

Agung Nugrawan Kutana¹, Yanico Hadi Prayogo², Imam Wahyudi²,
Kidung Tirtayas Putra Pangestu^{3*}, Nisrina Putri Hanifah¹, Irma Wahyuningtyas¹

Physical Properties of Three Commercial Hardwoods in Indonesia

Fizička svojstva triju komercijalnih vrsta drva listača u Indoneziji

ORIGINAL SCIENTIFIC PAPER

Izvorni znanstveni rad

Received – prispjelo: 8. 3. 2026.

Accepted – prihvaćeno: 8. 6. 2026.

UDK: 630*81; 674.038

<https://doi.org/10.5552/drvind.2026.0341>

© 2026 by the author(s).

Licensee University of Zagreb Faculty of Forestry and Wood Technology.

This article is an open access article distributed

under the terms and conditions of the

Creative Commons Attribution (CC BY) license.

ABSTRACT • Indonesia has abundant biodiversity and valuable timber species are used as essential raw materials in various industries. The objective of this study was to provide physical properties and dimensional stability information of three kinds of wood species that are categorized as fast-growing wood, namely *Gmelina* (*Gmelina arborea* Roxb.), *Nyatoh* (*Palaquium* spp.), and *Waru* (*Hibiscus tiliaceus*), which can support the appropriate and sustainable use of these woods. *Gmelina* exhibited the lowest tangential-to-radial shrinkage ratio (T/R) (1.01), indicating better dimensional stability compared to *Nyatoh* and *Waru*. *Nyatoh* exhibited intermediate physical properties with a T/R ratio of 1.83. *Waru* exhibited the lowest dimensional stability with a T/R ratio of 2.13. Overall, the results of this study highlight the differences in physical properties and dimensional stability among the three wood species under identical testing conditions and provide reference data to support material selection and further research on these commercially important tropical woods.

KEYWORDS: commercial wood; *gmelina*; *nyatoh*; *waru*; wood physical properties

SAŽETAK • Indonezija obiluje bioraznolikošću, a njezine vrijedne drvene vrste služe kao ključne sirovine u različitim industrijama. Cilj ovoga istraživanja bio je utvrditi fizička svojstva i dimenzijsku stabilnost triju brzorastućih vrsta drva: *gmelina* (*Gmelina arborea* Roxb.), *nyatoha* (*Palaquium* spp.) i *warua* (*Hibiscus tiliaceus*), kako bi se pridonijelo njihovoj pravilnoj i održivoj primjeni. Za drvo *gmelina* zabilježen je najmanji omjer tangencnoga i radijalnog utezanja (T/R), koji je iznosio 1,01, što upućuje na bolju dimenzijsku stabilnost u usporedbi s drvom *nyatoha* i *warua*. Drvo *nyatoha* pokazalo je prosječna fizička svojstva s T/R omjerom od 1,83. Najmanja dimenzijska stabilnost izmjerena je za drvo *warua*, s T/R omjerom od 2,13. Zaključno, rezultati ovoga istraživanja istaknuli su razlike u fizičkim svojstvima i dimenzijskoj stabilnosti triju ispitivanih vrsta drva u jednakim uvjetima ispitivanja te su dali referentne podatke kao podlogu za odabir materijala i daljnja istraživanja tih komercijalno važnih tropskih vrsta drva.

KLJUČNE RIJEČI: komercijalne vrste drva; *gmelina*; *nyatoh*; *waru*; fizička svojstva drva

* Corresponding author

¹ Authors are researchers at State Agricultural Polytechnic of Samarinda, Department of Environment and Forestry, Study Program of Forest Products Processing, Samarinda, Indonesia. <https://orcid.org/0000-0002-5039-5800>, <https://orcid.org/0009-0007-3477-9517>, <https://orcid.org/0009-0006-3563-9084>

² Authors are researchers at IPB University, Faculty of Forestry and Environment, Department of Forest Products Technology. <https://orcid.org/0000-0002-5418-3637>, <https://orcid.org/0000-0001-9062-9264>

³ Author is researcher at Hasanuddin University, Faculty of Forestry, Department of Forestry, Makassar, Indonesia. <https://orcid.org/0000-0001-7341-8967>

1 INTRODUCTION

1. UVOD

Indonesia is known as one of the countries with abundant forest resources, including a high diversity of economically valuable timber species (Djafar *et al.*, 2023). Wood is an essential raw material in various industries such as construction, furniture, and handicrafts (Barbu and Tudor, 2022). Among the different types of traded wood, gmelina wood (*Gmelina arborea* Roxb.), nyatoh wood (*Palaquium spp.*), and waru wood (*Hibiscus tiliaceus*) are three well-known and widely used species in the local timber industry (Basri *et al.*, 2019; Yunianti, *et al.*, 2019; Meiganati *et al.*, 2023). These three types of wood are interesting for further study. In addition to being fast-growing and adaptable to tropical environments, especially in Southeast Asia, they are also widely available in local markets and are widely used in community-based industries such as furniture, handicrafts, and light construction (Husna *et al.*, 2021; Phang *et al.*, 2023; Kabir *et al.*, 2025). Although their use has become widespread, these types of wood are still classified as lesser-known species in the global timber market. In practice, their use is based more on experience than on scientific foundations, particularly regarding their physical properties, especially in small and medium-scale timber industries. This situation creates a mismatch between material performance and end-use requirements, which has the potential to lead to inefficient processing, reduced product durability, and limited value-added utilization.

Gmelina is a fast-growing wood that is often cultivated in agroforestry and community forests (Suri *et al.*, 2021). It is widely used in the light furniture, particle boards, and handicraft industries (Setiadi, 2018; Vallesteros, 2020). Nyatoh, which belongs to several species in the Sapotaceae family, has a smooth texture and attractive color, making it widely used for construction and interior materials (Muchtar *et al.*, 2024; Putra *et al.*, 2024). Waru, although classified as lightweight wood, is frequently utilized for panels, packaging boxes, lightweight construction, boats, and lightweight structural components in coastal areas because of its ability to grow in coastal environments (Irwan and Aras, 2023).

Although physical property datasets exist for many tropical wood species, most studies have focused only on well-established commercial species, while comparative and standardized data for widely used community-level wood species, such as gmelina, nyatoh, and waru, remain fragmented, inconsistent, or derived from varying test conditions. This lack of comparable data hinders direct evaluation of their relative performance and limits broader industry acceptance and global recognition of these wood species. Further-

more, previous studies generally report physical and mechanical properties individually for a particular species, with limited efforts to provide side-by-side comparisons under uniform sampling, preparation, and testing procedures. Such comparative analyses are important because differences in site conditions, sampling methods, and testing procedures can significantly affect the measured physical properties, leading to uncertainty when the data is used for material selection or industrial processing (Cai *et al.*, 2019). Therefore, there is a clear research gap regarding the provision of comparative and standardized evaluations of the physical properties and dimensional stability of these three Indonesian wood species, which have high commercial value but have not been extensively studied.

This has led to the limited and less innovative utilization of these woods, considering that recent investigations on wood modification have been of interest to many researchers worldwide (Zelinka *et al.*, 2022). Physical properties, such as moisture content, density, and specific gravity, are important indicators for determining wood strength, durability, and suitability for specific uses (Shukla, 2025). For instance, higher density is often associated with greater mechanical strength, while high moisture content reduces dimensional stability and weakens bonding performance in wood processing. Dimensional stability, which is the ability of wood to maintain its shape and size in response to changes in environmental humidity, is a critical factor for ensuring the longevity and quality of the final product (Sargent, 2022). Based on these considerations, this study proposes the hypothesis that gmelina, nyatoh, and waru exhibit significantly different physical properties and dimensional stability when evaluated under the same test conditions, and that these differences can be used to identify their suitability for specific industrial applications. Accordingly, the objective of this study is not only to report physical properties but also to provide a standardized comparative dataset and identify the relative performance of these three species as a scientific basis for material selection, value-added processing, and sustainable utilization.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

2.1 Materials

2.1. Materijali

The materials used in this study were Gmelina (*Gmelina arborea* Roxb.), Nyatoh (*Palaquium spp.*), and Waru (*Hibiscus tiliaceus*). These woods were harvested from a community forest in Bogor, West Java. A total of three mature and healthy trees were sampled for each species ($n=3$ trees per species). Trees were selected to represent similar age class (≈ 6 years), diam-

eter class (31-37 cm), and site conditions to reduce environmental variability. Logs were taken from the bottom section of the stem (0-2 m height) to ensure comparable wood maturity among trees.

2.2 Sample preparation

2.2. Priprema uzoraka

Test samples were prepared according to British Standard BS 373:1957. From each tree, boards were obtained from the radial direction and carefully separated into sapwood and heartwood zones based on color and anatomical appearance. Samples were taken from middle radial position (between pith and bark) to minimize radial variability. Only clear wood specimens free from knots, checks, and reaction wood were selected.

Test samples measuring 2 cm × 2 cm × 2 cm were prepared to measure moisture content, density, and specific gravity. Meanwhile, test samples were made into 5 cm × 5 cm × 1 cm pieces to measure the dimensional stability. For each species, a total of 9 specimens were tested for each property (3 trees × 3 specimens per tree), and each measurement was conducted in triplicate.

2.3 Physical properties test

2.3. Ispitivanje fizičkih svojstava

Moisture content, density, and specific gravity were evaluated according to BS-373:1957. The selection of BS 373:1957 was justified because this standard is still widely used in tropical wood research, enabling direct comparison with existing datasets and previous studies on Indonesian wood species. The initial volume and weight of the test sample were measured, then dried at 103 ± 2 °C using an oven (Memmert UN55, Germany) until the weight was constant, and finally, the volume and weight were measured. Moisture content, density, and specific gravity were calculated as follows (Nugroho *et al.*, 2024; Savero *et al.*, 2020):

$$MC_g (\%) = \frac{W_g - W_{od}}{W_{od}} \cdot 100 \quad (1)$$

$$MC_{ad} (\%) = \frac{W_{ad} - W_{od}}{W_{od}} \cdot 100 \quad (2)$$

$$D (\text{g/cm}^3) = \frac{W_g}{V_g} \quad (3)$$

$$SG = \frac{\frac{W_{od}}{V_g}}{\rho_{\text{water}}} \quad (4)$$

Where MC_g is the green moisture content (%), W_g is green weight (g), W_{od} is oven dried weight (g), MC_{ad} is air-dried moisture content (%), W_{ad} is air-dried weight (g), D is density (g/cm³), V_g is green volume (cm³), SG is specific gravity, and ρ_{water} is water density at 4 °C (g/cm³).

