Pertanika J. Sci. & Technol. 32 (S5): 149 - 166 (2024)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Potential Utilisation of Solar-Assisted Kiln Dryer in Bamboo Drying

Zahidah Zafhian[1,2]*, Adlin Sabrina Muhammad Roseley[2,3], Sik Huei Shing[1], Ong Chee Beng[1] and Zairul Amin Rabidin[1]

[1]Forest Product Division, Forest Research Insitute Malaysia, 52109 Kepong, Selangor, Malaysia
[2]Faculty of Forestry and Environment, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
[3]Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

ABSTRACT

Bamboo is increasingly used as an alternative material for producing renewable and environmentally friendly products. Bamboo should be dried before use to increase its stability and improve its resistance against biodeterioration agents. The most common drying method for bamboo is through air-drying. Alternatively, artificial drying, such as solar drying, can produce optimum drying results regarding the drying rate and quality of bamboo throughput. This study investigated the potential utilisation of solar drying methods for processing local bamboo. The drying characteristics and physical and mechanical properties of solar-dried *Gigantochloa levis* bamboo culms' bottom, middle, and top sections were determined. The drying time of *G. levis* culm has been reduced to about 40 days compared to the conventional air drying of 70 days using the solar-assisted kiln dryer. Solar-dried culms have a lower final moisture content of 20% than air-dried ones. The average circumference and diameter shrinkage values of solar-dried *G. levis* culms from green to approximately 12% moisture content were 3.22% and 4.29%, respectively, and the wall thickness shrinkage was 8.12%. The mean values of modulus of rupture and modulus of elasticity of solar-dried *G. levis* culm were 63.75 and 12567.99 N mm^{-2}, respectively, while its mean values of compression and shear parallel to fibre were 45.87 and 10.01 N mm^{-2}, respectively. The quality of solar-dried *G. levis* culms produced in this study showed the viability of using a solar-assisted kiln-dryer as a potential alternative processing method for drying local bamboo species in Malaysia.

Keywords: Bamboo, density, drying, mechanical, moisture content, shrinkage, solar

ARTICLE INFO

Article history:
Received: 15 March 2024
Accepted: 02 August 2024
Published: 30 October 2024

DOI: https://doi.org/10.47836/pjst.32.S5.08

E-mail addresses:
zahidah@frim.gov.my (Zahidah Zafhian)
adlin@upm.edu.my (Adlin Sabrina Muhammad Roseley)
sik@frim.gov.my (Sik Huei Shing)
ongcb@frim.gov.my (Ong Chee Beng)
zairul@frim.gov.my (Zairul Amin Rabidin)
*Corresponding author

ISSN: 0128-7680
e-ISSN: 2231-8526

INTRODUCTION

Bamboo is classified as a monocotyledon plant in the larger grass family of Poaceae and subfamily Bambusoidae (Singhal et al., 2018). About 36.8 million hectares of bamboo plantation area with about 100 genera and over 1500 bamboo species were reported worldwide (Xu et al., 2020). In the Asia country region, the bamboo plantation area was dominated by China, followed by Japan, India, Indonesia, Philippines, Myanmar, and Vietnam (Li & He, 2019). Malaysia has about 0.6 million hectares of bamboo plantation, whereby 31% are in Peninsular Malaysia, 45% in Sarawak, and 24% in Sabah (Kamaruzaman et al., 2016). About 70 bamboo species are reported in Malaysia, and the most commonly exploited bamboo species are *Gigantochloa scortechinii, Gigantochloa levis* and *Dendrocalamus asper* (Azmi & Appanah, 1995).

Bamboo is known as the fastest-growing woody plant in the world and can reach maturity as early as 3 to 4 years old. Bamboo has become one of the most important lignocellulosic materials in the timber-based industry. Bamboo is regarded as a sustainable, highly renewable, and environmentally friendly resource material that has the potential to replace wood in the future. Due to its fast-growing characteristics, satisfactory strength properties, and flexibility for diverse products, bamboo has been accepted as an alternative resource that can offer great potential to contribute to Malaysia's economic growth.

