14-year-old teak clone planted at four sites in India. From these results, when teak plantations are established in Indonesia, interaction between genotype and environment in growth characteristics, SWV, and Py should be considered. However, further study is needed to clarify interaction between genotype and environment in teak wood properties.

Relationships among characteristics

Table 6 shows the correlation coefficients among tested characteristics. Highly positive significant correlations were found among growth characteristics (*D*, *H*, and *V*). High correlation coefficients of *D* and *H* were also observed for teak trees by other researchers [4, 5]. In

Table 5 Across-site analysis of variance in growth characteristics, SWV, and Py

Source of variation	Degree of freedom	Mean square				
		D	*H*	*V*	SWV	Py
Site	1	638.40**	291.6**	1.08**	0.07ns	4.70 ns
Clone	14	93.64**	24.96**	0.23**	0.06**	15.60**
Site × clone	14	25.74**	11.12*	0.07**	0.04*	3.21*
Error	60	8.77	5.74	0.02	0.02	1.52

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

* Significance at the 5 % level

** Significance at the 1 % level

Table 6 Correlation coefficients between growth characteristics, SWV, and Py of 15 clones of teak trees at the two test sites

Properties	*D*	*H*	*V*	SWV	Py
D		0.76**	0.99**	0.04ns	0.86**
H	0.85**		0.68**	0.09ns	0.60**
V	0.99**	0.85**		0.03ns	0.89**
SWV	0.34ns	0.29ns	0.33ns		-0.18ns
Py	0.91**	0.66**	0.94**	0.39ns	

Values in lower side of diagonal and upper side of diagonal showed correlation coefficients in Cepu and Ciamis, respectively. Used data, mean values from 15 clones

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

** Significance at the 1 % level

addition, Monteuuis et al. [4] reported that *D* and *H* were positively correlated with *V*. These results indicate that growth characteristics are closely related with each other in teak clones. Thus, *D* is one of suitable criteria in tree breeding programs of teak for selecting plus trees with good diameter and height growth, and high bole volume.

Some researchers reported no correlation or significant but weak negative correlations between growth characteristics and SWV for some hardwood species [14, 22–24]. In the present study, no significant correlation was observed between growth characteristics and SWV in both sites (Table 6), suggesting that SWV of teak is also independent of growth characteristics. Thus, it can be said that mechanical properties are also important criteria for selecting the plus trees in tree breeding programs.

In the present study, relatively high significant correlation coefficients were obtained between growth characteristics and Py in teak trees planted in both sites (Table 6). In general, Py is closely related to the wood density at outer part of stem [16, 25]. Therefore, it can be said that trees with good growth characteristics resulted in trees with lower wood density. However, further research is required to clarify the relationship between *D* and Py in teak tree.

Conclusion

Growth characteristics (*D*, *H*, and *V*), SWV, and Py varied among clones of 12-year-old teak trees planted at two different sites in Indonesia. In addition, repeatability of measured characteristics showed relatively moderate to high values, indicating that these characteristics are closely related to genetic factors. Interaction between genotype and environment was found in *D*, *H*, *V*, SWV, and Py. These results suggest that interaction between genotype and environment should be considered, when the teak plantations are established in Indonesia. Furthermore, highly positive correlations were found between growth characteristics. However, no significant correlation was found between growth characteristics and SWV, suggesting that SWV is independent of growth characteristics of teak trees. From these results obtained, it is concluded that the wood properties of teak trees can be improved by implementation of an appropriate tree breeding program.

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