2.4 Dimensional stability measurement

2.4. Mjerenje dimenzijske stabilnosti

Dimensional stability was evaluated by measuring the volume of the longitudinal, tangential, and radial sections of the wood sample after oven-drying at 103 ± 2 °C until it reached a constant weight. Subsequently, the volume was measured again in a similar plane. Dimensions were measured before and after drying to determine the dimensional changes in each anatomical direction. The dimensions of each specimen (in the longitudinal, tangential, and radial directions) were measured using a digital caliper with an accuracy of ± 0.01 mm. The mass of the samples was measured using an analytical balance with a precision of ± 0.001 g. The ratio of tangential shrinkage to radial shrinkage (T/R ratio) was used as an indicator of the dimensional stability. The dimensional stability of wood can be indicated by a T/R ratio close to one (Savero *et al.*, 2020). All measurements were taken three times, and the average values were used for further analysis.

2.5 Statistical analysis

2.5. Statistička analiza

All data were analyzed using statistical methods to evaluate variability and differences among species. For each property, results are presented as mean ± standard deviation (SD). Data normality was evaluated using the Shapiro–Wilk test, and homogeneity of variance was checked using Levene's test. Differences among wood species were analyzed using one-way analysis of variance (ANOVA) at a 95 % confidence level ($\alpha = 0.05$). All statistical analyses were performed using statistical software.

3 RESULTS AND DISCUSSION

3. REZULTATI I RASPRAVA

3.1 Moisture content

3.1. Sadržaj vode

The green moisture contents of *G. arborea*, *Palaquium spp.*, and *H. tiliaceus* were 176.41 ± 13.84 %, 103.45 ± 0.84 %, and 82.49 ± 2.53 %, respectively (Figure 1). The ANOVA results indicate that wood species have a highly significant effect on fresh moisture content ($F = 131.14$; $p < 0.001$). The mean values show that Gmelina has the highest fresh moisture content, followed by Nyatoh and Waru. This highly significant difference indicates that water-holding capacity in the fresh state is strongly influenced by the characteristics of the wood species. Green moisture content is a critical factor affecting the suitability and performance of wood during mechanical processing operations (Seta *et al.*, 2023). This is because wood with a high level of green moisture content tends to be more prone to cracking, surface checking, and dimensional instability during cutting and drying, whereas lower levels may

reduce workability but improve drying efficiency (Mezui *et al.*, 2022; Elustondo *et al.*, 2022). The results of the green moisture content study on all types of wood are aligned with those reported by Shmulsky and Jones (2011), which range from 33 – 249 %. A green moisture content value greater than 100 % indicates that wood contains a significant amount of water in living trees (Bergman, 2021). The difference in the moisture content of wood under green conditions is influenced by the trees age and growing location, and changes according to the temperature and humidity of the surrounding air (Bowyer *et al.*, 2007; Uslinawaty *et al.*, 2024). For example, younger trees generally contain higher amounts of water due to the dominance of juvenile wood, while older trees tend to show lower values as mature wood develops (Alfikri *et al.*, 2020). In this study, *G. arborea* showed the highest green moisture content, reflecting its fast-growing nature and higher proportion of juvenile tissues. *Palaquium spp.* exhibited intermediate values, consistent with its denser structure and slower growth rate, whereas *H. tiliaceus* had the lowest green moisture content, making it relatively more dimensionally stable compared to the other two species. These differences highlight the importance of considering both species characteristics and growth conditions when evaluating wood utilization.

The green moisture content of *G. arborea* wood was slightly higher than that reported by Yau *et al.* (2024), who reported that the green moisture content of *G. arborea* wood ranged from 121.6 – 171.82 %, which increased from the apical to the middle section of the wood and began to decrease at the base. This was caused by the presence of juvenile wood in the middle section of the wood, which formed a thinner cell wall

with larger lumens and cavities that accommodate larger amounts of moisture. Moya and Fo (2008) also stated that the lumen diameter and cell wall thickness of *G. arborea* wood were 12.25 – 35.53 μm and 2.37 – 6.01 μm . Augustina *et al.* (2020a) found that the lumen diameter and cell wall thickness of *Palaquium spp.* were 25.01 μm and 3.61 μm . On the other hand, *H. tiliaceus* has a lumen diameter of 19.96 μm and cell wall thickness of 4.09 μm , according to Andianto *et al.* (2024). This is in accordance with the assumption that wood with a smaller lumen diameter and thicker cell walls has a remarkable effect on the lower moisture content of wood (Klement *et al.*, 2020). In terms of wood processing, a higher moisture content can facilitate wood cutting. However, it can also increase the susceptibility of the cutting tool to corrosion, thereby increasing maintenance costs (Bendikiene and Keturakis 2017). A higher moisture content also accelerates wood decay by fungi and termites, leading to a loss of wood performance, especially in its mechanical properties (Marais *et al.*, 2020; Kherais, *et al.*, 2024). In addition, this parameter also plays an important role in wood bonding with adhesives, as a higher water quantity reduces the adhesion strength (Favis *et al.*, 2024). As green wood dries, most of the water evaporates and the wood tends to reach equilibrium with the relative humidity of the surrounding air (Bergman 2021). Under these conditions, the air-dried moisture content of wood can facilitate wood processing by reducing the tendency for dimensional changes and the risk of wood defects (Coto 2005).

The air-dried moisture content of *G. arborea*, *Palaquium spp.*, and *H. tiliaceus* was 16.34 ± 3.30 %, 17.65 ± 0.76 %, and 12.18 ± 0.49 %, respectively (Figure 1). The type of wood also had a significant effect on

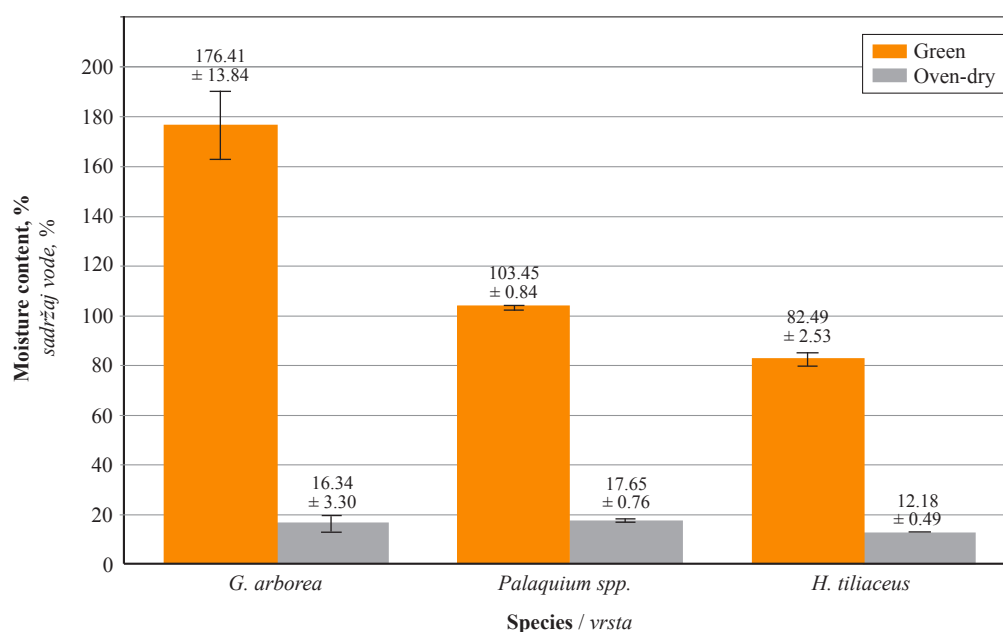


Figure 1 The average moisture content in green and air-dried conditions

Slika 1. Prosječni sadržaj vode u sirovome i prosušenom drvu

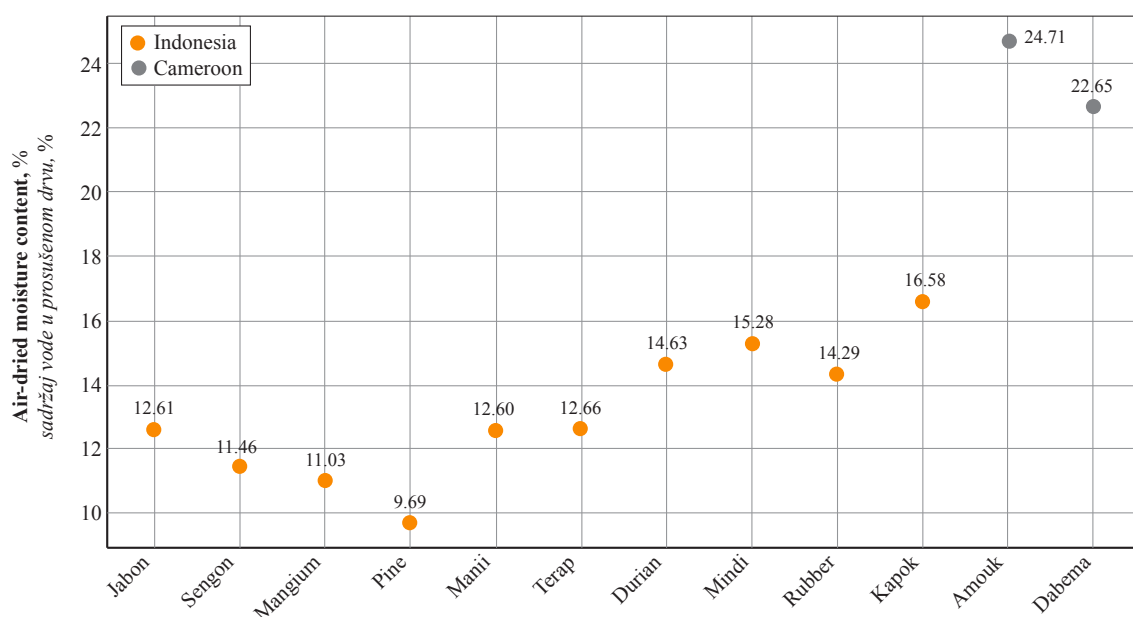


Figure 2 Comparison of air-dried moisture content in tropical wood species from Indonesia and other countries (Hadi *et al.*, 2022; Komariah *et al.*, 2015; Herawati *et al.*, 2021; Nawawi *et al.*, 2023; Kana *et al.*, 2024)

Slika 2. Usporedba sadržaja vode u prosušenom drvu tropskih vrsta iz Indonezije i drugih zemalja (Hadi *et al.*, 2022.; Komariah *et al.*, 2015.; Herawati *et al.*, 2021.; Nawawi *et al.*, 2023.; Kana *et al.*, 2024.)

the dry air moisture content ($F = 9.70$; $p = 0.013$). The mean values indicate that Nyatoh and Gmelina have relatively higher equilibrium moisture contents than Waru. This suggests that the hygroscopic properties of wood vary among species. After reaching the air-dried moisture content, the wood no longer underwent significant water absorption or release into the air. The air-dried moisture content results for all types of wood were directly proportional to those reported by Rahmayanti *et al.* (2016), who stated that the moisture content in Indonesia's climate ranges between 12 – 20 %. The results of this study showed that the air-dried moisture content of *G. arborea*, *Palaquium spp.*, and *H. tiliaceus* falls within the range comparable to most tropical wood species listed in Figure 2. For instance, the air-dried moisture content of Jabon, Sengon, Mangium, Manii, and Terap are comparable to that observed in *H. tiliaceus*. Meanwhile, Kapok and Mindi exhibit values that are relatively comparable to *G. arborea* and *Palaquium spp.*

On the other hand, several tropical wood species from outside Indonesia, such as Amouk and Dabema from Cameroon, show much higher values than the average of tropical wood species in Indonesia. These differences highlight that both species characteristics and growing conditions significantly influence the physical properties of wood, particularly air-dried moisture content. Air dried moisture content above 20 % is more susceptible to attacks by wood-destroying organisms, such as fungi (Simangunsong, 2016). This condition

indicates that Indonesia tropical wood species tend to be more stable under air-dried conditions and fall within a safe range for drying processes as well as industrial applications.