Bamboo is traditionally used as a household utensil for chopsticks, toothpicks, joss sticks, skewers, poultry cages, and handicrafts. With the advancement of technology and innovation in bamboo processing techniques, bamboo is increasingly used for structural materials in housing and building construction, such as scaffolding, bridges, poles, purlins, and fencing (Azreena et al., 2016). Furthermore, developing engineered products from bamboo, such as laminated bamboo, plybamboo, and reconstituted densified bamboo board, has led to the increasing demand to produce value-added products such as laminated wall panels, beams, and high-end furniture.

Bamboo's physical and mechanical properties are reported to be comparable to selected tropical hardwood species. According to Abdullah Siam et al. (2019), the density of selected commercial bamboo species ranged from 355–751 kg/m^{-3}, approximately equivalent to light hardwood timber species (400 to 720 kg/m^{-3}). Meanwhile, the Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) of 4-year-old *Schizostachyum zollingeri* bamboo are 143 Nmm^{-2} and 9717 Nmm^{-2}, respectively which is comparable to the MOR and MOE of selected plantation timber species such as *Acacia mangium* and *Hopea odorata* (Mohamad Omar & Mohd Jamil, 2011; Mohamad Omar & Khairul, 2020).

Drying removes water molecules from the material through evaporation and then moves them to the ambient air. Drying is integral in the timber-based processing sector as it determines the production capacity and revenue generated by the mills. Drying could enhance the quality of bamboo by increasing its dimensional stability and improving its resistance against biological degradation. Well-dried bamboo is stronger and has better glueing and finishing quality than wet bamboo (Liese & Tang, 2015). In general, the rate of drying is mainly influenced by its structural features, density, culm wall thickness, and the presence of internodes (Liese & Tang, 2015; Tang et al., 2013). The drying rate of young culms is generally faster than mature ones, and bamboo splits dry faster than the culms (Vetter et al., 2015).

Generally, air drying is the most common drying method for bamboo practised worldwide. According to Vetter et al. (2015), air drying of round bamboo takes about 6–12 weeks, and the drying duration depends on the initial moisture content of the bamboo, the environmental conditions, and the wall thickness. However, air drying involves a long drying time and depends on weather conditions. Furthermore, there is a high risk of fungal and insect attack, which causes decay and discolouration of the bamboo.

The use of environmentally friendly and energy-saving resources such as solar energy has been increasingly discussed as solar energy has a low impact on environmental pollution and involves a low operation cost. Solar drying kilns are widely used in the agricultural and food industries, where low drying temperatures and short drying cycles are required (Teussingka et al., 2023). Solar drying may become a potential technology for major energy saving because of its simplicity, ease of operation, and low cost (Sattar, 1992), especially in bamboo drying. Furthermore, solar drying is conducted in a controlled environment chamber, which offers a faster drying time with enhanced-quality bamboo throughput compared to conventional air-drying methods.

Research on the solar drying of bamboo, an important alternative to timber in the construction and furniture manufacturing industries, is still scarce, especially in Malaysia. Thus, a study was conducted to assess the potential utilisation of solar-assisted kiln dryers to improve the processing technique and treatment of bamboo in Malaysia. This study evaluated the drying characteristics and quality of solar-dried *Gigantochloa levis* bamboo culms regarding their physical and mechanical properties. The findings obtained may serve as a guide in optimising the bamboo processing technique through solar drying methods, which could contribute to the development of bamboo applications in Malaysia.

MATERIALS AND METHODS

Sampling

The material used for this study was 4-year-old *Gigantochloa levis* (Beting) bamboo culm obtained from Sungai Lui, Hulu Langat, Selangor, Malaysia. The bamboo culms were cut into nine meters long and then cut equally into three sections of three meters in length, i.e., top, middle and bottom. The dimensions of each bamboo culm were measured for its diameter, wall thickness, and internode length.

