GROWTH AND WOOD TRAITS EVALUATION OF 15-YEAR-OLD TENGKAWANG (*Shorea* spp.) TREE STANDS IN GUNUNG WALAT UNIVERSITY FOREST, WEST JAVA, INDONESIA

Fifi Gus Dwiyanti[1*], Henti Rosdayanti[2], Kusumadewi Sri Yulita[3], Henti Hendalastuti Rachmat[3], Yahya Ayyasy[4], Karima Fauziah Muharam[4], Mohamad Miftah Rahman[5], Ulfa Adzkia[6], and Iskandar Zulkarnaen Siregar[1]

[1]Department of Silviculture, Faculty of Forestry and Environment, IPB University, Jl. Ulin, IPB Dramaga Campus, Dramaga Bogor, West Java, 16680, Indonesia
[2]Research Centre for Applied Botany, National Research and Innovation Agency (BRIN), Jl. Raya Jakarta – Bogor Km. 46, Cibinong, Bogor, West Java, 16911, Indonesia
[3]Research Centre for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Jl. Raya Jakarta – Bogor Km. 46, Cibinong, Bogor, West Java, 16911, Indonesia
[4]Alumni of Department of Silviculture, Faculty of Forestry and Environment, IPB University, Jl. Ulin, IPB Dramaga Campus, Dramaga, Bogor, West Java, 16680, Indonesia
[5]Department of Forest Products, Faculty of Forestry and Environment, IPB University, Jl. Ulin, IPB Dramaga Campus, Dramaga, Bogor, West Java, 16680, Indonesia
[6]Forestry Study Program, Faculty of Agriculture and Forestry, West Sulawesi University (UNSULBAR), Jl. Hasanuddin, Lutang, Banggae Timur, Majene, West Sulawesi, 91412, Indonesia

Received: 12 December 2022, Revised: 7 November 2023, Accepted: 14 October 2024

GROWTH AND WOOD TRAITS EVALUATION OF 15-YEAR-OLD TENGKAWANG (SHOREA SPP.) TREE STANDS IN GUNUNG WALAT UNIVERSITY FOREST, WEST JAVA, INDONESIA. Gunung Walat University Forest (GWUF) in Sukabumi Regency, Indonesia, plays a crucial role in providing various ecosystem services. Five important *Shorea* trees, i.e., *Shorea stenoptera, S. mecisopteryx, S. pinanga*, *S. palembanica*, and *S. leprosula* have been planted in GWUF as an effort for its conservation and object of research. An evaluation of the adaptability and suitability of these species to the GWUF ecosystem, as well as their wood characteristics, needs to be carried out regularly. Therefore, the study aimed to examine the growth performances and physical wood properties of five *Shorea* species, i.e., *Shorea stenoptera*, *S. mecisopteryx, S. pinanga*, *S. palembanica,* and *S. leprosula* at the age of 15-year-old planted in GWUF. The results indicated that *S. leprosula* exhibited the best growth performance in terms of average diameter (19.64 cm), volume (0.27 m^3), slenderness (126.58), and wood density (0.94 g/cm^3), and *S. stenoptera* showed the best performance in average height (23.35 m). While the poor performance was shown by *S. palembanica* in terms of average diameter (6.73 cm), height (11.15 m), volume (0.02 m^3), wood density (0.87 g/cm^3), and specific gravity (0.45), and *S. stenoptera* in terms of average slenderness (202.73). In addition, significant differences in tree height, diameter, volume, wood density, specific gravity, and moisture content were found in *S. palembanica* compared with other species. The relationship between the growth and physical wood properties parameters varied between species. The study revealed that planting the five *Shorea* species in GWUF is suitable for increasing vegetation cover and conserving the species.

Keywords: Dipterocarps, ex-situ conservation, education forest, non-timber forest products (NTFPs), *Shorea* spp.

EVALUASI PERTUMBUHAN DAN KARAKTER KAYU TEGKAWANG (SHOREA SPP.) UMUR 15 TAHUN DI HUTAN PENDIDIKAN GUNUNG WALAT, JAWA BARAT, INDONESIA. Hutan Pendidikan Gunung Walat (HPGW) di Kabupaten Sukabumi, Indonesia berperan penting dalam menyediakan berbagai jasa ekosistem. Lima pohon Shorea penting, yaitu Shorea stenoptera, S. mecisopteryx, S. pinanga, S. palembanica, dan S. leprosula ditanam di HPGW sebagai upaya konservasi dan objek penelitian. Evaluasi kemampuan beradaptasi dan kesesuaian dari spesies ini pada ekosistem HPGW serta karakteristik kayunya perlu dilakukan secara berkala. Oleh karena

*Corresponding author: fifi_dwiyanti@apps.ipb.ac.id

 doi:10.59465/ijfr.2024.11.2.243-258

itu, tujuan dari penelitian ini adalah untuk menguji performa pertumbuhan dan sifat fisik kayu dari lima jenis pohon Shorea yaitu Shorea stenoptera, S. mecisopteryx, S. pinanga, S. palembanica, dan S. leprosula berumur 15 tahun yang ditanam di HPGW. Hasil penelitian menunjukkan bahwa pertumbuhan terbaik ditunjukkan oleh S. leprosula dengan rata-rata diameter (19.64 cm), volume (0.27 m^3), kelangsingan (126.58), dan kerapatan kayu (0.94 g/cm^3), dan S. stenoptera pada tinggi rata-rata (23.35 m). Sedangkan performa yang buruk ditunjukkan oleh S. palembanica dengan rata-rata diameter (6.73 cm), tinggi (11.15 m), volume (0.02 m^3), kerapatan kayu (0.87 g/cm^3), dan berat jenis (0.45), dan S. stenoptera pada kelangsingan rata-rata (202.73). Selain itu, perbedaan yang signifikan pada tinggi pohon, diameter, volume, kerapatan kayu, berat jenis, dan kadar air ditemukan di S. palembanica dibandingkan dengan spesies lainnya. Hubungan antara parameter pertumbuhan dan sifat fisik kayu bervariasi antar spesies. Hasil penelitian mengungkapkan bahwa penanaman lima jenis pohon Shorea di HPGW sesuai untuk meningkatkan tutupan vegetasi dan melestarikan jenisnya..

Kata kunci: Dipterokarpa, konservasi ex-situ, hutan pendidikan, Hasil Hutan Bukan Kayu (HHBK), Shorea *spp*

I. INTRODUCTION

An educational forest is a forest allocated for education and research activities conducted by students, academics, and researchers to study all aspects related to forestry and the interrelationships among the components of its ecosystem (Wahyudi et al., 2014). Gunung Walat University Forest (GWUF) is one of the educational forests in West Java Province, Indonesia. It was established in 1951 and is currently managed by the Faculty of Forestry and Environment, IPB University. The GWUF is assigned as a forest model that applies the concept of Sustainable Small Scale Forest Management (SSSFM) by relying on non-timber forest products and environmental services (Yahya et al., 2015). This forest has been used as a research location covering almost all physical, biological, social, economic, and environmental aspects by students and researchers from IPB University and other universities (Yahya et al., 2015). As a dense-complex man-made forest ecosystem, GWUF provides various ecosystem services, including provisioning services (e.g. resin from pine and agathis trees, food and feed, energy sources such as firewood and wood pellet, medicinal plants, poisonous plants, and wildlife), regulating services (hydrological, erosion, and flood control functions, air and climate regulating functions, pest and disease prevention, and windbreaker functions), cultural services (ritual site), and supporting services (habitat for various organisms and farming) (Yahya et al., 2015).

Nowadays, GWUF also enhances its supporting services by conserving vulnerable and important Indonesian tree species such as red meranti (*Shorea* spp.) from the Dipterocarpaceae family, which produce not only timber but also non-timber forest products from their fruit known as tengkawang or illipe nut or Borneo tallow nut. The fruit can be used as raw material for vegetable fat, which has a higher value compared to other vegetable oils (e.g., coconut oil) (Winarni et al., 2004; Leksono & Hakim, 2018; Ramadhani et al., 2021). Tengkawang fat quality hinges on several critical physicochemical parameters such as fatty acid, acid number (AN), peroxide number (PN), iodine number (IN), saponification number, and melting point (Abd-Aziz et al., 2023). Tengkawang fat is a blend of triglycerides, consisting of glycerol esters and several unsaturated fatty acids, ranging from 50% to 70% (Ketaren, 2008). The composition of fatty acids in tengkawang fat is mainly made up of stearic acid, oleic acid, and palmitic acid. The percentages for these acids range from 40-46%, 30-32%, and 16-24%, respectively (Darmawan et al., 2020; Abd-Aziz et al., 2023). This makes tengkawang fat a valuable component of cocoa butter equivalent (CBE) blends and allows it to be used directly without further processing (Abd-Aziz et al., 2023). This is also supported by the high melting point of this fat, which is between 34-39^{o}C (Winarni et al., 2004; Leksono & Hakim, 2018; Ramadhani et al., 2021; Abd-Aziz et al., 2023). The properties of tengkawang fat are similar to cocoa butter (Leksono & Hakim, 2018), so the fat can be a substitute for cacao butter in the chocolate industry, margarine, vegetable fat raw material, and cosmetic products such as soap and lipstick (Blicher-Mathiesen, 1994; Lipp & Anklam, 1998; Winarni et al., 2004; Leksono & Hakim, 2018), which are exported to Japan and Europe (Purwaningsih, 2004; Winarni et al., 2017). Tengkawang oil can also be used as a rice seasoning by local people, as a preservative for wet noodles, and in the pharmaceutical industry (Winarni et al., 2004; Setiadi, 2019).