The moisture content under air-dry conditions obtained in this study falls within the range commonly reported for tropical hardwoods. However, direct comparisons with previous studies should be interpreted with caution because moisture content is strongly influenced by environmental conditions, sample conditioning protocols, and the location where the trees grew. Some previous reports on Gmelina, Nyatoh, and Waru were conducted under different climatic conditions or equilibrium moisture contents, which may explain the variations between studies (Marini *et al.*, 2021; You *et al.*, 2021). This study reduces such variability by conditioning all samples under identical laboratory conditions, thereby producing a more reliable set of comparative data among the three species.

3.2 Density

3.2. Gustoća drva

Wood density is the ratio of wood mass to volume under the same conditions (Wulandari *et al.*, 2024). The density values of *G. arborea*, *Palaquium spp.*, and *H. tiliaceus* wood are 0.9 ± 0.04 g/cm³, 0.76 ± 0.02 g/cm³, and 0.67 ± 0.03 g/cm³, respectively (Figure 3). The ANOVA results showed a significant difference in density among the wood species ($F = 11.26$; $p = 0.009$). Gmelina had the highest density, followed by Nyatoh and Waru. These differences confirm that spe-

cies variation has a strong influence on the physical structure of wood. The results of this study are much larger than those of previous studies (Iwuoha *et al.*, 2021; Arifudin and Wahyudi, 2020; Reyes *et al.*, 1992), which reported *G. arborea* densities of 0.69, 0.55, and 0.57 g/cm³. These results are known to be higher compared to short and long rotation teak wood (0.66 and 0.47 g/cm³, respectively), as the most well-known commercial wood in Indonesia (Rizanti *et al.*, 2018). In addition to wood type, wood density is influenced by its location on the tree, growing conditions, and tree age (Miranda *et al.*, 2011; Savero *et al.*, 2020; Wulandari and Amin, 2023). Furthermore, wood density is also an important parameter in determining wood quality (Li *et al.*, 2024). Deepa and Shukla (2024) found a strong correlation between wood density and chemical extractives with wood durability and mechanical properties, especially wood hardness (Damayanti *et al.*, 2020). Thus, the relatively high density indicates potential mechanical strength, although mechanical testing was not conducted in this study (Cabral *et al.*, 2022), and therefore structural suitability should be interpreted with caution.

The density of *G. arborea* is relatively high compared to most tropical woods found in Indonesia and other countries (Figure 4). This value is comparable to imported woods such as Bilinga (0.73 – 0.89 g/cm³) and Tali (0.8 – 1.05) from Brazil, indicating the potential of *G. arborea* as a wood with good structural quality. This is in line with several studies reporting that *G. arborea* can be used for furniture and construction (Iwuoha *et al.*, 2021; Olaniran *et al.*, 2024).

In *Palaquium spp.*, the density value is in the moderate range, higher than most tropical woods found in Indonesia such as Jabon, Sengon, Mangium, Teak, Manii, Terap, Durian, Mindi, Rubber, Kapok, Cundlenut, and Samama, but still lower than *G. arborea* and hardwoods from Brazil such as Iroko, Bilinga, and Tali. Meanwhile, Pine is Indonesian tropical wood comparable to the density of *Palaquium spp.*, as well as Dabema from Cameroon (Figure 4). This places *Palaquium spp.* as a wood with moderate to heavy density with quite a potential for light construction applications. This is in line with Arifudin and Wahyudi (2020), who reported that this wood can be used for light construction, furniture, and flooring. In addition, Meiganati (2023) added that *Palaquium spp.* can be used as raw material for pencil sticks and veneer.

Meanwhile, *H. tiliaceus* has the lowest density among the three species studied. This value is still higher than that of Jabon, Sengon, Manii, Terap, Durian, Mindi, Rubber, Kapok, Cundelnut, and Samama, but lower than that of Pine from Indonesia as well as Bilinga and Tali from Brazil. However, its density is comparable to Teak from Indonesia, as well as several types of tropical wood from other countries such as Iroko, Amouk, and Dabema (Figure 4). Thus, *H. tiliaceus* has the potential to be used for non-structural or industrial purposes. This is in line with several studies indicating that *H. tiliaceus* is widely used for making bags, ropes, and woven products (Purnowidodo *et al.*, 2020; Wirawan *et al.*, 2023). The density values obtained are generally consistent with the wide range of densities reported for these species in the previous lit-

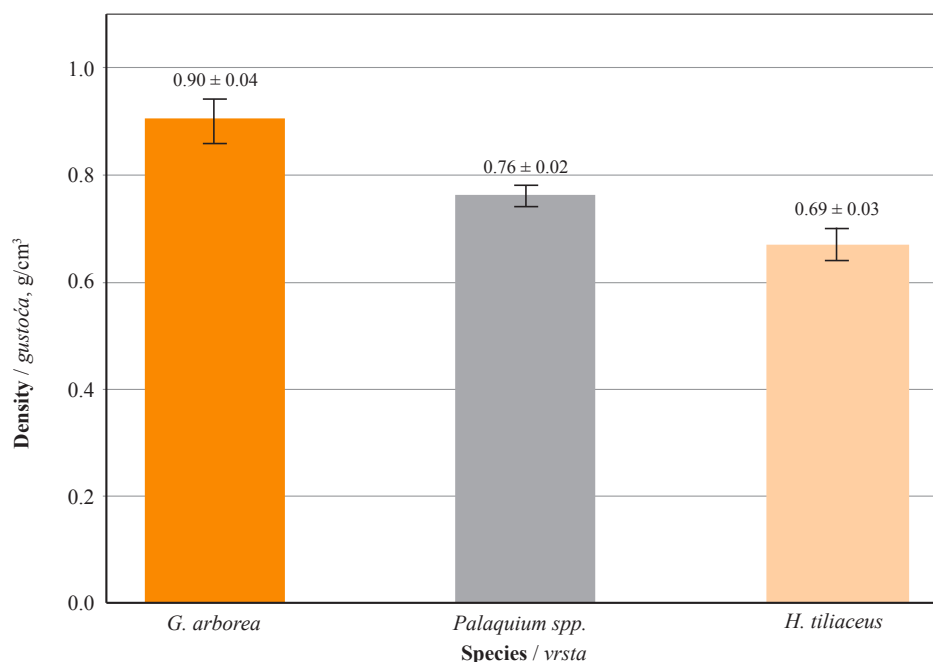


Figure 3 Density
Slika 3. Gustoća drva

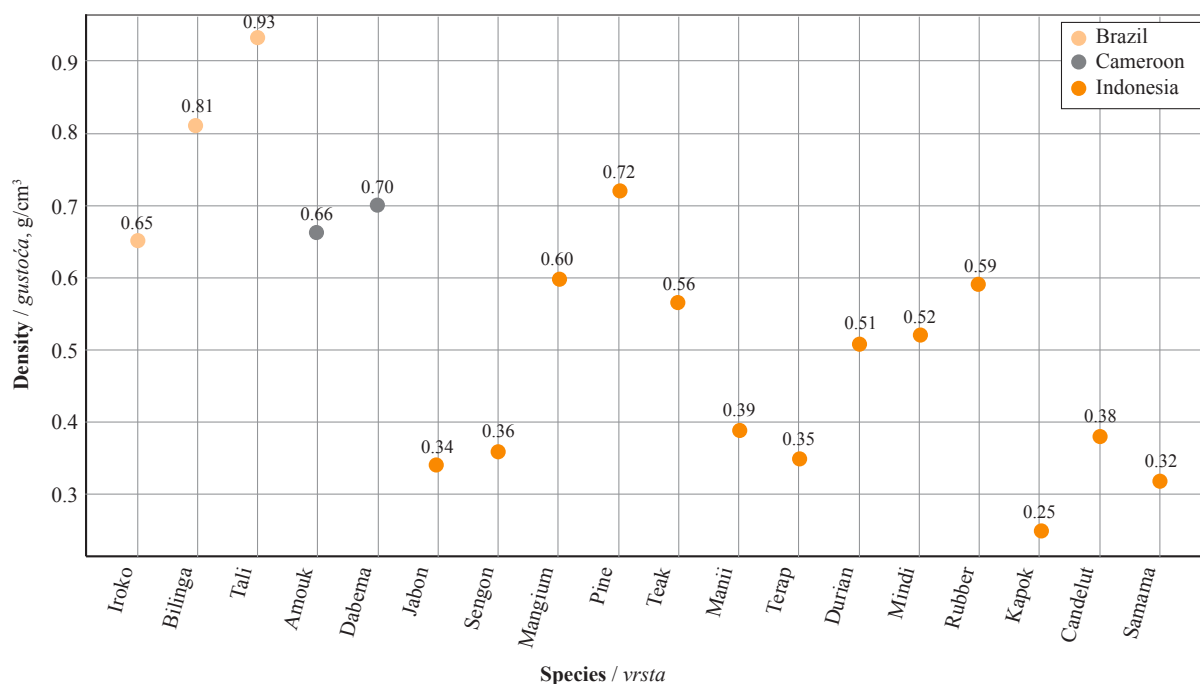


Figure 4 Comparison of density in tropical wood species from Indonesia and other countries (Hadi *et al.*, 2022; Rizanti *et al.*, 2018; Komariah *et al.*, 2015; Herawati *et al.*, 2021; Nawawi *et al.*, 2023; Azis *et al.*, 2020; Augustina *et al.*, 2023; Myondo *et al.*, 2017; Kana *et al.*, 2024)

Slika 4. Usporedba gustoće tropskih vrsta drva iz Indonezije i drugih zemalja (Hadi *et al.*, 2022.; Rizanti *et al.*, 2018.; Komariah *et al.*, 2015.; Herawati *et al.*, 2021.; Nawawi *et al.*, 2023.; Azis *et al.*, 2020.; Augustina *et al.*, 2023.; Myondo *et al.*, 2017.; Kana *et al.*, 2024.)

erature. However, previous studies have often shown wide variations due to differences in tree age, site quality, and sampling location within the trunk. In contrast, this study minimized these sources of variation through standardized sampling and testing procedures. This highlights the importance of standardized comparative measurements, as the density differences observed in this study are more likely to reflect the inherent characteristics of the species rather than methodological differences.