Solar-assisted Kiln Dryer

The solar-assisted kiln dryer established at Forest Research Institute Malaysia (FRIM) Kepong, Selangor, Malaysia, has a dimension of 6 x 3 x 4 meter (length x height x width) with a capacity of up to 24 tons or 34 m^3 (Figure 1). The greenhouse-concept drying kiln was made of a stainless-steel frame structure and covered with two layers of transparent ultraviolet (UV) plastic anchored on the concrete foundation. A black-coloured fabric-like material is fitted under the transparent plastic as a heat absorber from solar radiation. It will help to increase the temperature inside the kiln. The kiln was equipped with three industrial-sized fans, each operating at 1 horsepower respectively. The fans were mounted on a plywood wall to circulate heated air uniformly throughout the chamber. The kiln was equipped with an exhaust fan to effectively remove excess moisture from the chamber and transfer it to the surrounding air. The kiln's monitoring system was equipped with a proportional integral derivative (PID) kiln control instrumentation to efficiently monitor temperature and relative humidity during drying.

Solar Drying of Bamboo

Approximately 5 m^3 of freshly *G. levis* bamboo culms, each 3 meters long, were dried in a solar-assisted kiln dryer. Before the commencement of the drying trial, ten per cent sampling methods were carried out based on the total kiln charge, whereby the bamboo culms were randomly selected from the stacks as sample boards. The dimension of each sample board was measured for its diameter, wall thickness, and circumference. The sample boards' initial moisture content (MC) was determined according to the Indian Standards Institution (Anonymous, 1976), whereby a 20 x 20 mm strip was cut from the edge of each sample board. Each MC strip was weighed before and after drying in an oven of temperature 103 ± 2°C for 24 hours. The initial MC of each sample board was calculated based on the formula (1):

$$\text{Moisture content, MC (\%)} = \left(\frac{W_g - W_o}{W_o}\right) \times 100 \quad (1)$$

Where W_g is the weight (g) of the specimen in green condition, and W_0 is the specimen's oven-dry weight (g).

The sample boards were placed within the bamboo stacks. The drying process was monitored by weighing the sample boards daily until they reached a constant weight. The oven-dry weight (W_0) and current moisture content (MCc) of the sample board were estimated based on the formulas (2) and (3):

$$\text{Oven dry weight}, W_o\,\text{(kg)} = \frac{W_g \text{ x } 100}{\text{MC} + 100} \quad (2)$$

$$\text{Current moisture content, } MC_c\ (\%) = \left(\frac{W_c - W_o}{W_o}\right) \times 100 \quad (3)$$

Where W_g is the initial weight (kg) of the sample board, MC is the moisture content (%) of the MC specimen, and W_c is the current weight (kg) of the sample board.

The air velocity in the solar kiln was measured using a digital anemometer. The kiln's temperature and relative humidity readings were recorded regularly using a psychrometer consisting of dry bulb and wet bulb thermometers. The relative humidity was calculated based on wet bulb depression (subtracting the temperature of the wet-bulb thermometer from the temperature on the dry-bulb thermometer) and dry bulb temperature. Air drying of *G. levis* culms was also conducted by stacking the bamboo on an open site under the shed.