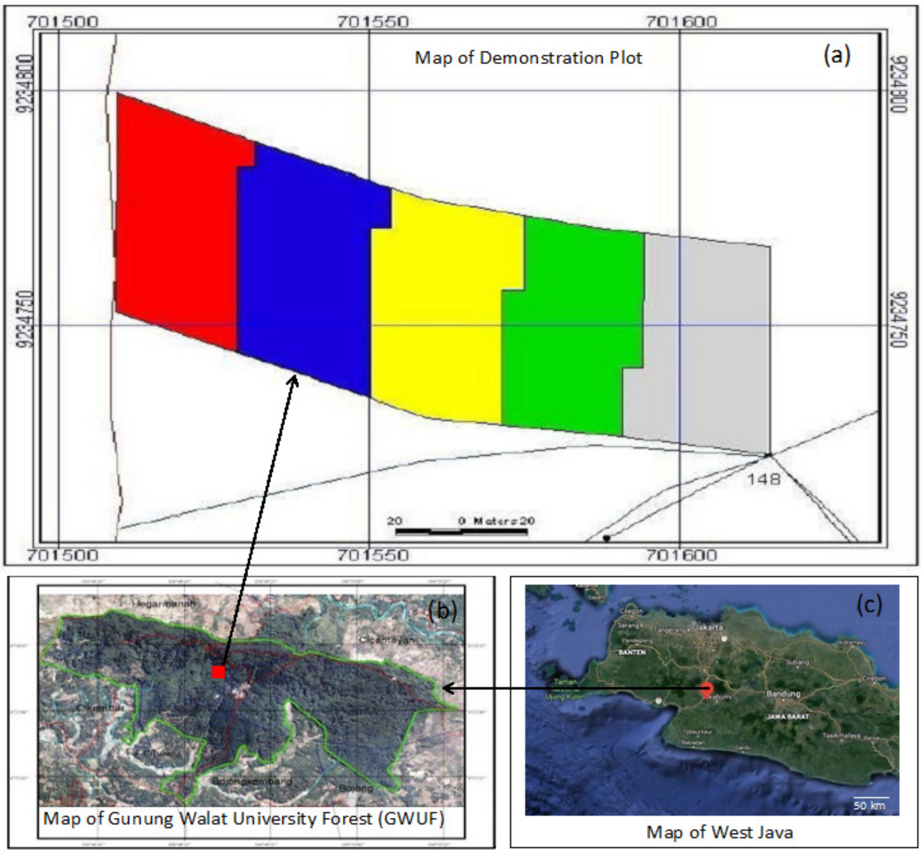
Tengkawang-producing species have a wide natural distribution in Asia, including Indonesia, Malaysia, Sarawak, Sabah, Thailand, the Philippines, and India (Kettle, 2010; Saner et al., 2012; Widiyatno et al., 2014; Winarni et al., 2017) with natural distribution in Indonesia covering Kalimantan and a small part of Sumatera islands (Purwaningsih, 2004; Winarni et al., 2017; Kettle, 2010). Indonesia has about 13 species of tengkawang-producing trees, of which 10 species are found in Kalimantan and 3 other species in Sumatera (Supartini & Fajri, 2014; Leksono & Hakim, 2018). The existence of tengkawang-producing trees in natural forests is decreasing due to increasing illegal logging and timber exploitation activities that do not consider the sustainability aspect (Leksono & Hakim, 2018; Winarni et al., 2017). Besides that, the overexploitation of tengkawang fruits from natural forests and an irregular fruit season hinder natural regeneration (Leksono & Hakim, 2018). In West Kalimantan, for example, a massive harvest season for large fruit tengkawang species occurs once every 3-4 years during the fruit seasons (Bunyamin et al., 2020; Heri et al., 2020). Therefore, several species are currently classified as critically endangered species, such as *Shorea palembanica* (Ashton, 1998).

Ex-situ conservation measures through the establishment of an ex-situ conservation plot and tree breeding programs, such as selecting superior trees for seed sources of tengkawang seedlings, are essential to be carried out. GWUF has planted four tengkawang-producing species namely *Shorea stenoptera*, *S. mecisopteryx*, *S. pinanga*, and *S. palembanica*, and another high-value red meranti that does not produce tengkawang fruit, *Shorea leprosula* (meranti tembaga). Planting these species in the GWUF would not only enrich tree stands in the GWUF and conserve the species but also provide a seed source for cultivation that eventually provides provisioning services through tengkawang production. Previous studies on the relationship between growth and wood quality, especially on the dynamic modulus of elasticity (MOE) and wood density, have been carried out by assessing the tree growth performance and wood quality of the five species when the stands were 7 and 9 years old. However, only 7 individual trees were assessed for each species in each measurement year (Karlinasari et al., 2018). Meanwhile, evaluation of the adaptability and suitability, as well as the wood traits of all stands of the five species in the GWUF area, has not yet been assessed. Thus, this study aimed to examine the growth performance and wood properties of five *Shorea* species i.e., *S. stenoptera*, *S. mecisopteryx*, *S. pinanga*, *S. palembanica*, and *S. leprosula*, 15 years after planting in the GWUF. The results of this study were expected to provide basic information in formulating strategies for species enrichment in GWUF specifically and the ex-situ conservation and breeding program of these species in Indonesia extensively.

II. MATERIAL AND METHOD

A. Study Site

The research was conducted at the *Shorea* spp. demonstration plot in Gunung Walat University Forest (GWUF), Cibadak and Cicantayan Subdistricts, Sukabumi Regency, West Java Province, Indonesia (Figure 1), which is geographically located between 6^{o}54'23"



Source: Harahap et al. (2018)

Figure 1. Map of the study site. (a) Map of *Shorea* spp. demonstration plot with red color for *S. palembanica* stands, blue for *S. mecistopteryx*, yellow for *S. stenoptera*, green for *S. leprosula*, and grey for *S. pinanga*; (b) Map of GWUF; and (c) Map of West Java in Java Island

S - 6º55'35" S and 106º48'27" E - 106º50'29" E (Damayanti et al., 2020). The GWUF was originally an abandoned land covering an area of 359 ha, most of which was open land, some were covered with shrubs, and several hectares were covered with *Agathis lorantifolia* stands (Yahya et al., 2015). However, since the Faculty of Forestry and Environment IPB managed GWUF in 1969, this area was then planted gradually with various tree species by the IPB students, alumni, and local communities. Currently, the forest is 95% covered with 15 tree species, including *Agathis dammara*, *Pinus merkusii*, *Schima wallichii*, *Maesopsis eminii*, *Swietenia macrophylla*, *Altingia excelsa*, *Dalbergia latifolia*, *Gliricidia* sp., *Paraserianthes falcataria*, *Shorea leprosula*, *Shorea stenoptera*, *Shorea mecisopteryx*, *Shorea pinanga*, *Shorea palembanica*, and *Acacia mangium*, and also 11 woody shrub species such as *Calliandra calothyrsus*, *Etlingera solaris*, *Clidemia hirta*, *Melastoma candidum*, *Sellaginella doederleinii*, *Cynodon dactylon*, *Curculigo latifolia*, *Claoxylon indicum*, *Leea sambucina*, *Equisetum debile*, and *Coffea arabica* (Yahya et al., 2015; Damayanti et al., 2020).