3.3 Specific gravity

3.3. Specifična gustoća drva

The specific gravities of three different commercial wood species were successfully evaluated in this study. Shmulsky and Jones (2011) stated that the specific gravity of wood is the ratio of the oven-dried weight to the volume of wood under green conditions. The specific gravities of *G. arborea*, *Palaquium spp.*, and *H. tiliaceus* wood are 0.33 ± 0.01 , 0.37 ± 0.01 , and 0.39 ± 0.01 , respectively (Figure 5). The type of wood has a highly significant effect on specific gravity ($F = 61.80$; $p < 0.001$). Waru and Nyatoh exhibited higher specific gravity values than *Gmelina*. The very large F -value indicates that the variation among species is the dominant factor influencing wood specific gravity. At first glance, the density and specific gravity values appear inconsistent, particularly for *G. arborea*, which

shows high density but relatively low specific gravity. This discrepancy is due to the different reference conditions used in the calculations. In this study, density was calculated based on air-dry volume, while specific gravity was calculated using oven-dry mass divided by green volume, in accordance with BS 373:1957. As wood undergoes volumetric shrinkage during drying, the air-dry volume is smaller than the green volume, resulting in a higher density value compared to specific gravity. Therefore, these results are methodologically consistent and not contradictory.

Based on the specific gravity values obtained, all wood types were classified as having relatively low specific gravity values. According to the PKKI 1961 classification, the three types of wood were included in strength class IV. Based on PKKI classification, the three species fall into strength class IV. This classification suggests potential suitability for light and non-structural applications, although mechanical testing is required for confirmation (Somadona *et al.*, 2020). Interestingly, Yau *et al.* (2024) reported that the specific gravity of *Gmelina arborea* from Nigeria reached 0.51, which is higher than the value obtained in the present study. This discrepancy may be attributed to several factors, including differences in site conditions, growth rates, and age of the sampled trees, as well as variations in sample preparation and measurement methods (Listyanto *et al.*, 2020).

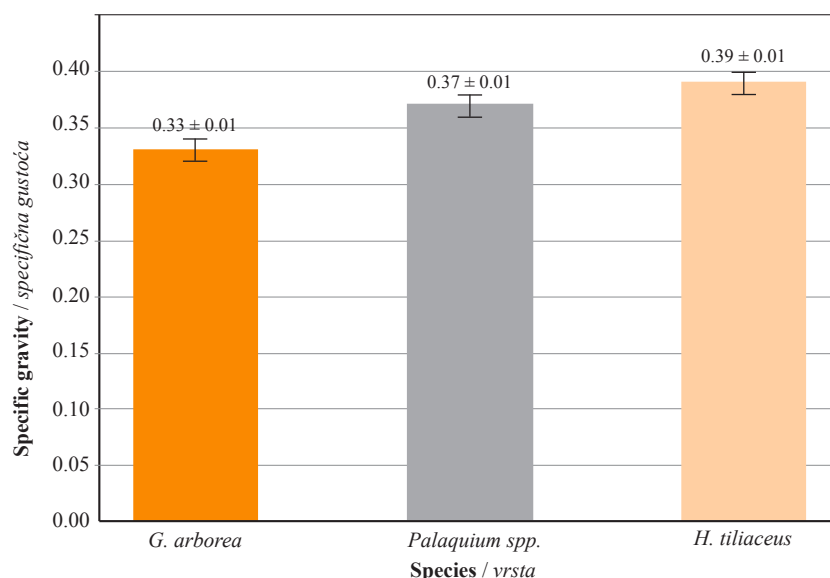


Figure 5 Specific gravity

Slika 5. Specifična gustoća drva

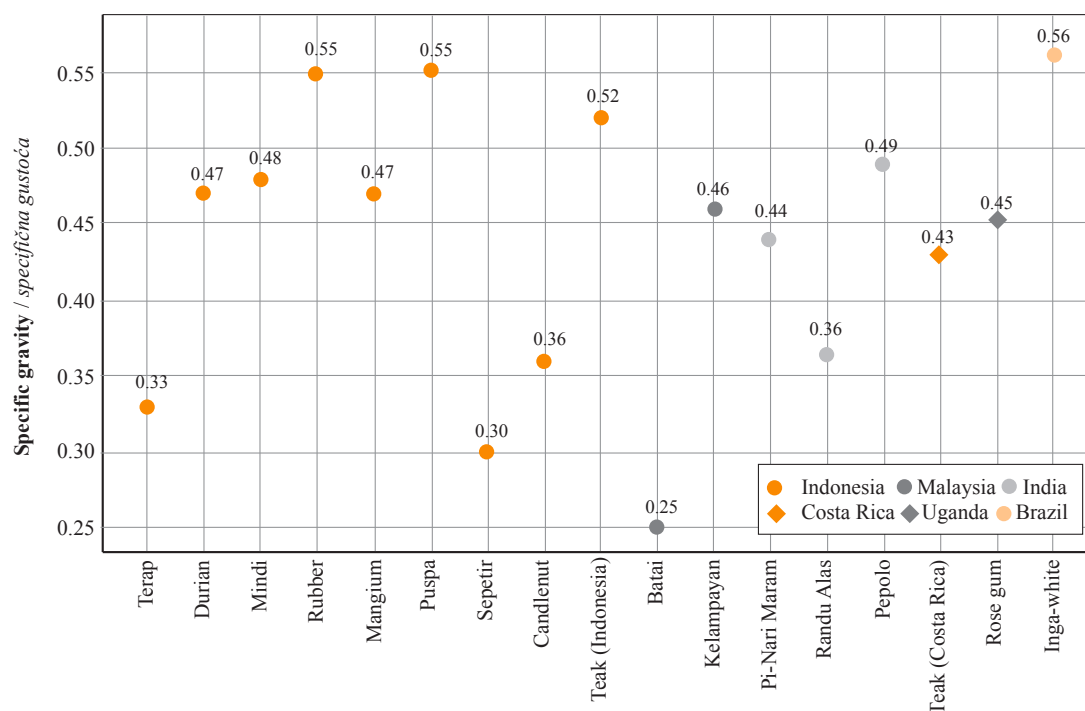


Figure 6 Comparison of specific gravity in tropical wood species from Indonesia and other countries (Herawati *et al.*, 2021; Hariz *et al.*, 2023; Augustina *et al.*, 2020b; Azis *et al.*, 2020; Savero *et al.*, 2020; Rahman *et al.*, 2020; Meghwal *et al.*, 2020; Pati *et al.*, 2025; Berrocal *et al.*, 2018; Sseremba *et al.*, 2020; Nascimento *et al.*, 2023)

Slika 6. Usporedba specifične gustoće tropskih vrsta drva iz Indonezije i drugih zemalja (Herawati *et al.*, 2021.; Hariz *et al.*, 2023.; Augustina *et al.*, 2020b; Azis *et al.*, 2020.; Savero *et al.*, 2020.; Rahman *et al.*, 2020.; Meghwal *et al.*, 2020.; Pati *et al.*, 2025.; Berrocal *et al.*, 2018.; Sseremba *et al.*, 2020.; Nascimento *et al.*, 2023.)

The results of this study are not linear with the wood density obtained in this study, which differs from the results of Damayanti *et al.* (2020), who stated that there was a positive correlation between density, specific gravity, and wood hardness. However, the relationship between density and specific gravity cannot be directly explained by anatomical characteristics in this study, because microscopic measurements were not performed (Borrega *et al.*, 2015). Unfortunately, this parameter was

not tested in the present study. Several previous studies by Moya and Fo (2008), Augustina *et al.* (2020a), and Andianto *et al.* (2024) mentioned that the cell wall thicknesses of *G. arborea*, *Palaquium spp.*, and *H. tiliaceus* woods are 2.37 – 6.01, 3.61, and 4.09 μm , respectively. Agustina *et al.* (2020) stated that variations in specific gravity values in several wood species are correlated with their microscopic structure and cell wall composition. In addition to influencing the mechanical character-

istics and utilization of wood, specific gravity is also closely related to its biological resistance and interaction with wood-degrading organisms (Kutana *et al.*, 2025). Thus, understanding the specific gravity of wood can provide an important basis for determining the application and utilization of each type of wood.

When compared to the data in Figure 6, the three types of wood tested show a relatively lower specific gravity than other tropical woods found in Indonesia, such as Durian, Mindi, Rubber, Mangium, Puspa, and Teak, which are in the moderate category (strength class III). However, their values are still comparable to Terap, Sepetir, and Candlenut. This condition indicates that the wood species studied have light characteristics with low specific gravity, making them more suitable for use in products with low structural loads (Yau *et al.*, 2025). As stated by Herawati *et al.* (2021), wood species with a low strength class (IV) are suitable for light construction. However, when compared to species from abroad, it can be seen that the specific gravity value of Inga-white found in Brazil is much higher, namely 0.56, thus falling into the category of wood with better strength (Nascimento *et al.*, 2023). On the other hand, Kelampayan, Pi-Nari Maram, Pepolo, and Teak wood found in several other countries also have a higher specific gravity range than species tested in this study. These differences further emphasize the influence of species and growing environment on the variation in the physical properties of wood (Nagar *et al.*, 2021). The specific gravity values reported in previous studies vary widely across regions and experimental conditions. This variability makes it difficult for practitioners to rely on values cited in literature when making industrial decisions. The results of this study present a controlled

comparison under identical testing conditions, which strengthens the reliability of cross-species comparisons and provides a more practical reference for wood processing and product design. However, direct comparisons with previous studies should be interpreted with caution, as differences in tree age, site conditions, sampling methods, moisture conditions, and testing procedures between studies may affect the reported values. Therefore, the comparisons presented in this study are intended for general reference only, while the interpretation of comparative performance remains limited.