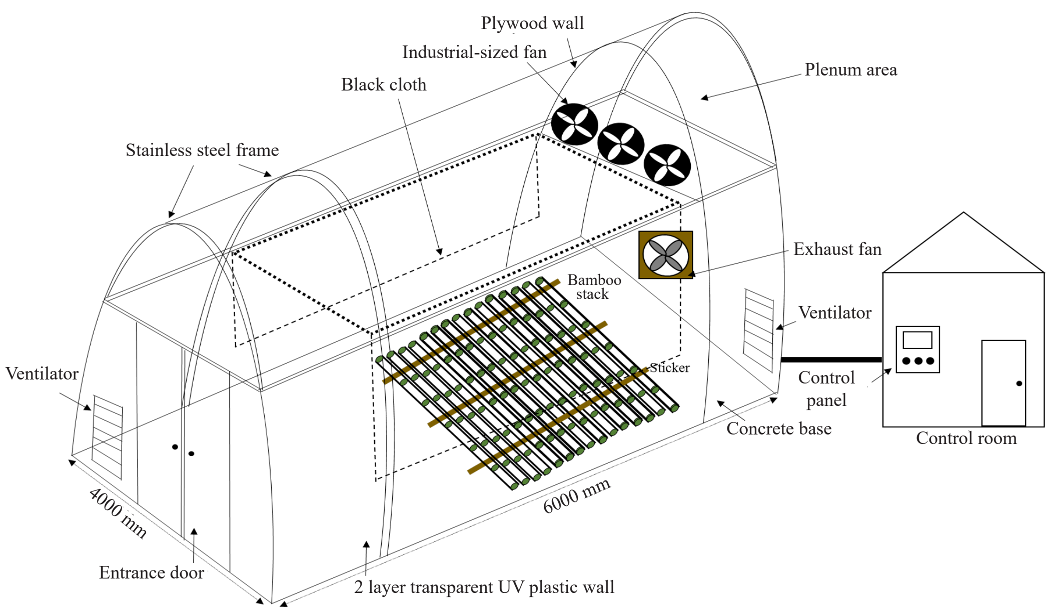


Figure 1. Schematic diagram of solar-assisted kiln dryer

Assessment of Dried Sample

After the completion of the drying trial, the final MC and dimension of the sample boards were determined, and the estimated current moisture content of the sample boards was normalised accordingly. Specimens measuring 20 mm x 20 mm x culm wall thickness (mm) were obtained from the dried bamboo culms' bottom, middle, and top sections to determine final moisture content and density according to the Indian Standards Institution (Anonymous, 1976). A total of 30 specimens were used in the test. The density (ρ) of each specimen was calculated using formula (4):

$$\text{Density, } \rho \text{ (kgm}^{-3}\text{)} = \frac{W_g}{V_g} \quad (4)$$

Where W_g is the weight (kg), and V_g is the volume (m^3) of the specimens.

The shrinkages (%) of the dried culms were calculated from the initial and final dimensions of the sample board using formula (5):

$$\text{Shrinkage, } \beta \text{ (\%)} = \frac{D_g - D_0}{D_g} \text{ X } 100 \quad (5)$$

Where D_g is the corresponding circumference, diameter, and thickness dimensions (mm) of the green culms and D_0 is the corresponding circumference, diameter, and thickness dimensions (mm) of the dried culms.

Mechanical Properties Test

The bottom, middle, and top sections of the solar-dried *G. levis* bamboo culms were cut based on specific dimensions for mechanical testing following ISO 22157:2019(E). A total of 30 bamboo culms samples comprising the bottom, middle, and top sections were used in each test. The static bending test included Modulus of Rupture (MOR), a measure of maximum strength that a bamboo material can withstand, and Modulus of Elasticity (MOE), a measure of the stiffness of the bamboo culms. A 3-point static bending test was conducted by subjecting the specimen of 3 meters in length to load heads that move at a constant speed of 8 mm min^{-1} and span of 2.3 m (Figure 2). Compression parallel to fibres and shear parallel to fibres tests for both node and internode specimens of 70 mm in length were performed by applying load at a constant rate movement of 0.6 mm min^{-1} and 0.4 mm min^{-1}, respectively.

Figure 2. Arrangement for 3-point static bending test of 3-meter-long bamboo culms

Statistical Analysis

Statistical analysis was conducted using one-way analysis of variance (ANOVA) to determine the significant variation of physical and mechanical properties of dried bamboo culm at different height positions.

RESULTS AND DISCUSSION

Green Moisture Content (MC)

The average green MC of *G. levis* culm in the present study was 104.13% (50.25–147.33%). The green MC at the bottom section ranged from 116.79 to 147.33%, averaging 130%. The average green MC of the middle and top culms was 99.15% and 83.24%, with range values of 67–116.55% and 50.25–118.55%, respectively. Based on all samples tested, the green MC decreased from the bottom towards the top parts of the culm, and the variation was significantly different at $p > 0.5$.