B. Species Selection and Plot Establishment

In this study, we examined five *Shorea* species; four of them are tengkawang-producing trees, namely *S. stenoptera*, *S. mecisopteryx*, *S. pinanga*, and *S. palembanica*; and one is a non-tengkawang-producing-tree, namely *S. leprosula*. These species are included in the red meranti group, which has high economic and ecological value (Newman et al., 1999). These species were selected based on different growth performance (Karlinasari et al., 2018), namely (i) fast-growing species (*Shorea leprosula*), (ii) moderate-growing species (*Shorea stenoptera* and *S. mecistopteryx*), and (iii) slow-growing species (*Shorea pinanga* and *S. palembanica*). This selection was important so as to obtain growth performance and wood properties data of these five species as a basis for determining whether these species can adapt and are suitable for the site in GWUF.

There were 26 individuals of *Shorea leprosula*, 30 individuals of *S. stenoptera*, 58 individuals of *S. mecistopteryx*, 10 individuals of *S. pinanga*, and 10 individuals of *S. palembanica* planted among existing mixed tree stands with a planting distance of 5 m × 5 m in the species trial block (06°55'0" S - 106°49'30" E) in 2006 (Figure 1a). The existing stands consist of adult trees that have a diameter at breast height (dbh) of more than 40 cm (Karlinasari et al., 2018). In total, 134 trees of *Shorea* species were evaluated in this study.

C. Data Collection

The adaptability and suitability of 15-year-old *Shorea leprosula*, *S. stenoptera*, *S. mecisopteryx*, *S. pinanga*, and *S. palembanica* planted in GWUF were evaluated by examining the tree growth parameters. Wood traits were evaluated by assessing the physical wood properties of standing trees. Tree growth parameters for each species examined in this study included (i) total tree height (m) measured using Haga Hypsometer, (ii) stem diameter (cm) at breast height (dbh 1.3 m) using measuring tape, (iii) tree volume (m^3) by calculating it using Equation 1 (Forest Area Consolidation Center Agency Denpasar VIII, 2021), and (iv) slenderness by calculating the ratio of the total height and stem diameter at breast height (Wang et al., 1998).

Tree Volume (m^3) = Tree basal area × tree height × form factor ....(1)

Where,
Tree basal area (m^2): $(3.14/4) \times (\text{dbh})^2$
Form factor: 0.7

The physical wood properties of five *Shorea* species in this study were evaluated by analyzing the wood moisture content, wood density, wood specific gravity, and pilodyn penetration. In order to measure wood moisture content, density, and specific gravity, the wood core samples from each stem were collected using a hollow punch (Prohex Germany) with a diameter of 10 mm and a length of 2-3 cm. The wet volume of the wood core (cm^3) was determined by water displacement using a graduated cylinder (Archimedes method; Cornelissen et al., 2003), while the oven-dry weight was determined by the weight of the wood core after drying in an oven at 105°C for 24 hours (Kalanatarifard & Yang, 2012) in Mycorrhiza Laboratory at Department of Silviculture, Faculty of Forestry and Environment, IPB University, Bogor. This oven-dry weight was then used to calculate moisture content (%) by using Equation 2 (Hartley & Marchant, 1995). Whereas, the wet volume was used to calculate the wood density (g/cm^3) by using Equation 3 (Zabel et al., 2020) and wood specific gravity by using Equation 4 (Simpson, 1993).

Wood Moisture Content (%) = ((Green weight – oven-dry weight)/oven-dry weight) × 100 % ....(2)

Wood Density (g/cm^3) = Green weight/wet volume of the wood core ....(3)

Wood Specific Gravity = $((Wd/Vg)/\rho)$ ....(4)

Where,
Wd: oven-dry weight of the wood core
Vg: wet volume of the wood core
ρ: water density (1 g/cm^3)

In addition, the pilodyn penetration parameter was also used in this study to evaluate the wood density of the standing tree. Pilodyn penetrometer 6J was used to measure the penetration depth of a spring-loaded blunt pin (2.5 cm diameter) fired into the tree stem at breast height (1.3 m) without removing the bark with an exact force to a maximum depth of 40 mm (Gregory et al., 2007; Fundova et al., 2018).

D. Statistical Data Analysis

The data of growth parameters and physical wood properties parameters, including tree height, stem diameter at breast height, tree volume, slenderness, wood moisture content, wood density, wood specific gravity, and pilodyn penetration, were interpreted by using a box-plot analysis to determine the data distribution of each parameter. The analysis of variance (ANOVA) at the 5% level of significance was performed to observe the variation between each species and each growth parameter as well as physical wood properties parameters. Further analysis using the Duncan multiple range test at the 5% level was also performed if there was a significant difference in observed variables (Sumida et al., 2013). Those analyses were performed using SPSS software (IBM Corp., 2020). In addition, the relationship among parameters was analyzed using Pearson Correlation Analysis, which was performed using SPSS software (IBM Corp., 2020), and the Principal Component Analysis (PCA), which was performed using Minitab software version 16 (Minitab, 2021).

III. RESULTS AND DISCUSSION

A. Tree Growth Performance of 15-Year-Old Five *Shorea* Species in GWUF

Tree growth, such as the increase in dimensions of height and diameter, is a transformation process in tree life that affects stand yields (Hardjana & Suastati, 2014). The parameters related to tree growth are basic information for forest resource management and forest ecology studies (Nugroho, 2014). In the present study, the data of four parameters of tree growth, such as tree height, stem diameter, tree volume, and slenderness, were analyzed using a box-plot analysis and further variance analysis.

The box-plot analysis on stem diameter (at breast height) showed that the *Shorea leprosula* stand has the highest box position than the other *Shorea* stands with a diameter range of ±5-33 cm (Figure 2a), and the *S. palembanica* stand has the lowest box position with a diameter range of ±5-6 cm (Figure 2a). These results revealed that *S. leprosula*, as a fast-growing species, showed the highest stem-diameter growth compared to moderate-growing species and slow-growing species. While, *S. palembanica*, as a slow-growing species, showed the lowest stem diameter compared to other species. In addition, the average diameter of *S. leprosula* (19.64 cm) and *S. palembanica* (6.73 cm) was significantly different from the other species based on the Duncan test results at a 5% level (Table 1).

The high average diameter of *S. leprosula* was also reported in Karlinasari et al. (2018) study in GWUF, where 9-year-old *S. leprosula* stands had the highest and significant average diameter (9.714 cm) compared to *Shorea stenoptera* (8.857 cm), *Shorea mecisopteryx* (8.286 cm), *Shorea pinanga* (6.028 cm), and *Shorea palembanica* (6.185 cm), as well as in Istomo et al. (1999) study in Haurbentes Research Forest in West Java Province, Indonesia, where 13-year-old *S. leprosula* stands had the highest average diameter (30.65 cm) compared to *S. stenoptera* (23.63 cm) and *S. pinanga* (14.69 cm). However, the average diameter of 13 years old *S. leprosula* stands in Haurbentes Research Forest is better than the 15-year-old stand in GWUF. This pattern is possible considering that the *Shorea* species grown in Haurbentes Research Forest were planted in bare land that was not shaded by other large tree crowns that had been planted prior to *Shorea* planting. Unlike, the five *Shorea* species grown in GWUF were planted between old tree stands with a diameter of more than 40 cm so that the distribution of light intensity in these stands could vary (Karlinasari et al., 2018), which then also caused variations in the stem diameter of each species (Figure 2a), even though *Shorea* spp. is a species that requires shade in the seedling phase and more sunlight to grow to the next phase (Krisnawati & Wahjono, 2010; Wistara et al., 2016). Seedlings of *Shorea* spp. grow well on the forest gap with light intensity between 42.71% to 45.73% or 52.1% to 55% (the Spherical Crown Densiometer scale) (Stuckle et al., 2001; Wahyudi et al., 2016). Therefore, silvicultural treatment such as removing the closest competitor trees, called thinning, is needed for future stand maintenance activities to provide better growth space, including increasing the spacing and reducing competition for light, nutrients, and minerals to stimulate the growth of *Shorea* stem diameter (Krisnawati & Wahjono, 2010; Wistara et al., 2016; Indrioko et al., 2020; Pamoengkas et al., 2020).

The distribution of tree height data of five *Shorea* species based on box-plot analysis showed that *Shorea leprosula* stand has the highest box position compared to the other species, with a tree height range of ±11-32 m (Figure 2a), and *S. palembanica* stand has the lowest box position compared to the other species with a tree height range of ±9-13 m (Figure 2a). However, the average tree height showed that *S. stenoptera* was higher (23.35 m) and significantly different from other species, followed by *S. leprosula* (22.38 m) (Table 1), while *S. palembanica* was lower (11.15 m) and significantly different from other species (Table 1). This pattern was slightly different from the results of Karlinasari et al., (2018) study in GWUF, where 9-year-old *S. leprosula* showed a higher and significant average tree height (13.271 m) compared to *S. stenoptera* (8.857 m), *S. mecisopteryx* (8.286 m), *S. pinanga* (5.971 m) and *S. palembanica* (5.457 m). In addition, the current pattern was also slightly different from Istomo et al., (1999) study in Haurbentes Research Forest in West Java Province, Indonesia, where 13-year-old *S. leprosula* stands has the greater average tree height (19.88 m) compared with *S. stenoptera* (16.15 m) and *S. pinanga* stands (12.39 m).