3.4 Dimensional stability

3.4. Dimenzijska stabilnost drva

Changes in wood dimensions owing to increased moisture content are the primary factors affecting dimensional stability and wood quality, particularly in structural applications and material engineering. Wood exhibits anisotropic properties, meaning that shrinkage does not occur uniformly in all three directions of wood fiber orientation. Figure 7 shows the shrinkage values with significant variations in the longitudinal, radial, and tangential directions. The longitudinal shrinkage values ranged from 0.48 ± 0.02 % to 0.74 ± 0.01 %, with *H. tiliaceus* having the lowest value and *G. arborea* having the highest. Radial and tangential shrinkage values are important indicators for determining the degree of anisotropy and dimensional deformation tendency of wood. *G. arborea* exhibited similar radial and tangential shrinkages of 4.95 ± 0.02 % and 4.98 ± 0.03 %, respectively, indicating good wood shrinkage. According to Owoyemi *et al.* (2015), Gmelina shrinkage ranged from 8.65 % to 9.30 %, based on the position of the cut within the log. Addi-

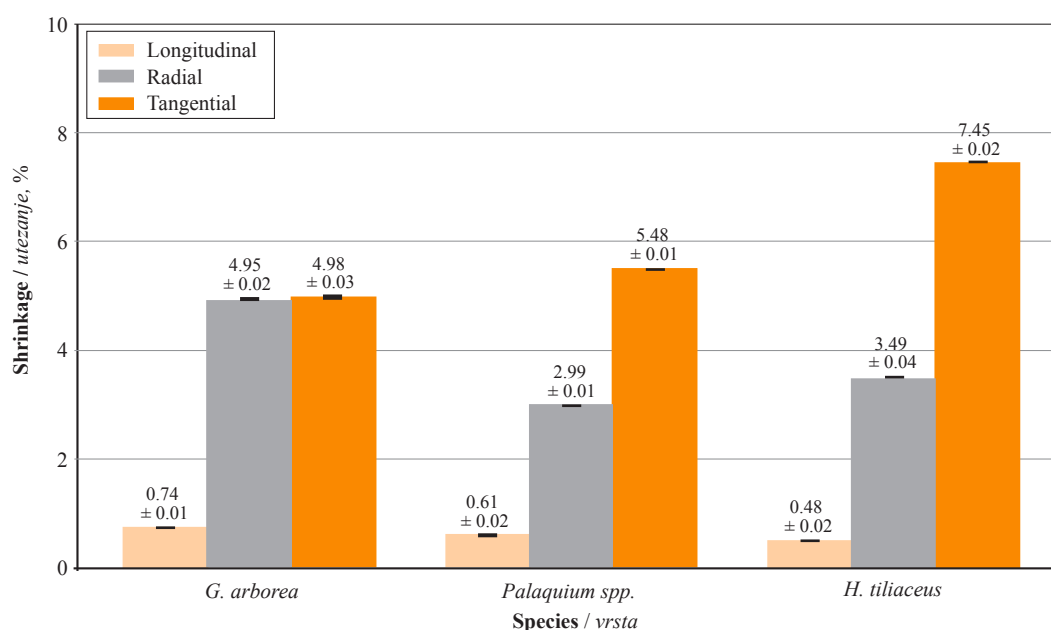


Figure 7 Shrinkage
Slika 7. Utezanje drva

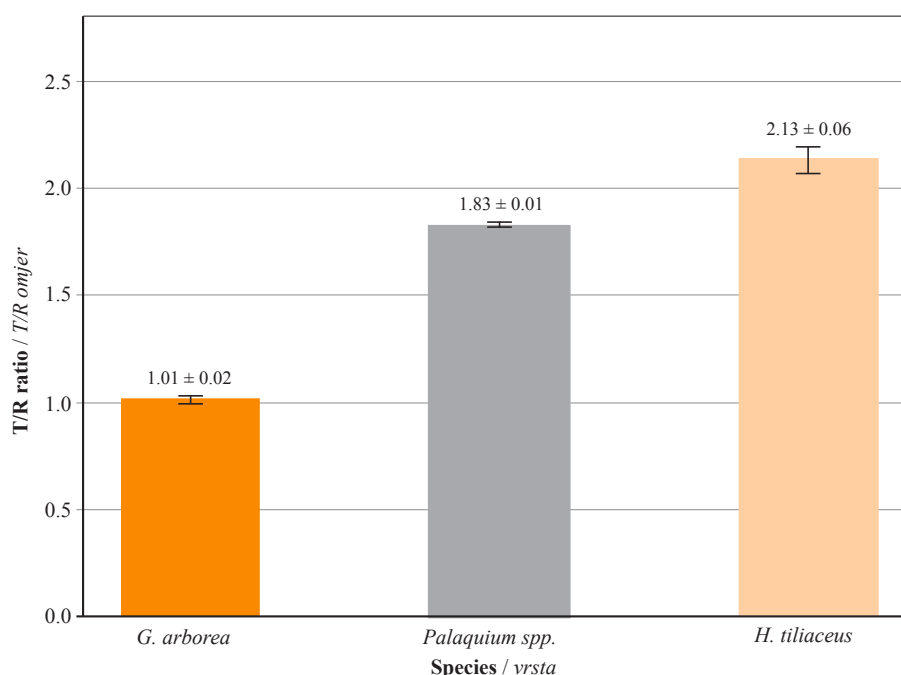


Figure 8 T/R ratio

Slika 8. Omjer tangენტnoga i radijalnog utezanja

tionally, Olaniran and Miltz (2024) stated that Gmelina subjected to thermal treatment exhibited a tangential-to-radial shrinkage ratio (T/R ratio) of 1.4 and experienced approximately 9.36 % shrinkage, indicating low volume changes in the wood. As shown in Figure 8, the T/R ratio of gmelina is 1.01 ± 0.02 , indicating excellent dimensional stability. The T/R ratio is an important parameter for wood dimensional stability, suggesting that the best use of wood in terms of drying quality leads to dimensional stability (Christoforo *et al.*, 2016; Seta *et al.*, 2023).

Unlike nyatoh, although it has a lower longitudinal shrinkage (0.61 ± 0.02 %), its tangential shrinkage is quite high (5.48 ± 0.01 %) and radial shrinkage (2.99 ± 0.01 %) (Figure 7). These values resulted in a T/R ratio of 1.83 ± 0.01 , indicating a higher risk of deformation compared to that of *G. arborea* (Figure 8). This ratio suggests that changes in moisture content can cause significant changes in shape, particularly in wood products, such as boards or veneers. *H. tiliaceus* had the lowest longitudinal shrinkage but produced the highest tangential shrinkage value of 7.45 ± 0.02 %, with a radial shrinkage of 3.49 ± 0.04 % (Figure 7). This results in a T/R ratio of 2.13 ± 0.06 , which significantly exceeds the ideal stability threshold and indicates high potential for shape changes and cracking during drying (Figure 8).

The results indicate that gmelina is the most dimensionally stable wood among the wood samples, as evidenced by a T/R ratio close to 1 and a minimal difference between radial and tangential shrinkage. The results for *Palaquium spp.* showed moderate deforma-

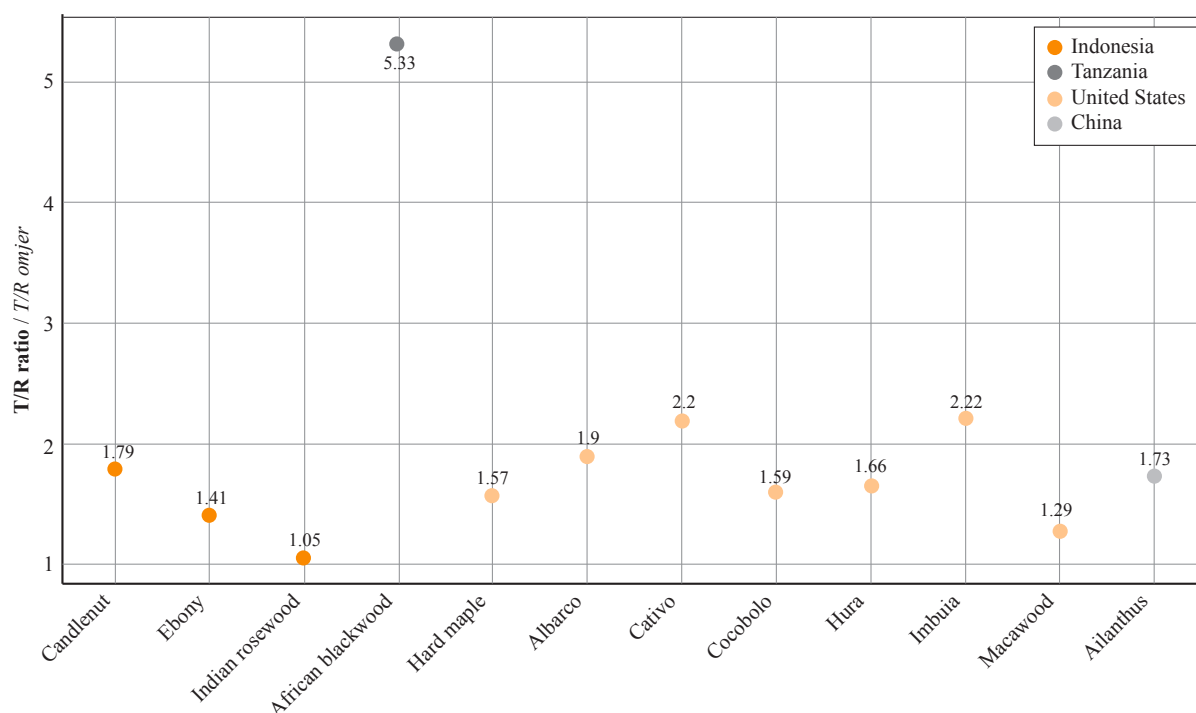
tion tendencies, particularly with respect to cupping. In contrast, *H. tiliaceus* exhibited the lowest stability. Therefore, its use should be limited to non-structural applications or decorative products that do not require high dimensional stability. Variations in the shrinkage ratio between the tangential and radial directions significantly influence the development of internal stresses during the wood drying process. This anisotropic behavior, particularly the T/R ratio, is a critical factor to consider in industrial applications, as it directly affects the dimensional stability and potential deformation of wood products over time (Fu *et al.*, 2016).

The results show that the three species of wood tested exhibit varying shrinkage behavior in all three directions, particularly radial and tangential. Compared to the data in Table 1 and Figure 9, the shrinkage value of *G. arborea* is within a range comparable to that of Indian Rosewood, an Indonesian tropical wood, which has a T/R ratio close to 1 (Liu *et al.*, 2020). This indicates fairly good dimensional stability. Meanwhile, *Palaquium spp.* and *H. tiliaceus* have shrinkage and T/R ratio values comparable to several Indonesian tropical woods such as Candlenut and Ebony. In addition, the two woods studied also have T/R ratios comparable to several tropical woods from other countries, such as Hard Maple, Albarco, Catiyo, Cocobolo, Hura, Imbuia, and Macawood from the United States, as well as Ailanthus from China. In fact, African Blackwood tropical wood from Tanzania has a T/R ratio that is very far from the indicator of wood dimensional stability.