The green MC range of *G. levis* culms was substantially comparable to India's green MC bamboo *Dendrocalamus strictus* (Wakchaure & Kute, 2012). The freshly cut bamboo culms were reported to have MC from 70 to 150%, with an average value of 103%. The findings in the recent study align with Vetter et al. (2015). He found that the *Bambusa vulgaris* MC from Brazil decreased vertically from bottom to top. Furthermore, Wakchaure and Kute (2012) reported that the MC of 3-year-old *Dendrocalamus strictus* from India varies along the culm height, with the top portions having consistently lower moisture content than the middle or bottom. The green MC of Malaysian bamboo is also highest near the bottom part (Azmi & Appanah, 1995). Age, anatomical structure, species, and harvesting season influence the difference in MC from the bottom to the top. Furthermore, bamboo is a heterogeneous material with different cellular structures and chemical compositions, which may affect its moisture sorption behaviour.

Drying Characteristic

Gigantochloa levis culms were dried in a solar kiln at 30 to 50°C and relative humidity of 50.7 to 86.3%, respectively (Figure 3). The solar kiln exhibited a higher temperature than the ambient temperature (Figure 4) because the solar kiln is equipped with appropriate drying equipment, such as a fan and ventilator, to effectively remove excess moisture to the surroundings and facilitate the circulation of heated air throughout the kiln. The relative humidity of the solar kiln decreases with an increase in the temperature due to the increment of the water-holding capacity of the air (Simo-Tagne et al., 2018). The increase in temperature will subsequently decrease the equilibrium moisture content and cause the moisture to be removed from the bamboo and transferred to the surroundings (Sasongko et al., 2020).

Gigantochloa levis culms could dry from an average initial MC of 95.63% to approximately 12.23% in 43 days, with a moisture loss rate of 1.9% per day (Figure 5). Based on the drying curve, the drying rate below the fibre saturation point (FSP) from 18 to 10% MC was 0.02%/h and varies according to the height position. In comparison, the drying rate above FSP is faster by more than 80% with a drying rate of 0.14%/h. *G. levis* was found to be able to dry uniformly along the culm, and the variation of final MC between height positions was within the permissible range of 3.5% (Table 1). Therefore, the drying of *G. levis* culms can be performed in one kiln charge without pre-sorting according to a specific height before drying.

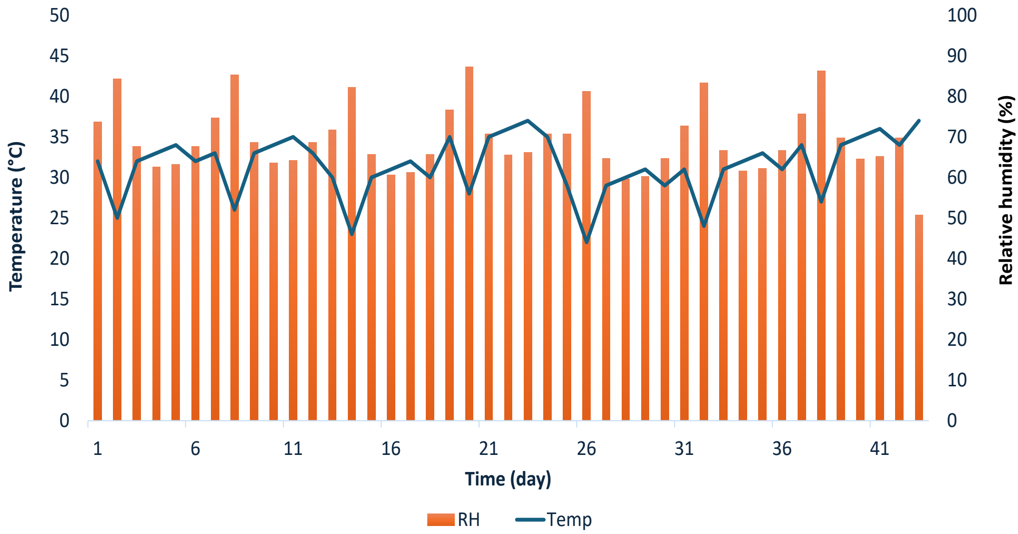


Figure 3. Temperature and relative humidity of the solar kiln during drying trial