In the present study, the tree height pattern contradicts the stem diameter pattern, especially in the case of *S. stenoptera*,. This suggests that the impact of tree height and stem diameter varies between stands and within the same stand over time (Nugroho, 2014; Curtis, 1967; Paulo et al., 2011). Differences in site quality (Larsen & Hann, 1987; Wang & Hann, 1988; Nugroho, 2014), stand density (Sharma & Parton, 2007; Temesgen et al., 2008; Nugroho, 2014), and stand age (VanderSchaaf, 2008; Nugroho, 2014) may lead to variations in stand-to-stand. However, all *Shore*a stands in this study were of the same age so the stand density was the most influential factor on stand variation. Whereas variation over time within the same stand can be attributed to the arrangement of trees in a stand (Temesgen & Gadow, 2004; Nugroho, 2014) and the spatial distribution pattern (Aguirre et al., 2003; Zhang et al., 2004).

The results of box-plot analysis on tree volume were similar to the stem diameter results, which showed that *Shorea leprosula* stand has the highest box position compared to other species, indicating the stand had a more growth stage at tree volume ±0.01-1.1 m^3 (Figure 2b), and *S. palembanica* stands have the lowest tree volume (±0.09-0.26 m^3) compared to other species (Figure 2b). Besides that, the average tree volume of *S. leprosula* was also the highest (0.27 m^3) and significantly different from other species (Table 1), while the average tree volume of *S. palembanica* (0.02 m^3) was the lowest among other species although it was not significantly different from *S. stenoptera*, *S. mecisopteryx*, and *S. pinanga* (Table 1). The current tree volume evaluation results in the three 15-year-old *Shorea* species are slightly similar to the results of the tree volume evaluation when these five *Shorea* species were 9-year-old, where *S. leprosula* showed a higher average tree volume (0.066 m^3) and *S. pinanga* showed a lower average tree volume (0.013 m^3) compared to other species (Karlinasari et al., 2018).

In order to support the results of tree height, diameter at breast height, and volume, another parameter, such as the slenderness of this tree *Shorea* species, was also determined. The distribution data on slenderness (Figure 2c, Table 1) showed that *S. stenoptera* has the highest mean value of slenderness (202.73) and was significantly different from other species, while *S. leprosula* has the lowest mean value (126.58) and is significantly different from other species (Figure 2c, Table 1). The highest value of *S. stenoptera* indicated that the stand of this

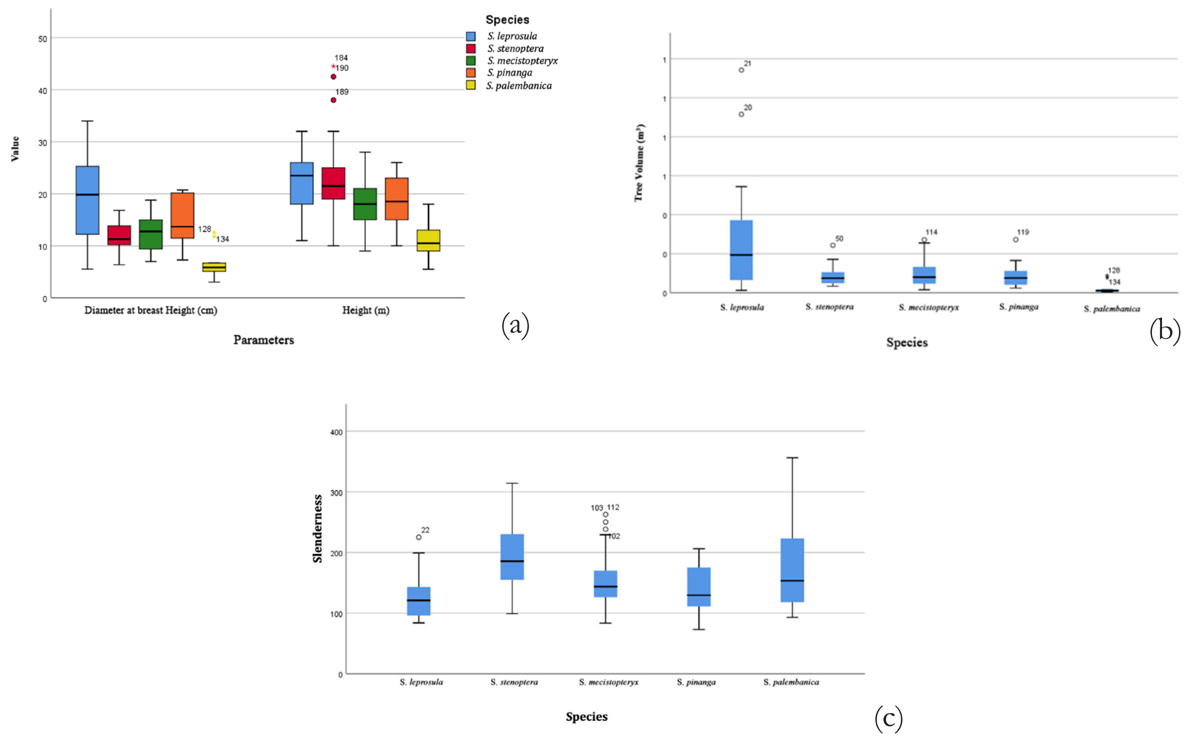


Figure 2. Box-plot diagram of *Shorea* spp. tree growth (open circle: outliers). (a) Stem diameter and tree height, and (b) Tree volume, and (c) Slenderness in each *Shorea* species

Table 1. Mean values of 15-year-old *Shorea* spp. growth parameters

Growth Rate	Species	n	Diameter (cm)	Height (m)	Tree Volume (m^3)	Slenderness
Fast	*Shorea leprosula*	26	19.64^{c} (±8.179)	22.38^{cd} (± 5.441)	0.27^{b} (±0.276)	126.58^{a} (±37.200)
Moderate	*Shorea stenoptera*	30	11.86^{b} (± 2.461)	23.35^{d} (±7.742)	0.09^{a} (±0.048)	202.73^{c} (±69.865)
Moderate	*Shorea mecistopteryx*	58	12.47^{b} (± 3.316)	18.17^{b} (±4.419)	0.10^{a} (± 0.066)	151.15^{ab} (±38.808)
Slow	*Shorea pinanga*	10	14.45^{b} (± 4.655)	18.70^{bc} (±4.809)	0.09^{a} (±0.077)	136.90^{a} (±39.909)
Slow	*Shorea palembanica*	10	6.73^{a} (± 3.040)	11.15^{a} (±4.096)	0.02^{a} (±0.031)	186.00^{bc} (±91.658)

Notes: Mean ± standard deviation (SD) with different letters in the same column indicate significant differences at $P<0.05$ (Duncan's test); n = number of samples.

species is dominated by the slender tree shape, which is generally susceptible to wind damage (Wang et al., 1998). While the lowest value of *S. leprosula* indicated that the stand has an ideal proportion of height and stem diameter and might have a longer crown (Wang et al., 1998). However, the tree slenderness coefficient can also change with age and site (Rottman, 1986); for example, tree slenderness increases in young trees, culminates, and then gradually decreases in softwood species (Konopka et al., 1987), and it also increases on better quality sites (Oliveira, 1987).

B. Physical Wood Properties of 15-Year-Old *Shorea* Species in GWUF

Moisture content, wood density, specific gravity, and pilodyn penetration are physical properties that need to be considered in wood utilization (Wistara et al., 2016). In this study, the results of the moisture content of five *Shorea* species showed that *S. palembanica* stand has the highest box position (Figure 3a) and the highest average moisture content (92.87%) compared to other species (Table 2). The average of *S. palembanica*'s moisture content also showed statistically significant differences among species, suggesting that the stand had the highest moisture content. While *S. pinanga* stand has the lowest box position (Figure 3a) and average moisture content (66.10%) compared to other species (Table 2) indicated the stand had the lowest moisture content.

In the case of wood density evaluation of five *Shorea* spp. in GWUF showed that *Shorea leprosula* stand has the highest box position (Figure 3b) and the highest average wood density (0.92 g/cm^3) compared to other species (Table 2). The *S. stenoptera* stand has a moderate box position (Figure 3b) and moderate average wood density (0.90 g/cm^3) compared to other species (Table 2), that the stand had a moderate wood density. Besides that, the *S. palembanica* stand has the lowest box position (Figure 3b), and average wood density (0.87 g/cm^3) compared to other species (Table 2) which indicated the stand had the lowest wood density. However, the wood density in the studied *Shorea* spp. was not significantly different based on the Duncan test at a 5% level of significance.