The differences in shrinkage values and dimensional stability between tropical wood from Indonesia

Table 1 Comparison of shrinkage in tropical wood species from Indonesia and other countries**Tablica 1.** Usporedba utezanja tropskih vrsta drva iz Indonezije i drugih zemalja

Species / Vrsta	Tangential <i>Tangentno utezanje</i>	Radial <i>Radijalno utezanje</i>	Country <i>Zemlja</i>	Reference / Referenca
Candlenut (<i>Aleurites moluccanus</i> (L.) Willd.)	2.37	1.32	Indonesia	Azis <i>et al.</i> (2020)
Ebony (<i>Diospyros crassiflora</i> J. Kenig ex Retz.)	2.56	1.81	Indonesia	Liu <i>et al.</i> (2020)
Indian rosewood (<i>Dalbergia latifolia</i> Roxb.)	1.97	1.88	Indonesia	Liu <i>et al.</i> (2020)
African blackwood (<i>Dalbergia melanoxylon</i> Guill. & Perr.)	0.16	0.03	Tanzania	Liu <i>et al.</i> (2020)
Hard maple (<i>Acer saccharum</i>)	2.74	1.74	United States	Liu <i>et al.</i> (2020)
Albarco (<i>Cariniana spp.</i>)	5.4	2.8	United States	Glass and Zelinka (2021)
Cativo (<i>Prioria copaifera</i>)	5.3	2.4	United States	Glass and Zelinka (2021)
Cocobolo (<i>Dalbergia retusa</i>)	4.3	2.7	United States	Glass and Zelinka (2021)
Hura (<i>Hura crepitans</i>)	4.5	2.7	United States	Glass and Zelinka (2021)
Imbuia (<i>Phoebe porosa</i>)	6	2.7	United States	Glass and Zelinka (2021)
Macawood (<i>Platymiscium spp.</i>)	3.5	2.7	United States	Glass and Zelinka (2021)
Ailanthus (<i>Ailanthus desf.</i>)	3.08	1.78	China	Liu <i>et al.</i> (2021)

**Figure 9** Comparison of T/R ratio in tropical wood species from Indonesia and other countries (Azis *et al.*, 2020; Liu *et al.*, 2020; Glass and Zelinka, 2021; Liu *et al.*, 2021)**Slika 9.** Usporedba T/R omjera tropskih vrsta drva iz Indonezije i drugih zemalja (Azis *et al.*, 2020.; Liu *et al.*, 2020.; Glass i Zelinka, 2021.; Liu *et al.*, 2021.)

and species from other countries are not only influenced by anatomical factors, cell wall proportions, and variations in chemical composition, but also by ecological conditions and growing environments (Fejfer *et al.*, 2020; Zhao and Yang, 2025). The humid climate with high rainfall and relatively constant temperatures in Indonesia causes tropical wood to grow faster, resulting in low to medium specific gravity. However, this study shows that Indonesian tropical wood, par-

ticularly Gmelina and Indian Rosewood, actually exhibits better dimensional stability than some species from other countries. This can be attributed to the relatively homogeneous anatomical structure of the wood, balanced cell wall proportions, and more even pore distribution, which reduces the level of shrinkage anisotropy (Fredriksson *et al.*, 2023). On the other hand, wood from regions with long dry seasons, such as Africa or Latin America, often grows more slowly and

has a high specific gravity. This growth does produce denser fibers, but it also increases the risk of differences in shrinkage between the radial and tangential directions, resulting in lower dimensional stability (Qian *et al.*, 2022; Nascimento *et al.*, 2023). Thus, understanding the shrinkage value and T/R ratio can be used as a basis for determining the suitability of wood applications, both for structural and non-structural needs, especially for products that require high dimensional stability.

Overall, a comparison with previous studies indicates that the variability reported in the literature is influenced not only by species characteristics but also by methodological differences across studies. Therefore, the main contribution of this study is not merely to generate additional data, but to provide a statistically supported and methodologically consistent comparison among three commercially important yet underrepresented tropical timber species. This standardized dataset helps bridge the gap between fragmented literature and practical industry needs.

4 CONCLUSIONS

4. ZAKLJUČAK

The green moisture content was highest in *G. arborea* (176.41 %), followed by *Palaquium spp.* (103.45 %) and *H. tiliaceus* (82.49 %). At the air-dried condition, the moisture content decreased to 16.34 %, 17.65 %, and 12.18 % for *G. arborea*, *Palaquium spp.*, and *H. tiliaceus*, respectively. The density values were 0.90 g/cm³ for *G. arborea*, 0.76 g/cm³ for *Palaquium spp.*, and 0.67 g/cm³ for *H. tiliaceus*. In contrast, the specific gravity values were 0.33 for *G. arborea*, 0.37 for *Palaquium spp.*, and 0.39 for *H. tiliaceus*. *G. arborea* showed the lowest T/R ratio (1.01), indicating better dimensional stability compared to *Palaquium spp.* (1.83) and *H. tiliaceus* (2.13). These results indicate differences in physical properties and dimensional stability among the three species under identical testing conditions. *G. arborea* demonstrated comparatively higher dimensional stability, while *H. tiliaceus* showed greater tangential shrinkage and higher T/R ratio. *Palaquium spp.* exhibited intermediate characteristics. The findings of this study are limited to physical properties and dimensional stability; therefore, further research including mechanical and durability testing is necessary before determining suitability for specific structural or engineering applications.

Acknowledgements – Zahvala

This research was supported by IPB University, Bogor, Indonesia, and the Integrated Laboratory of Wood Quality Improvement Technology, IPB University, Bogor, Indonesia.

5 REFERENCES

5. LITERATURA

- Andianto; Wahyudi, I.; Sari, R. K.; Pari, G., 2024: Fiber quality of seven mangrove wood species. *Journal of Korean Wood Science and Technology*, 52 (4): 393-403. <https://doi.org/10.5658/WOOD.2024.52.4.393>
- Arifudin, M.; Wahyudi, D., 2020: Macro-features and density of various timber species from Papua. *Jurnal Kehutanan Papuasiasia*, 6 (2): 141-148. <https://doi.org/10.46703/jurnalpapuasiasia.vol6.iss2.207>
- Augustina, S.; Wahyudi, I.; Darmawan, I. W.; Malik, J., 2020a: Ciri anatomi, morfologi serat, dan sifat fisis tiga jenis lesser-used wood spesies asal Kalimantan Utara, Indonesia. *Jurnal Ilmu Pertanian Indonesia*, 25 (4): 599-609. <https://doi.org/10.18343/jipi.25.4.599>
- Augustina, S.; Wahyudi, I.; Darmawan, I. W.; Malik, J.; Basri, E.; Kojima, Y., 2020b: Specific gravity and dimensional stability of boron-densified wood on three lesser-used species from Indonesia. *Journal of Korean Wood Science and Technology*, 48 (4): 458-471. <https://doi.org/10.5658/WOOD.2020.48.4.458>
- Augustina, S.; Marbun, S. D.; Sudarmanto; Narto; Tri-satya, D. R.; Santoso, E. B.; Pramadani, D.; Afni, N. N.; Fariha, T. A.; Tobing, G. W. L.; Syafi'i, W.; Cahyono, T. D.; Novriyanti, E.; Bula, M.; Bahanawan, A.; Sejati, P. S.; Kim, N. H.; Dwianto, W.; Gerardin, P., 2023: Dimensional stability and mechanical properties of citric acid impregnated samama wood (*Anthocephalus macrophyllus* (Roxb) Havil) at high curing temperatures. *Journal of Korean Wood Science and Technology*, 51 (6): 431-446. <https://doi.org/10.5658/WOOD.2023.51.6.431>
- Azis, A.; Yuniarti, A. D.; Agussalim, A., 2020: Changes in the density, specific gravity and dimensional stability of candlenut wood (*Aleurites moluccanus* (L.) Willd.) from several variation temperatures with oil-heat treatment. *IOP Conference Series: Materials Science and Engineering*, p. 012031. <https://doi.org/10.1088/1757-899X/935/1/012031>
- Barbu, M. C.; Tudor, E. M., 2022: State of the art of the Chinese forestry, wood industry and its markets. *Wood Material Science & Engineering*, 17 (6): 1030-1039. <https://doi.org/10.1080/17480272.2021.1891457>
- Basri, E.; Yuniarti, K.; Saefudin, 2019: Basic properties and potential uses of 35 wood species from moluccas, Indonesia. *IOP Conference Series: Earth and Environmental Science*, p. 012105. <https://doi.org/10.1088/1755-1315/399/1/012105>
- Bendikiene, R.; Keturakis, G., 2017: The influence of technical characteristics of wood milling tools on its wear performance. *Journal of Wood Science*, 63: 606-614. <https://doi.org/10.1007/s10086-017-1656-x>
- Bergman, R., 2021: Drying control of moisture content and dimensional changes. In: *Wood Handbook*, Chapter 13. United States, Department of Agriculture, Forest Service, Forest Products Laboratory.
- Berrocá, A.; Alvarez, J. G.; Moya, R.; Solís, D. F.; Malavassi, E. O., 2018: Development of heartwood, sapwood, bark, pith and specific gravity of teak (*Tectona grandis*) in fast-growing plantations in Costa Rica. *Journal of Forestry Research*, 31: 667-676. <https://doi.org/10.1007/s11676-018-0849-5>
- Borrega, M.; Ahvenainen, P.; Serimaa, R.; Gibson, L., 2015: Composition and structure of balsa (*Ochroma pyramidale*) wood. *Wood Science and Technology*, 49 (2): 403-420. <https://doi.org/10.1007/s00226-015-0700-5>