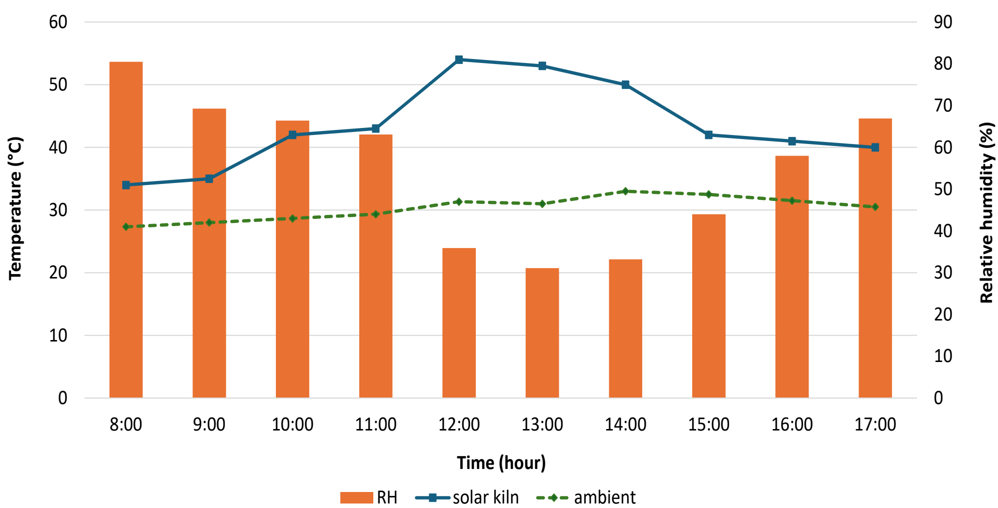


Figure 4. Ambient and solar kiln temperature

The solar drying method reduces the drying time of *G. levis* culms by approximately 40% compared to the air-drying method (Figure 6). In addition, solar-dried culms have a lower final moisture content of 20% compared to air-dried culms, which are suitable for indoor applications (Table 2). Significant drying defects were not observed in solar-dried bamboo culms. However, slight end checks and bowing were observed in 11% of the culms. No other defects, such as cupping, surface checking, and twisting, were observed in all

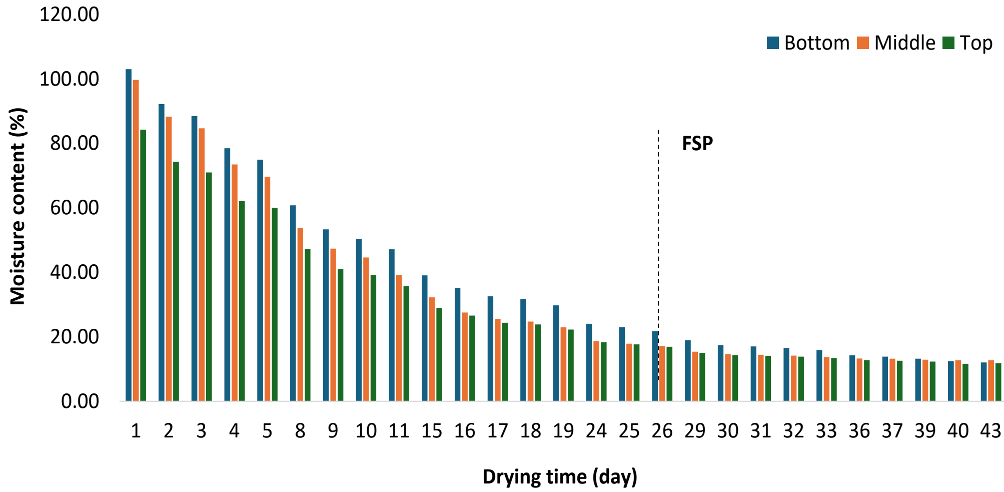


Figure 5. Drying time and moisture content of *Gigantochloa levis* at different height positions during the solar drying process