The specific gravity evaluation in this study showed that the *Shorea pinanga* stand has a moderate box position (Figure 3c) but has the highest and significant average specific gravity (0.59) compared to other species (Table 2), indicating the stand had the highest specific gravity. While, *S. palembanica* stand has the lowest box position (Figure 3c) and average specific gravity (0.45) compared to other species (Table 2) indicated the stand had the lowest specific gravity. Besides moisture content, wood density, and specific gravity, the pilodyn penetration parameter was also determined, and the results showed that *S. stenoptera*, as a moderate-growing

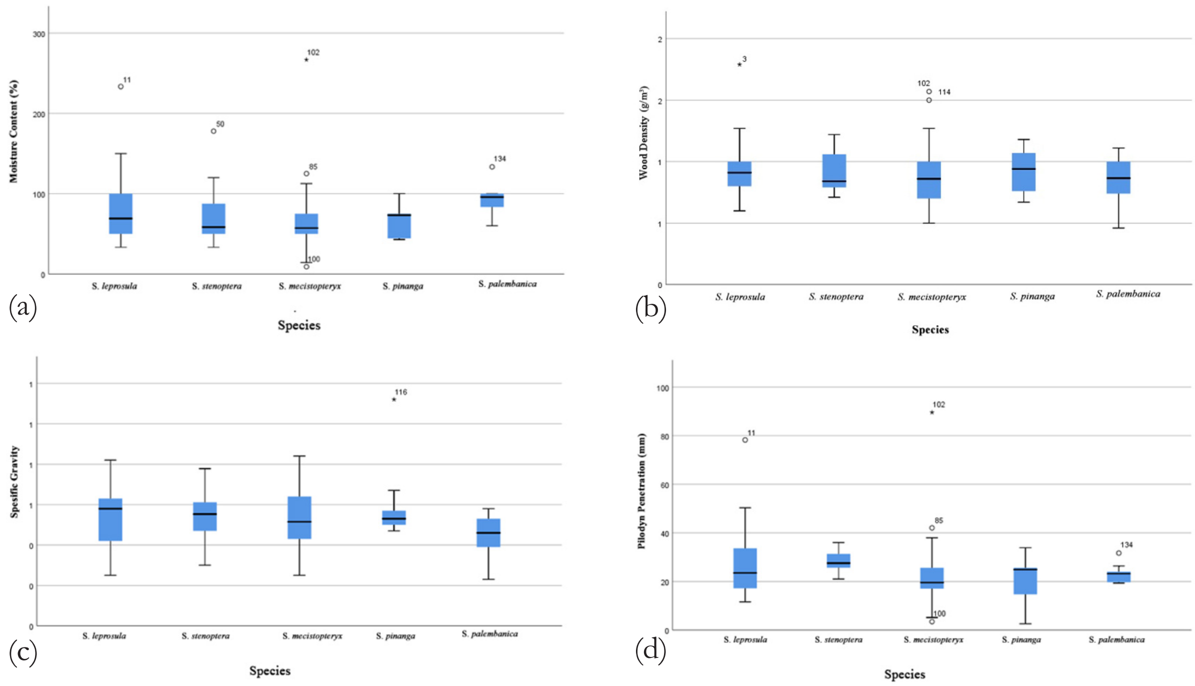


Figure 3. Box-plot diagram of *Shorea* spp. physical wood properties (open circle: outliers).
(a) Moisture content, (b) Wood density, (c) Specific gravity, and
(d) Pilodyn penetration in each *Shorea* species

Table 2. Mean values of 15-year-old *Shorea* spp. physical wood properties

Growth Rate	Species	n	Moisture Content (%)	Wood Density (g/cm^3)	Specific Gravity	Pilodyn Penetration (mm)
Fast	*Shorea leprosula*	26	81.79[a] (±44.532)	0.94[a] (± 0.024)	0.54[ab] (±0.150)	27.82[a] (±14.826)
Moderate	*Shorea stenoptera*	30	69.89[a] (± 29.004)	0.90[a] (± 0.011)	0.54[ab] (± 0.120)	28.32[a] (± 3.444)
Moderate	*Shorea mecistopteryx*	58	65.74[a] (±35.410)	0.88[a] (± 0.022)	0.54[ab] (±0.127)	22.38[a] (±11.825)
Slow	*Shorea pinanga*	10	66.10[a] (± 19.419)	0.92[a] (±0.031)	0.59[b] (± 0.194)	20.96[a] (± 9.056)
Slow	*Shorea palembanica*	10	92.87[b] (± 19.689)	0.87[a] (± 0.122)	0.45[a] (± 0.107)	23.18[a] (± 3.770)

Notes: Mean ± standard deviation (SD) with different letters in the same column indicate significant differences at $P<0.05$ (Duncan's test); n = number of samples

species, has the highest mean value (28.32 mm) but was not significantly different from the other species, while *S. pinanga* as a slow-growing species has the lowest mean value (20.96 mm) and was not significantly different from the other species (Figure 3d, Table 2).

Physical wood properties of 15 years old *Shorea leprosula*, *S. stenoptera*, *S. mecisopteryx*, *S. pinanga*, and *S. palembanica* planted in GWUF indicated by moisture content, wood density, and specific gravity, and pilodyn penetration revealed that the pattern of moisture content in the present study was the same as the evaluation results when the stands were 9 years old, where *S. palembanica* had high moisture content (82.57 %) compared to other species (Karlinasari et al., 2018). This study was also in accordance with other studies, which reported that wood properties such as wood density and moisture content depend on the plant growth rate. In general, slow-growing trees have higher wood density compared to fast-growing trees (Barajas-Morales, 1987; Evans, 1992; Suzuki, 1999; Muller-Landau, 2004). The decrease in wood density due to the increase in growth rate that occurs in subtropical wood is caused by the acceleration of earlywood formation compared to latewood (Jaakkola et al., 2006), thereby increasing the proportion of earlywood to latewood (Peltola et al., 2007). In addition, pilodyn penetration results in this study are also in accordance with other studies, which reported that the lower wood density, such as *Shorea leprosula*, the higher pilodyn penetration as the hardness in xylem or wood was related to wood density (Anna et al., 2020; Chen et al., 2015).

C. Correlation Analysis between Growth and Physical Wood Properties Parameters of Five *Shorea* Species in GWUF

In this study, the Pearson correlation analysis was performed to determine the relationship between growth parameters and physical wood properties parameters. The result (Table 3) showed that the height has a positive and significant correlation (confidence level of 0.01%) with stem diameter (correlation coefficient r = 0.551), volume (r = 0.534), and slenderness (r = 0.235). The diameter has a positive and very strong correlation with volume (r = 0.859) and a weak correlation with specific gravity (0.310). The tree volume has a positive and strong correlation with specific gravity (0.235). The slenderness has a positive and weak correlation with moisture content (r = 0.227) and wood density (0.234).

On the other hand, specific gravity negatively and strongly correlates with moisture content (r = -0.424). This pattern was possible because

Table 3. Statistical analysis of Pearson correlation between growth parameters and physical wood properties parameters of five *Shorea* species

Pearson Correlation	Height (m)	Diameter (cm)	Volume (m^3)	Slender-ness	Moisture Content (%)	Wood Density (g/cm^3)	Specific Gravity	Pilodyn Penetration (mm)
Height (m)	1	0.551**	0.534**	0.253**	0.069	-0.498**	0.103	0.070
Diameter (cm)		1	0.859**	-0.523**	-0.153	-0.470**	0.310**	-0.110
Volume (m^3)			1		-0.151	-0.315**	0.235**	-0.164
Slenderness				1	0.227**	0.243**	-0.139	0.173*
Moisture Content (%)					1	0.088	-0.424**	0.878**
Wood Density (g/cm^3)						1	-0.110	-0.009
Specific Gravity							1	-0.337**
Pilodyn Penetration (mm)								1

Notes: ** = correlation is significant at the 0.01 level (2-tailed), and * = correlation is significant at the 0.05 level (2-tailed).