13. Bowyer, J. L.; Shmulsky, R.; Haygreen, J. G., 2007: Forest Products and Wood Science – An Introduction. Iowa, Iowa State University Press.
14. Cabral, J. P.; Kaffle, B.; Subhani, M.; Reiner, J.; Ashraf, M., 2022: Densification of timber: A review on the process, material properties and application. *Journal of Wood Science*, 68 (20). <https://doi.org/10.1186/s10086-022-02028-3>
15. Cai, C.; Herajarvi, H.; Haapala, A., 2019: Effects of environmental conditions on physical and mechanical properties of thermally modified wood. *Canadian Journal of Forest Research*, 49 (11): 1434-1440. <https://doi.org/10.1139/cjfr-2019-0180>
16. Christoforo, A. L.; de Almeida, T. H.; de Almeida, D. H.; dos Santos, J. C.; Panzera, T. H.; Lahr, F. A. R., 2016: Shrinkage for some wood species estimated by density. *International Journal of Materials Engineering*, 6 (2): 23-27. <https://doi.org/10.5923/j.ijme.20160602.01>
17. Coto, Z., 2005: Reducing equilibrium moisture content improving dimensional stability of wood through heating and restraining. *Jurnal Ilmu dan Teknologi Kayu Tropis*, 3 (1): 27-31.
18. Damayanti, R.; Dewi, L. M.; Ozarska, B.; Illic, J.; Pari, H.; Krisdianto, 2020: Assessing ultrastructure and density properties to predict wood hardness of young fast grown plantation teak. *IOP Conference Series: Material Science and Engineering*, 935: 012026. <https://doi.org/10.1088/1757-899X/935/1/012026>
19. Djafar, E. M.; Widayanti, T. F.; Saidi, M. D.; Muin, A. M.; Ratnawati, 2023: Forest management to achieve sustainable forestry policy in Indonesia. *IOP Conference Series: Earth and Environmental Science*, p. 012021. <https://doi.org/10.1088/1755-1315/1181/1/012021>
20. Elstundo, D.; Matan, N.; Langrish, T.; Pang, S., 2023: Advances in wood drying research and development. *Drying Technology*, 41 (6): 890-914. <https://doi.org/10.1080/07373937.2023.2205530>
21. Favis, J.; Balboni, B.; Wessels, C. B., 2024: Effect of wood moisture content and adhesive open time on the adhesion strength of wet bonded *Pinus radiata* wood. *European Journal of Wood and Wood Products*, 81 (1): 557-560. <https://doi.org/10.1007/s00107-024-02050-w>
22. Fejfer, M.; Majka, J.; Zborowska, M., 2020: Dimensional stability of waterlogged scots pine wood treated with PEG and dried using an alternative approach. *Forests*, 11 (12): 1254. <https://doi.org/10.3390/f11121254>
23. Fredriksson, M.; Ruggeberg, M.; Larsen, T. N.; Beck, G.; Thybring, E. E., 2023: Water sorption in wood cell walls-data exploration of the influential physicochemical characteristics. *Cellulose*, 30: 1857-1871. <https://doi.org/10.1007/s10570-022-04973-0>
24. Fu, Z.; Zhao, J.; Yang, Y.; Cai, Y., 2016: Variation of drying strains between tangential and radial directions in Asian white birch. *Forests*, 7 (3): 59. <https://doi.org/10.3390/f7030059>
25. Glass, S.; Zelinka, S., 2021: Moisture relations and physical properties of wood. Chapter 4 in *FPL-GTR-282*, 4-1.
26. Hadi, Y. S.; Herliyana, E. N.; Pari, G.; Pari, R.; Abdillah, I. B., 2022: Furfurylation effects on discoloration and physical-mechanical properties of wood from tropical plantation forests. *Journal of Korean Wood Science and Technology*, 50 (1): 46-58. <https://doi.org/10.5658/WOOD.2022.50.1.46>
27. Hariz, T. M. R.; Hadi, Y. S.; Lubis, M. A. R.; Maulana, M. I.; Sari, R. K.; Hidayat, W., 2023: Physical and mechanical properties of cross-laminated timber made of combination of mangium-puspa wood and polyurethane adhesive. *Jurnal Sylva Lestari*, 11 (1): 37-65. <https://doi.org/10.23960/jsl.v11i1.645>
28. Herawati, E.; Hartono, R.; Sinaga, H. M. M., 2021: Physical and mechanical properties of four wood species from community forests in Binjai Regency, North Sumatra. *IOP Conference Series: Earth and Environmental Science*, p. 012024. <https://doi.org/10.1088/1755-1315/912/1/012024>
29. Husnah, M.; Suhartono, S.; Ismail, Y. S., 2021: A current perspective on antibacterial and antibiofilm properties of waru (*Hibiscus tiliaceus* L.). *IOP Conference Series: Earth and Environmental Science*, p. 012019. <https://doi.org/10.1088/1755-1315/711/1/012019>
30. Irwan, M.; Aras, N. R. M., 2023: Analisis kekuatan impact komposit serat batang pohon waru (*Hibiscus tiliaceus*). *Jurnal Teknik Mesin Indonesia*, 18 (2): 27-30. <https://doi.org/10.36289/jtmi.v18i2.439>
31. Iwuoha, S. E.; Seim, W.; Onyekwelu, J. C., 2021: Mechanical properties of *Gmelina arborea* for engineering design. *Constructional and Building Materials*, 288: 123123. <https://doi.org/10.1016/j.conbuildmat.2021.123123>
32. Kabir, C. R.; Islam, M.; Hassan, M. B.; Rahman, M., 2025: Impact of local climate and large-scale climate drivers on the growth of *Gmelina arborea* Roxb. in a South Asian moist tropical forest. *Trees*, 39: 41. <https://doi.org/10.1007/s00468-025-02618-w>
33. Kana, S. K.; Biwole, A. B.; Huisken, P. W. M.; Koun-gang, B. M. G. K.; Mvondo, R. R. N.; Tounkam, M. N.; Njeugna, E., 2024: Physical and mechanical properties of two tropical wood (*Detarium macrocarpum* and *Piptadeniastrum africanum*) and their potential as substitutes to traditionally used wood in Cameroon. *International Wood Products Journal*, 15 (1): 5-19. <https://doi.org/10.1177/20426445241233343>
34. Kherais, M.; Csébfalvi, A.; Len, A.; Fülöp, A.; Pál-Schreiner, J., 2024: The effect of moisture content on the mechanical properties of wood structure. *Pollack Periodica*, 19(1): 1-6. <https://doi.org/10.1556/606.2023.00917>
35. Klement, I.; Vilkovská, T.; Vilkovský, P.; Hýsek, Š., 2020: Structural differences between reaction wood and opposite wood with different drying temperatures. *BioResources*, 15 (2): 4407-4416. <https://doi.org/10.15376/biores.15.2.4407-4416>
36. Komariah, R. N.; Hadi, Y. S.; Massijaya, M. Y.; Suryana, J., 2015: Physical-mechanical properties of glued laminated timber made from tropical small-diameter logs grown in Indonesia. *Journal of the Korean Wood Science and Technology*, 43 (2): 156-167. <https://doi.org/10.5658/WOOD.2015.43.2.156>
37. Kutana, A. N.; Nandika, D.; Arinana, A., 2025: Feeding preferences of subterranean termite *Schedorhinotermes javanicus* on tusam (*Pinus merkusii*) wood. *Jurnal Sylva Lestari*, 13 (1): 45-59. <https://doi.org/10.23960/jsl.v13i1.1063>
38. Li, F.; Qian, H.; Sardans, J.; Amishev, D. Y.; Wang, Z.; Zhang, C.; Wu, T.; Xu, X.; Tao, X.; Huang, X., 2024: Evolutionary history shapes variation of wood density of tree species across the world. *Plant Diversity*, 46 (3): 283-293. <https://doi.org/10.1016/j.pld.2024.04.002>
39. Listyanto, T.; Nichols, J. D.; Glencross, K.; Schoer, L., 2020: Variation in density and shrinkage of six eucalyptus species and interspecific hybrid combinations at three sites in Northern New South Wales. *IOP Conference Series: Materials Science and Engineering*, p. 012035.
40. Liu, M.; Peng, L.; Lyu, S.; Liu, J., 2020: Properties of common tropical hardwoods for fretboard of string in-

- struments. *Journal of Wood Science*, 66 (1):1-11. <https://doi.org/10.1186/s10086-020-01862-7>
41. Liu, X. Y.; Tu, X. W.; Liu, M., 2021: Effects of light thermal treatments on the color, hygroscopy and dimensional stability of wood. *Wood Research*, 66 (1): 95-104. <https://doi.org/10.37763/wr.1336-4561/66.1.95104>
 42. Marais, B. N.; Brischke, C.; Militz, H.; Peters, J. H.; Reinhardt, L., 2020: Studies into fungal decay of wood in ground contact. Part 1: The influence of water-holding capacity, moisture content and temperature of soil substrates on fungal decay of selected timbers. *Forests*, 11 (2): 1284. <https://doi.org/10.3390/f11121284>
 43. Marini, F.; Manetti, M. C.; Corona, P.; Portoghesi, L.; Vinciguerra, V.; Tamantini, S.; Kuzminsky, E.; Zikeli, F.; Romagnoli, M., 2021: Influence of forest stand characteristics on physical, mechanical properties and chemistry of chestnut wood. *Scientific Reports*, 11: 1549. <https://doi.org/10.1038/s41598-020-80558-w>
 44. Meghwal, S.; Chauhan, K.; Nagar, B.; Vijayan, A. S.; Neehta, P.; Arya, C. K.; Kumar, V., 2020: Wood specific gravity of important hardwood tree species of Jhalawar District. *International Journal of Chemical Studies*, 8 (6): 267-269. <https://doi.org/10.22271/chemi.2020.v8.i6d.11167>
 45. Meiganati, K. B.; Harta, W. G. Y.; Lidiawati, I.; Kridianto., 2023: Trade group anatomy structure and usage of nyatoh wood in the genus of *Palaquium*. *Jurnal Sains Natural*, 13 (3): 141-151. <https://doi.org/10.31938/jsn.v13i3.575>
 46. Mezui, E. N.; Nziengui, C. F. P.; Pitti, R. M.; Ikogou, S.; Ango, S. E.; Talla, P. K., 2022: Strain and cracks investigations on tropical green wood slices under natural drying: experimental and numerical approaches. *European Journal of Wood and Wood Products*, 81: 187-207. <https://doi.org/10.1007/s00107-022-01881-9>
 47. Miranda, I.; Sousa, V.; Pereira, H., 2011: Wood properties of teak (*Tectona grandis*) from a mature unmanaged stand in East Timor. *Journal of Wood Science*, 57 (3): 171-178. <https://doi.org/10.1007/s10086-010-1164-8>
 48. Moya, R.; Fo, M. T., 2008: Variation in the wood anatomical structure of *Gmelina arborea* (Verbenaceae) trees at different ecological conditions in Costa Rica. *Revista de Biología Tropical*, 56 (2): 689-704. <https://doi.org/10.15517/rbt.v56i2.5617>
 49. Muchtar, A.; Muib, R.; Herawati, H., 2024: Effect of compost dosing on the growth of Nyatoh (*Palaquium* sp) seedlings in the nursery. *Jurnal Wasian*, 11 (1): 01-08. <https://doi.org/10.62142/ntf8ng19>
 50. Mvondo, R. R. N.; Meukam, P.; Jeong, J.; Meneses, D. D. S.; Nkeng, E. G., 2017: Influence of water content on the mechanical and chemical properties of tropical wood species. *Results in Physics*, 7: 2096-2103. <https://doi.org/10.1016/j.rinp.2017.06.025>
 51. Nagar, B.; Rawat, S.; Pandey, R.; Kumar, M., 2021: Variation in specific gravity and carbon proportion of agroforestry tree species of Himalaya. *Environmental Challenges*, 4: 100156. <https://doi.org/10.1016/j.envc.2021.100156>
 52. Nascimento, C. S. D.; Cruz, I. D. A.; Nascimento, C. C. D.; Araujo, R. D. D.; Higuchi, N.; Santos, J. D., 2023: Technological properties of wood from small diameter in an area of forest exploitation of reduced impact in the tropical forest. *European Journal of Forest Research*, 142: 1225-1238. <https://doi.org/10.1007/s10342-023-01588-3>
 53. Nawawi, D. S.; Maria, A.; Firdaus, R. D.; Rahayu, I. S.; Fatrawana, A.; Pramatana, F.; Sinaga, P. S.; Fatriasari, W., 2023: Improvement of dimensional stability of tropical light-wood *Ceiba pentandra* (L) by combined alkali treatment and densification. *Journal of the Korean Wood Science and Technology*, 51 (2): 133-144. <https://doi.org/10.5658/WOOD.2023.51.2.133>
 54. Nugroho, W. D.; Na'iem, M.; Lukmandaru, G.; Widiyatno; Feriawan, Y.; Prastiwi, F. W.; Wibowo, A.; Puspitasari, D., 2024: Physical and mechanical properties of 20-Year-Old clonal teak trees in Ngawi, East Java, Indonesia. *Journal of the Korean Wood Science and Technology*, 52 (5): 459-472. <https://doi.org/10.5658/wood.2024.52.5.459>
 55. Olaniran, S.; Militz, H., 2024: Dimensional stability and mechanical properties of *Gmelina arborea* Roxb. wood thermally modified through open reactor and low-pressure closed reactor systems. *Forests*, 15 (3): 403. <https://doi.org/10.3390/f15030403>
 56. Olaniran, S. O.; Iyiola, E. A.; Oyekola, A. A., 2024: Investigation of wood properties and resistance of 25-year-old *Gmelina arborea* wood selected from crown region to termite attack. *Maderas. Ciencia y tecnología*, 26: 1-8. <https://doi.org/10.22320/s0718221x/2024.16>
 57. Owoyemi, S.; Oyodele, O.; Aladejana, J., 2015: Assessment of dimensional stability of *gmelina arborea* wood using modified green house dryer. *Pro Ligno*, 11 (2): 11-20.
 58. Pati, P. K.; Kaushik, P.; Khan, M. L.; Khare, P. K., 2025: Inventory of wood specific gravity for Indian forests. *Trees, Forests and People*, 19: 100775. <https://doi.org/10.1016/j.tfp.2025.100775>
 59. Phang, A.; Pezzini, F. F.; Burslem, D. F. R. P.; Khew, G. S.; Middleton, D. J.; Ruhsam, M.; Wilkie, P., 2023: Target capture sequencing for phylogenomic and population studies in the Southeast Asian genus *Palaquium* (Sapotaceae). *Botanical Journal of the Linnean Society*, 203 (2): 134-147. <https://doi.org/10.1093/botlinnean/boad022>
 60. Purnowidodo, A.; Sutedja; Djarot, B. D.; Khairul, A., 2020: Tensile strength and fatigue crack growth behaviour of natural fibre metal laminates. *Journal of Engineering Science and Technology*, 15 (4): 2809-2822.
 61. Putra, R. H.; Retnowati, D.; Cordova, D. M.; Zahra, A. A.; Primahana, G.; Dewi, R. T.; Filaila, E.; Sukirno; Prastya, M. E., 2024: Antibacterial and antioxidant properties of bioactive compounds derived from endophytic bacteria isolated from nyatoh (*Palaquium amboinense* B.). *Jurnal Sumberdaya Hayati*, 10 (1): 25-32. <https://doi.org/10.29244/jsdh.10.1.25-32>
 62. Qian, J.; Gao, J.; He, Z.; Yi, S., 2022: Self-shrinking *Ailanthus altissima* substrate obtained by ultrasonic-assisted treatment: Density and pore structure characteristics. *Industrial Crops and Products*, 175: 114221. <https://doi.org/10.1016/j.indcrop.2021.114221>
 63. Rahman, W. M. N. W. A.; Sa'ad, M. F.; Misran, S.; Sofian, N. N.; Yunus, N. Y. M., 2020: Wood and veneer properties of fast growing species from Batai, Eucalyptus and Kelampayan. *International Journal of Management and Humanities*, 4 (8): 65-71. <https://doi.org/10.35940/ijmh.H0772.044820>
 64. Rahmayanti, R.; Erniwati, E.; Hapid, A., 2016: Sifat fisika kayu jabon (*Anthocephalus cadamba* Miq.) berdasarkan arah aksial dari Desa Alindau Kabupaten Donggala Sulawesi Tenggara. *Jurnal Warta Rimba*, 4 (1).
 65. Reyes, G.; Brown, S.; Chapman, J.; Lugo, A. E., 1992: Wood densities of tropical tree species. Department of Agriculture, Forest Services, United States, Southern Forest Experiment Station. <https://doi.org/10.2737/so-gtr-088>
 66. Rizanti, E. E.; Darmawan, W.; George, B.; Merlin, A.; Dumarcay, S.; Chapuis, H.; Gerardin, C.; Gelhaye, E.; Raharivelomanana, P.; Sari, R. K.; Syafii, W.; Mohamed, R.; Gerardin, P., 2018: Comparison of teak wood properties according to forest management: short versus long rotation. *Annals of Forest Science*, 75 (39): 1-12. <https://doi.org/10.1007/s13595-018-0716-8>
 67. Sargent, R., 2022: Evaluating dimensional stability in modified wood: an experimental comparison of test