Table 1
Final moisture content and density of solar-dried G. levis *culms*

Final moisture content (%)				
Height position	Bottom	Middle	Top	Overall
Mean	13.37 (1.01)	12.92 (0.33)	12.35 (1.02)	12.88 (0.79)
Range	11.67–14.99	12.16–13.38	11.34–14.06	11.34–14.99
Density (kg m^{-3})				
Mean	657 (53) [a]	643 (87) [b]	754 ± (105) [c]	685 (82)
Range	579–731	512–797	573–884	512–884

Figures in parentheses are standard deviations. The values with different superscript letters in each row are significantly different ($p > 0.05$)

culms. Bowing and end checks could be attributed to the excessive and non-uniform water movement from the inner to the outer part of the culms. In addition, no sign of fungal and insect attacks was observed in all solar-dried bamboo culm. Air-dried *G. levis* culms show some observable fungal attacks, especially for the sample located at the bottom stacks, due to the prolonged exposure to humid conditions where low ventilation and uneven air flow through the stacks have slowed down the process of moisture loss from the bamboo, which subsequently encourages the growth of fungi.

The bamboo culms could achieve a lower equilibrium moisture content (EMC) than the air-drying method using a solar drying kiln. The solar drying method could dry the bamboo up to 10–12% MC, which is the MC that the air-drying process could not achieve. Solar-dried bamboo has a lower MC than air-dried bamboo, which is suitable for fabricating

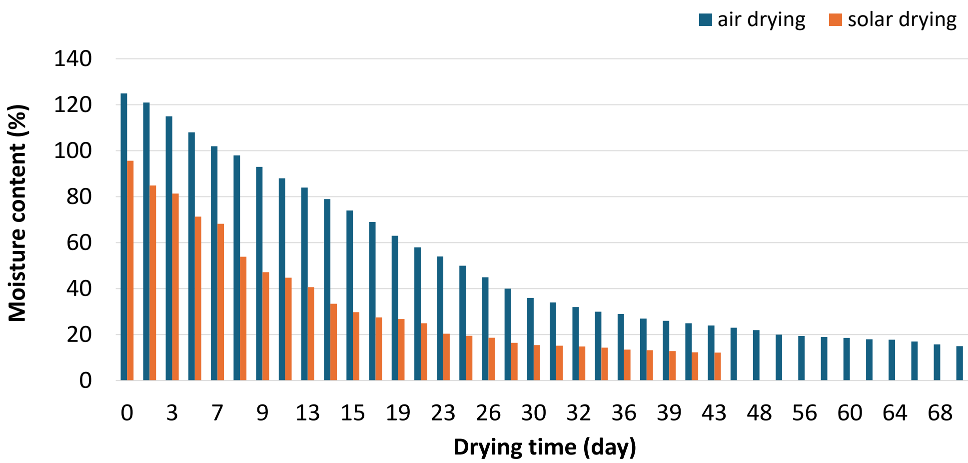


Figure 6. The drying curve of *Gigantochloa levis* dried using solar drying and air-drying methods

Table 2
Drying characteristics of G. levis *culms*

Condition	Initial MC (%)	Final MC (%)	Drying time (days)
Solar-dried	95.63	12.23	43
Air-dried	97.64	15.64	70

bamboo products intended for indoor applications such as furniture components and souvenirs, as well as value-added products such as laminated ply bamboo. Solar drying is more efficient than air drying in terms of drying time. Since the solar kiln was equipped with proper ventilation and heat-trapping system for efficient heat generation and optimum air circulation throughout the drying process, the drying time of the bamboo culms could be reduced effectively. Furthermore, the solar drying method could enhance the quality of bamboo culms by protecting against biological deterioration attacks such as fungi and mold. Moreover, the drying defects, such as splits and checks in bamboo, could be reduced with the solar drying method due to the reduction of temperature at night, which would exhibit a mild reconditioning treatment, which encourages bamboo to release stress accumulated during the day (Haifaa et al., 2004).