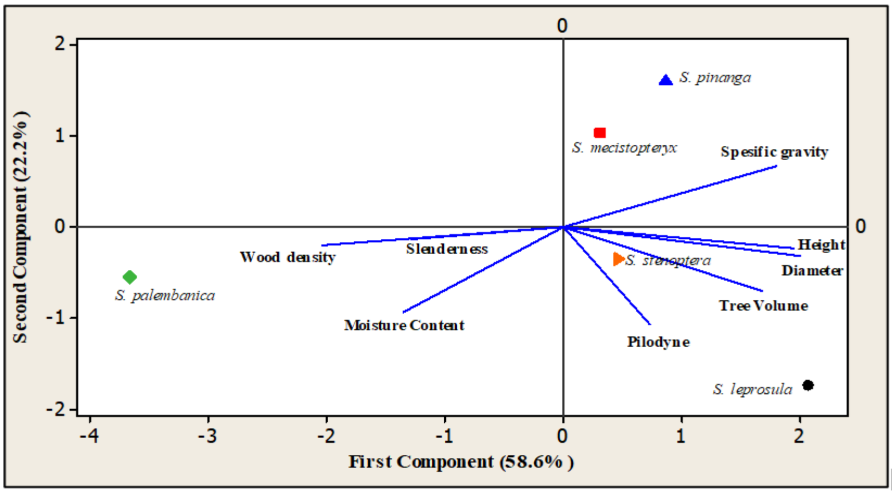


Figure 4. PCA analysis results of five *Shorea* species' growth parameters (height, diameter, volume, and slenderness) and physical wood properties parameters (moisture content, wood density, specific gravity, and pilodyn penetration

when the lumen volume is low, the moisture content becomes restricted, and the specific gravity is high (Simpson, 1993). Wood density has also a negative and moderate correlation with height (r = -0.498), diameter (r = -0.470), and volume (r = -0.315). A negative correlation between growth in height and diameter with wood density also occurs in some tropical wood species (Muller-Landau, 2004). This is because wood with low density tends to be less tolerant of shade (King et al., 2006). In addition, at the early growth stage, cellulose and hemicellulose are more dominant than lignin, which has a dominant role in vertical tree growth (Dhaka et al., 2020). In the next stages, when tree growth has reached the maximum, lignin will play a role in horizontal growth. Therefore, the higher the wood density, the smaller the height and diameter of the tree.

Besides that, pilodyn penetration has also a negative and significant correlation with specific gravity (r = -0.337) but has a positive and strong correlation with moisture content (r = 0.878). This was also reported in the research of Anna et al. (2020), where a decrease in penetration depth indicates an increase in the density and specific gravity. This is influenced by the age of the tree and the type of wood formed, which the youngest tree is still dominated by juvenile wood, and when the tree is old, it will have a xylem or wood mass that is harder and has good growth (Hidayati et al., 2013).

The relationship between growth parameters and physical wood properties parameters in this study was also analyzed using Principal Component Analysis (PCA) (Figure 4). The results showed that slenderness, wood density, and moisture content were the parameters that affected the *S. palembanica* growth performance. Besides that, height, diameter, tree volume, and pylodin penetration were the parameters that affected the *S. leprosula* and *S. stenoptera* growth performance. While specific gravity was the parameter that affected the *S. mecisopteryx* and *S. pinanga* growth performance.

The Pearson correlation analysis between growth performance and physical wood properties of five *Shorea* species in the present study showed that there was a positive and significant correlation among growth parameters such as height, stem diameter, volume, and slenderness, and there was also a positive and significant correlation among physical wood properties such as moisture content, wood density, specific gravity, and pilodyn penetration. Besides that, the physical wood properties such as wood density have also shown significant but negative correlation with growth parameters such as height, diameter, and volume. These patterns were in accordance with another study, such as *Neolamarckia cadamba* (Anna et al., 2020), which reported the correlation between pilodyn penetration and height, diameter, wood density, specific gravity, and moisture content. A strong and positive correlation between height, diameter, and volume on depth penetration of pilodyn was also found in several other wood species such as *Eucalyptus urophylla* in China (Wei & Borralho, 1997), *Acacia mangium* (Hidayati et al., 2019), and some species of hardwoods (Wu et al., 2011; Hidayati et al., 2013). In addition, the Principal Component Analysis in the present study showed that the growth performance of each *Shorea* species planted in GWUF was influenced by different parameters. Therefore, this parameter should be considered when planting these five Shorea species.

IV. CONCLUSION

The study revealed that *Shorea leprosula* showed the best growth performance and physical wood properties in terms of average diameter (19.64 cm), volume (0.27 m^3), slenderness (126.58), and wood density (0.94 g/cm^3); and *S. stenoptera* in terms of average height (23.35 m). While *S. palembanica* showed poor growth performance and physical wood properties in terms of average diameter (6.73 cm), height (11.15 m), volume (0.02 m^3), wood density (0.87 g/cm^3), and specific gravity (0.45); and *S. stenoptera* in terms of slenderness (202.73). In addition, significant differences in the tree height, diameter, volume, wood density, specific gravity, and moisture content were found in *S. palembanica* compared with other species.

This study also revealed the relationship between growth parameters and physical wood properties parameters in each species, which showed that slenderness, wood density, and moisture content could affect the growth performance of *S. palembanica*. Height, diameter, tree volume, and pilodyn penetration could affect the growth performance of *S. leprosula* and *S. stenoptera*. In addition to that, specific gravity could affect *S. mecisopteryx* and *S. pinanga* growth performance. This finding indicated that planting the four species of tengkawang trees (*Shorea stenoptera*, *S. mecisopteryx*, *S. pinanga*, and *S. palembanica*) and meranti tembaga (*Shorea leprosula*) in GWUF is suitable to increase land coverage as well as conserve the species, although the growth performance and physical properties differ between species, especially *S. palembanica*, which grew slowly. Besides that, the relationship between growth parameters and wood properties revealed in this present study must also be considered in the species selection strategy in future planting planning and the utilization of each species.

ACKNOWLEDGEMENT

The authors thank the Director of Gunung Walat University Forest (GWUF) for permission to conduct the research in *Shorea* spp. stands and Mr. Henry Adiprabowo (Administration Manager, Information System and Data Integration of GWUF) for his assistance during sampling in GWUF. High appreciation goes to Ms. Mariza Hidayati (Alumni of the Department of Silviculture, Faculty of Forestry and Environment, IPB University) and Ms. Triyati Handayani (Syah Kuala University) for their contribution in assisting data collection in the field. This study was supported by a Young Lecturers Research Program Grant (Hibah Program Penelitian Dosen Muda) 2021 for Basic Research Scheme in IPB University Number: 68/IT3/PN/2021 with contact number: 5512/IT3.L1/PT.01.03/M/T/2021 granted to the corresponding author and also supported by Rumah Program-National Research and Innovation Agency through Letter of Decree of Head of Research Organization of Life Sciences and Environmental number 10/III.5/HK/2023 which was received by Henti Hendalastuti Rachmat.

REFERENCES

Abd-Aziz, S., Gozan, M., Ibrahim, M. F., Phang, L. Y. (2023). *Chemical substitutes from agricultural and industrial by-products: Bioconversion, bioprocessing, and biorefining*. Weinheim: Wiley-VCH.

Aguirre, O., Hui, G., Gadow, K. V., & Jiménez, J. (2003). An analysis of spatial forest structure using neighborhood-based variables. *Forest Ecology and Management, 183*(1-3), 137–145. doi://10.1016/S0378-1127(03)00102-6.

Anna, N., Supriyanto, Karlinasari, L., Sudrajat, D. J., & Siregar, I. Z. (2020). The growth, pilodyn penetration, and wood properties of 12 *Neolamarckia cadamba* provenances at 42 months old. *Biodiversitas*, *21*(3), 1091–1100. doi://10.13057/biodiv/d210332.

Ashton, P. (1998). *Shorea palembanica*. The IUCN Red List of Threatened Species 1998 e.T33621A9798146. doi://10.2305/IUCN.UK.1998.RLTS.T33621A9798146.en. Downloaded on 01 September 2021.

Barajas-Morales, J. (1987). Wood specific gravity in species from two tropical forests in Mexico. *IAWA Bulletin* n.s., *8*(2), 143–148.

Blicher-Mathiesen, U. (1994). Borneo Illipe, a fat product from different *Shorea* spp. (Dipterocarpaceae). *Economic Botany*, *48*(3), 231–242.

Bunyamin, A., Purnomo, D., Taofik, S, Chuddin, M., & Sawitri, I. (2020). Innovation on food product development for local commodity with design thinking approach (Case study: tengkawang fruit (*Shorea stenoptera* Burck.) commodity in Bengkayang, West Kalimantan). *IOP Conference Series: Earth and Environmental Science*, *443*(012072), 1–9. doi://10.1088/1755-1315/443/1/012072.