- methods. *Forest*, 13 (4): 613. <https://doi.org/10.3390/f13040613>
68. Saverio, A. M.; Wahyudi, I.; Rahayu, I. S.; Yudianti, A. D.; Ishiguri, F., 2020: Investigating the anatomical and physical-mechanical properties of the 8-year-old superior teakwood planted in Muna Island, Indonesia. *Journal of the Korean Wood Science and Technology*, 48 (5): 618-630. <https://doi.org/10.5658/wood.2020.48.5.618>
 69. Seta, G. W.; Hidayati, F.; Widiyatno; Na'iem, M., 2023: Wood physical and mechanical properties of clonal teak (*Tectona grandis*) stands under different thinning and pruning intensity levels planted in Java, Indonesia. *Journal of the Korean Wood Science and Technology*, 51 (2): 109-132. <https://doi.org/10.5658/wood.2023.51.2.109>
 70. Setiadi, D., 2018: Upaya Pembangunan kebun benih semai uji keturunan *Gmelina arborea* Roxb dan evaluasi awal keragaman pertumbuhan umur 6 bulan di Trenggalek, Jawa Timur. Prosiding SNPBS (Seminar Nasional Pendidikan Biologi dan Sainstek), pp. 1-8.
 71. Shmulsky, R.; Jones, P. D., 2011: *Forest Products and Wood Science. An Introduction*. Sixth Edition. Chichester, United Kingdom, Wiley Blackwell.
 72. Shukla, S. R., 2025: *Wood Properties and Utilization*. In: *Textbook of Forest Science*. Singapore, Springer. https://doi.org/10.1007/978-981-97-8289-5_37
 73. Simangunsong, A. S.; Hapid, A.; Muthmainnah, M., 2016: Variasi sifat fisika kayu kemiri (*Aleurites moluccana*) berdasarkan arah aksial. *Jurnal Warta Rimba*, 4 (1).
 74. Somadona, S.; Sribudiani, E.; Valencia, D. E., 2020: Karakteristik balok laminasi kayu akasia (*Acacia mangium*) dan meranti merah (*Shorea leprosula*) berdasarkan susunan lamina dan berat labur perekat Styrofoam. *Wahana Forestra: Jurnal Kehutanan*, 15 (2): 53-64. <https://doi.org/10.31849/forestra.v15i2.5039>
 75. Sseremba, O. E.; Mugabi, P.; Banana, A. Y.; Wessels, B. C.; Plessis, M., 2020: Variation of basic density, calorific value and volumetric shrinkage within tree height and tree age of Ugandan grown *Eucalyptus grandis* wood. *Journal of Forestry Research*, 32: 503-512. <https://doi.org/10.1007/s11676-020-01141-7>
 76. Suri, I. F.; Purusatama, B. D.; Lee, S.; Kim, N.; Hidayat, W.; Ma'ruf, S. D.; Febrianto, F., 2021: Characteristic features of the oil-heat treated woods from tropical fast growing wood species. *Wood Research*, 66 (3): 365-378. <https://doi.org/10.37763/wr.1336-4561/66.3.365378>
 77. Uslinawaty, Z.; Pujirahayu, N.; Hadjar, N.; Kabe, A.; Hamzah, N.; Ronaldo, 2024: Uji kadar air titik jenuh serat beberapa jenis kayu perdagangan di Kabupaten Konawe Selatan. *Jurnal Kehutanan Indonesia Celebica*, 5 (1): 75-82. <https://doi.org/10.33772/jc.v5i1.83>
 78. Vallesteros, S. F., 2020: Tree traits that define timber ideotypes of *Gmelina arborea* Roxb. IOP Conference Series: Earth and Environmental Science, p. 012089. <https://doi.org/10.1088/1755-1315/475/1/012089>
 79. Wirawan, W. A.; Sabitah, A.; Choiron, M. A.; Muslimin, M.; Zulkarnain, A.; Budiarto, B. W., 2023: Effect of chemical treatment on the physical and thermal stability of *Hibiscus tiliaceus* Bark Fiber (HBF) as reinforcement in composite. *Results in Engineering*, 18: 101101. <https://doi.org/10.1016/j.rineng.2023.101101>
 80. Wulandari, F. T.; Amin, R., 2023: The effect of felt pressure and adhesive lath weight on the physical and mechanical properties of the combination of petung bamboo and sengon laminated boards. *Jurnal Biologi Tropis*, 23 (2): 263-271. <https://doi.org/10.29303/jbt.v23i2.4735>
 81. Wulandari, F. T.; Lestari, D.; Amin, R., 2024: Perbandingan sifat fisika dan mekanika papan laminasi bambu petung dengan papan laminasi kombinasi kayu kemiri bambu petung dan kayu sengon bambu petung sebagai bahan konstruksi. *Journal of Forest Science Avicennia*, 7 (1): 1-12. <https://doi.org/10.22219/avicennia.v7i1.31308>
 82. Yau, Y.; Ocholi, A.; Kaura, J. M.; Lawan, A.; Sulaiman, T. A., 2024: Experimental evaluation of the physical properties and sorption properties of *Gmelina arborea* timber for development of wood-based materials. *Convenant Journal of Engineering Technology*, 8 (2): 1-8.
 83. Yau, Y.; Ocholi, A.; Kaura, J. M.; Lawan, A.; Sulaiman, T. A.; Aliyu, H., 2025: Strength evaluation and characterization of *Gmelina arborea* timber for structural applications. *Nigerian Journal of Technological Development*, 22 (3): 171-186. <https://dx.doi.org/10.63746/njtd.v22i3.2837>
 84. You, R.; Zhu, N.; Deng, X.; Wang, J.; Liu, F., 2021: Variation in wood physical properties and effects of climate for different geographic sources of Chinese fir in subtropical area of China. *Scientific Reports*, 11: 4664. <https://doi.org/10.1038/s41598-021-83500-w>
 85. Yudianti, A. D.; Pangestu, K. T. P.; Suhasman; Taskirawati, I.; Agussalim; Muin, M., 2019: Modified densification process for increasing strength properties of pine and *gmelina* wood from community forest. *Journal of the Korean Wood Science and Technology*, 47 (4): 418-424. <https://doi.org/10.5658/wood.2019.47.4.418>
 86. Zelinka, S.; Altgen, M.; Emmerich, L.; Guigo, N.; Keplinger, T.; Kymäläinen, M.; Thybring, E. E.; Thygesen, L. G., 2022: Review of wood modification and wood functionalization technologies. *Forests*, 13: 1004. <https://doi.org/10.3390/f13071004>
 87. Zhao, M.; Yang, L., 2025: Free drying shrinkage of wood: a review. *BioResources*, 20 (3): 7890. <https://doi.org/10.15376/biores.20.3.Zhao>
 88. ***British Standards Institution, 1957: *Methods of Testing Small Clear Specimens of Timber*. London, BSI.
 89. ***Peraturan Konstruksi Kayu Indonesia, 1961: *Bandung*, Indonesia, Departemen Pembangunan Umum.

Corresponding address:

KIDUNG TIRTAYASA PUTRA PANGESTU

Hasanuddin University, Faculty of Forestry, Department of Forestry, Perintis Kemerdekaan Street, Makassar, INDONESIA, e-mail: kidung_pangestu@unhas.ac.id