Chen, Z. Q., Karlsson, B., Lundqvis, S. O., Gil, M. R. G., Olsson, L., & Wu, H. X. (2015). Estimating solid wood properties using Pilodyn and acoustic velocity on standing trees of Norway spruce. *Annals of Forest Science*, *72*, 499–508. doi://10.1007/s13595-015-0458-9.

Cornelissen, J. H. C., Lavorel, S., Garnier, E., Díaz, S., Buchmann, N., Gurvich, D. E., Reich, P. B., ter Steege, H., Morgan, H. D., van der Heijden, M. G. A., Pausas, J. G., & Poorter, H. (2003). A handbook of protocols for standardised and easy measurement of plant functional traits worldwide. *Australian Journal of Botany*, *51*, 335–380.doi://10.1071/BT02124.

Curtis, R. O. (1967). Height-diameter and height-diameter-age equations for second-growth douglas-fir. *Forest Science*, *13*(4), 365–375. doi://10.1093/forestscience/13.4.365.

Damayanti, A., Siregar, U. J., & Dwiyanti, F. G. (2020). Potency estimation of forest stands biomass in Gunung Walat Educational Forest, Sukabumi, West Java as fuel for electricity generation. *IOP Conference Series: Earth and Environmental Science*, *528*, 012062. doi://10.1088/1755-1315/528/1/012062.

Darmawan, M. A., Ramadhan, B. Z., Harahap, A. F. P. et al. (2020). Reduction of the acidity and peroxide numbers of tengkawang butter (*Shorea stenoptera*) using thermal and acid activated bentonites. *Heliyon*, *6*(12), e055742. doi://10.1016/j.heliyon.2020.e05742.

Dhaka, R. K., Gunaga, R. P., Sinha, S. K., Thakur, N. S., & Dobriyal, M. J. (2020). Influence of tree height and diameter on wood basic density, cellulose, and fibre characteristics in Melia dubia Cav. Families. *Journal of the Indian Academy of Wood Science*, 17, 138–144. doi://10.1007/s13196-020-00265-x.

Evans, J. (1992). *Plantation forestry in the tropics* (2nd ed.). New York, NY: Oxford University Press Inc.

Forest Area Consolidation Center Agency Denpasar VIII (Balai Pemantapan Kawasan Hutan Wilayah VIII Denpasar). (2021). *Enumerasi* TSP/PSP-pengolahan data. Denpasar, ID: Balai Pemantapan Kawasan Hutan Wilayah VIII Denpasar, Ministry of Forestry and Environment of Republic Indonesia. pp 5–6.

Fundova, I., Funda, T., & Wu, H. X. (2018). Non-destructive wood density assessment of Scots pine (*Pinus sylvestris* L.) using Resistograph and Pilodyn. *PLoS ONE*, *13*(9), e0204518. doi://10.1371/journal.pone.0204518.

Gregory, D., Jensen, P., Matthiesen, H., & Straetkvern, K. (2007). The correlation between bulk density and shock resistance of waterlogged archaeological wood using the pilodyn. *Studies in Conservation*, *52*(4), 289–298. http://www.jstor.org/stable/20619517.

Harahap, N. N., Siregar, I. Z., & Dwiyanti, F. G. (2018). Root architecture and its relation with the growth characteristics of three planted *Shorea* species (Dipterocarpaceae). IOP Conference Series: Earth and Environmental Science, 203, 012016. doi://10.1088/1755-1315-1315/203/1/012016.

Hardjana, A. K., & Suastati L. (2014). Productivity of stands of meranti tembaga (*Shorea leprosula* Miq.) from the wildings and cuttings. *Jurnal Penelitian Dipterokarpa*, *8*(1), 47–58.

Hartley, J., & Marchant, J. (1995). *Technical Paper No. 41*: Methods of determining the moisture content of wood. Sydney: Research Division of State Forests of New South Wales. pp. 3–4.

Heri, V., Bakara, D. O., Mulyana, A., Moeliono, M. & Yuliani, E. L. (2020). Illipe nut as the 'glue' for integrated watershed management: Experiences from the Labian-Leboyan watershed. *CIFOR Info Brief*, *295*, 1–8. doi:// 10.17528/cifor/007718.

Hidayati, F., Ishiguri, F., Iizuka, K., Makino, K., Takashima, Y., Danarto, D., Winanrni. W. W., Irawati, D., Na'iem, M., Yakota, S., & Yoshizawa, N. (2013). Growth characteristics, stress-wave velocity, and pilodyn penetration of 15 clones of 12 years old *Tectona grandis* trees planted at two different sites in Indonesia. *Journal of Wood Science*, *59*(3), 249–254. doi://10.1007/s10086-012-1320-4.

Hidayati F, Lukamandaru G, Indrioko S, Sunarti S, Nirsatmanto A. 2019. Variation in tree growth characteristics, pilodyn penetration, and stress-wave velocity in 65 families of *Acacia mangium* trees planted in Indonesia. *Journal Korean Wood Science Technology*, *47*(5), 633–643. doi://10.5658/WOOD.2019.47.5.633.

IBM Corp. (2020). IBM SPSS statistics for Windows, version 27.0. Armonk, NY: IBM Corp.

Indrioko, S., Widiyatno, & Wicaksono, B. A. (2020). The adaptability of six introduced *Shorea* spp. to the community forest in Sleman, Yogyakarta. *Advances in Biological Sciences Research*, *14*, 200–204.

Istomo, Wibowo, C., & Hidayati, N. (1999). Growth evaluation of meranti (*Shorea* spp.) plantation at Haurbentes, BKPH Jasinga KPH Bogor, Perum Perhutani Unit III Jawa Barat. *Jurnal Manajemen Hutan Tropika*, 2, 13–22.

Jaakkola, T., Mäkinen, H., & Saranpää, P. (2006). Wood density of Norway spruce: responses to timing and intensity of first commercial thinning and fertilization. *Forest Ecology and Management*, *237*, 513–521. doi://10.1016/j.foreco.2006.09.083.

Kalanatarifard, A., & Yang, G. S. (2012). Identification of the municipal solid waste characteristics and potential of plastic recovery at Bakri Landfill, Muar, Malaysia. *Journal of Sustainable Development*, *5*(7), 11–17. doi://10.5539/jsd.v5n7p11.

Karlinasari, L., Andini, S., Worabai, D., Pamungkas, P., Budi, S. W., & Siregar, I. Z. (2018). Tree growth performance and estimation of wood quality in plantation trials for *Maesopsis eminii* and *Shorea* spp. *Journal of Forestry Research*, *29*, 1157–1166. doi:..10.1007/s11676-017-0510-8.

Ketaren, S. (2008). *Pengantar teknologi minyak dan lemak pangan*. (in Indonesian) Jakarta: Universitas Indonesia Press.

Kettle, C. J. (2010). Ecological considerations for using dipterocarps for restoration of lowland rainforest in Southeast Asia. *Biodiversity and Conservation*, *19*, 1137–1151. doi://10.1007/s10531-009-9772-6.

King, D. A., Davies, K. J., Tan, S., MD Noor, & N. S. (2006). The role of wood density and stem support costs in the growth and mortality of tropical trees. *Journal Ecology*, *94*, 670-680. doi://10.1111/j.1365-2745.2006.01112.x.

Konopka, J., Petras, R., & Toma, R. (1987). Slenderness coefficient of the major tree species and its importance for static stability of stands. *Lesnictvi (Prague)*, *33*, 887–904.

Krisnawati, H., & Wahjono, D. (2010). Effect of post-logging silvicultural treatment on growth rates of residual stand in a tropical forest. *Journal of Forestry Research*, *7*(2), 112–124. doi://10.20886/ijfr.2010.7.2.112-124.

Larsen, D. R., & Hann, D. W. (1987). *Research Paper 49*: Height–diameter equations for seventeen tree species in Southwest Oregon. Oregon: Forest Research Lab. Oregon State University.

Leksono, B., & Hakim, L. (2018). Variation in illipe nut's fat yield of tengkawang-producing *Shorea* from several provenance and land races. *Journal of Forest Science*, *12*, 212–222.

Lipp, M., & Anklam, E. (1998). Review of Cacao butter and alternative fats for use in Chocolate-part A. Compositional data. *Food Chemistry*, *62*(1), 73–97. doi://10.1016/S0308-8146(97)00160-X.

Minitab, LLC. (2021). Minitab. Retrieved from https://www.minitab.com.

Muller-Landau, H. C. (2004). Interspecific and inter-site variation in wood specific gravity of tropical trees. *Biotropica*, *36*(1), 20–32. doi://10.1111/j.1744-7429.2004.tb00292.x.

Newman, M. F., Burgess, P. F., & Whitmore, T. C. (1999). *Pedoman identifikasi pohon-pohon Dipterocarpaceae*. (in Indonesian). Bogor: Prosea Indonesia.

Nugroho, N. P. (2014). Relationship between total tree height and diameter at breast height for tropical peat swamp forest tree species in Rokan Hilir District, Riau Province. *Indonesian Journal of Forestry Research*, *1*(2), 89–107. doi://10.20886/ijfr.2014.1.2.89-107.

Oliveira, A. M. (1987). The H/D ratio in maritime pine (*Pinus pinaster*) stands. In Proceedings of the IUFRO Conference Vol. 2 Forest Growth Modelling and Prediction. Ed Ek, A.R., Shifley, S. R., Burk, T. E. Vienna: International Union of Forest Research Organizations. pp. 881–888.

Pamoengkas, P., Rachmat, H. H., & Khalifa, N. (2020). The growth of *Shorea leprosula* at various planting distances and slopes in Gunung Dahu Research Forest, Bogor, Indonesia. *Biodiversitas*, *21*(9), 4396–4404. doi://10.13057/biodiv/d210959.

Paulo, J., Tomé, J., & Tomé, M. (2011). Nonlinear fixed and random generalized height–diameter models for Portuguese cork oak stands. *Annals of Forest Science*, *68*(2), 295–309. doi://10.1007/s13595-011-0041-y.

Peltola, H., Kilpela 'inen, H., Sauvala, K., Ra "isa "nen, T., & Ikonen, V. P. (2007). Effects of early thinning regime and tree status on the radial growth and wood density of Scots pine. *Silva Fennica*, *41*(3), 489–505.

Purwaningsih. (2004). Ecological distribution of Dipterocarpaceae species in Indonesia. *Biodiversitas*, *5*(2), 89–95. doi://10.13057/biodiv/d050210.

Ramadhani, N. K., Darmawan, M. A., Harahap, A. F. P., Ramadhan, M. Y. A., Silalahi, U. C., & Gozan, M. (2021). Simulation of illipe butter purification originated from West Kalimantan by SuperPro Designer. *IOP Conference Series: Journal of Physics*, *1726*(012013), 1–5. doi://10.1088/1742-6596/1726/1/012013.

Rottmann, M. 1986. Wind undstormschaden im Wald. University of Munich, J. D. Sauerlander Verlag, Frankfurtam Main.

Saner, P., Loh, Y. Y., Ong, R. C., & Hector, A. (2012). Carbon stocks and fluxes in tropical lowland dipterocarp rainforests in Sabah, Malaysian Borneo. *PLoS ONE*, *7*(1), e29642. doi://10.1371/journal.pone.0029642.

Setiadi. (2019). Sumber asal benih tengkawang (*Shorea* spp.) untuk konservasi dan komoditas masyarakat sekitar hutan. In proceedings of Seminar Nasional Pendidikan Biologi dan Saintek (SNPBS) IV. pp 89–98.

Sharma, M., & Parton, J. (2007). Height–diameter equations for boreal tree species in Ontario using a mixed-effects modeling approach. *Forest Ecology and Management*, *249*(3), 87–198. doi://10.1016/j.foreco.2007.05.006.

Simpson, W. T. (1993). *Specific gravity, moisture content, and density relationship for wood*. Medison, US: Department of Agriculture, Forest Service, Forest Products Laboratory. p.13.

Stuckle, I. C., Siregar, C. A., Supriyanto, & Kartana, J. (2001). *Forest health monitoring to monitor the sustainability of Indonesian tropical rain forest* (Volume 1). Bogor: ITTO and Seameo Biotrop. p. 124

Sumida, A., Miyaura, T., & Torii, H. (2013). Relationships of tree height and diameter at breast height revisited: analyses of stem growth using 20-year data of an even-aged *Chamaecyparis obtusa* stand. *Tree Physiology*, *33*(1), 106–118. doi://10.1093/treephys/tps127.

Supartini, & Fajri, M. (2014). Fruit production of tengkawang at several topography and tree dimension. *Jurnal Penelitian Dipterokarpa*, *8*(2), 109–116.

Suzuki, E. (1999). Diversity in specific gravity and water content of wood among Bornean tropical rainforest trees. *Ecological Research*, *14*, 211–224. doi://10.1046/j.1440-1703.1999.143301.x.

Temesgen, H., & Gadow, K. V. (2004). Generalized height–diameter models—an application for major tree species in complex stands of interior British Columbia. *European Journal of Forest Research*, *123*(1), 45–51. doi://10.1007/s10342-004-0020-z.

Temesgen, H., Monleon, V. J., & Hann, D. W. (2008). Analysis and comparison of nonlinear tree height prediction strategies for Douglas-fir forests. *Canadian Journal of Forest Research*, *38*(3), 553–565. doi://10.1139/X07-104.

VanderSchaaf, C. L. (2008). Stand level height-diameter mixed effects models: parameters fitted using loblolly pine but calibrated for sweetgum. In Proceedings of 16th Central Hardwoods Forest Conference (Vol. Gen. Tech. Rep. NRS-P-24) ed Jacobs, D.F., Michler, C.H., Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station.

Wang, C. H., & Hann, D. W. (1988). *Research Paper 51: Height–diameter equations for sixteen tree species in the central Willamette Valley of Oregon*. Oregon: Forest Research Lab., Oregon State University.

Wang, Y., Titus, S. J., & LeMay, V. M. (1998). Relationships between tree slenderness coefficients and tree or stand characteristics for major species in boreal mixedwood forests. *Canadian Journal of Forest Research*, *28*(8), 1171–1183. doi://10.1139/cjfr-28-8-1171.

Wahyudi, A., Harianto, S. P., & Darmawan, A. (2014). Tree diversity in the Tahura Wan Abdul Rachman Educational Forest. *Jurnal Sylva Lestari*, *2*(3), 1–10.

Wahyudi, Setiarno, Patricia, E., Hendra, T., Aguswan, Y., & Yosep. (2016). Performance of the high value native species of *Shorea parvifolia* planted under invasive species of *Acacia mangium*. *International Journal of Applied Environmental Sciences*, *11*(2), 457–466.

Wei, X., & Borralho, N. M. G. (1997). Genetic control of wood basic density and bark thickness and their relationships with growth traits of *Eucalyptus urophylla* in South East China. *Silvae Genetica*, *46*(4), 245-250.

Widiyatno, Soekotjo, Naiem, M., Purnomo, S., & Setiyanto, P. E. (2014). Early performance of 23 dipterocarp species planted in logged-over rainforest. *Journal of Tropical Forest Science*, *26*(2), 259–266.

Winarni, I., Sumadiwangsa, S., & Setyawan, D. (2004). The effect of growth site, species, and stem diameter of tengkawang trees on seed productivity. *Journal of Forest Product Research*, *22*(1), 23–33.

Winarni, B., Lahjie, A. M., Simarangkir, B. D. A. S., Yusuf, S., & Ruslim, Y. (2017). Tengkawang cultivation model in community forest using agroforestry systems in West Kalimantan, Indonesia. *Biodiversitas*, *18*(2), 765–772. doi://10.13057/biodiv/d180246.

Wistara, N. J., Sukowati, M., & Pamoengkas, P. (2016). The properties of red meranti wood (*Shorea leprosula* Miq.) from stand with thinning and shade-free gap treatments. *Journal of the Indian Academy of Wood Science*, *13*(1), 21–32. doi://10.1007/s13196-016-0161-y.

Wu, S. J., Xu, J. M., Li, G. Y., Risto, V., Lu, Z. H., Li, B. Q., & Wang, W. (2011). Estimation on basic density and modulus of elasticity of eucalypt clones in Southern China using non-destructive methods. *Journal of Tropical Forest Science*, *23*(1), 51-56.

Yahya, A. F., Damayanti, E. K., & Zuhud, E. A. M. (2015). Traditional forest-related knowledge for ecosystem services in Sundanese ethnic of Sukabumi District, West Java Province, Indonesia. XIV World Forestry Congress Durban, South Africa 11-17 September 2015.

Zabel, R. A., & Morrell, J. J. (2020). Changes in the strength and physical properties of wood caused by decay fungi. In Zabel, R. A., & Morrell, J. J., *Wood microbiology: Decay and Its Prevention Chapter 10* (pp 271–291). USA: Academic Press. doi://10.1016/B978-0-12-819465-2.00010-3.

Zhang, L., Bi, H., Cheng, P., & Davis, C. J. (2004). Modeling spatial variation in tree diameter– height relationships. *Forest Ecology and Management*, *189*(1-3), 317–329. doi://10.1016/j.foreco.2003.09.004.