Density

The density of solar-dried *G. levis* culms ranged from 512 to 884 kg m^{-3} with a mean value of 685 kg m^{-3} (Table 1). The density decreased slightly from the bottom to the middle and increased towards the top of the culms, but the value was not significantly different at $p < 0.05$. Generally, the density of bamboo tends to increase with height (Santhoshkumar &

Bhat, 2014; Zakikhani et al., 2017). This trend may be associated with the increase in the proportion of vascular bundles, silica content, and sclerenchyma fibres with culm height (Correal & Arbelaez, 2010; Wang et al., 2016). Furthermore, increased density could also be attributed to increased fibres to parenchyma ratio from the bottom upwards (Vetter et al., 2015).

Shrinkage

The shrinkage value of solar-dried and air-dried *G. levis* culms is presented in Table 3. The average circumference and diameter shrinkage values of solar-dried *G. levis* culms from green to approximately 12% moisture content were 3.22% and 4.29%, respectively. Meanwhile, the solar-dried culm has a wall thickness shrinkage of 8.12%. In this study, the bottom, middle, and top sections of solar-dried bamboo culms have a significantly ($p > 0.05$) lower shrinkage value of approximately 10 to 40% compared to air-dried culms. Solar kilns could maintain a higher humidity during the early drying stage by evading moisture from the bamboo material (Sattar, 1994). The high humidity could retard the drying process and provide a conditioning treatment to the bamboo, which could minimise the occurrence of shrinkage during the drying process.

Table 3
Shrinkage values of air-dried and solar-dried G. *levis bamboo culm*

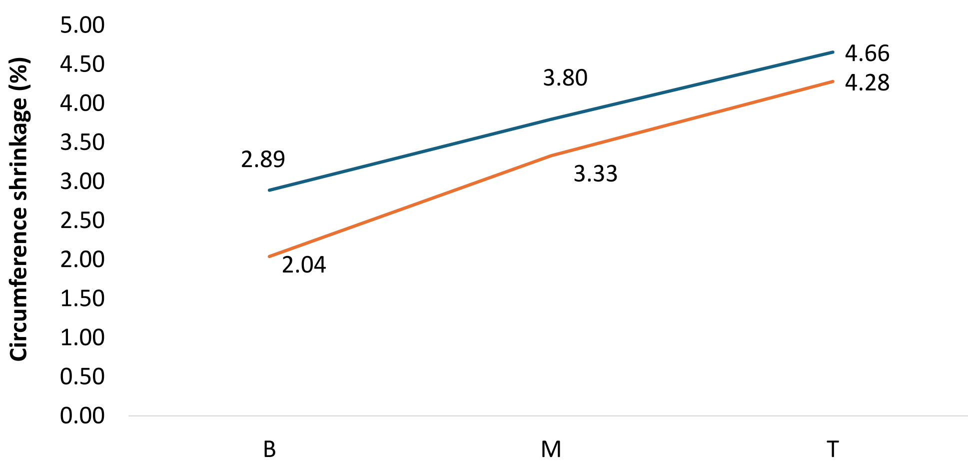
Condition	Height position		Shrinkage (%)		
			Wall thickness	Circumference	Diameter
Air-dried	Bottom	Mean	9.25	2.89	8.26
			(5.88)	(1.00)	(5.18)
		Range	2.13–18.15	1.41–4.69	3.56–20.16
	Middle	Mean	11.41	3.80	7.05
			(8.92)	(4.31)	(5.25)
		Range	2.33–29.06	0.00–13.64	0.00–17.07
	Top	Mean	13.21	4.66	5.83
			(8.74)	(4.86)	(3.96)
		Range	4.23–28.76	0.00–13.37	1.34–12.38
	Overall	Mean	10.89	3.60	7.30
			(7.90)	(3.57)	(5.06)
		Range	2.13–29.06	0.00–13.64	0.00–20.16
Solar-dried	Bottom	Mean	4.99	2.04	6.39
			(2.08)	(1.63)	(6.87)
		Range	2.38–7.46	0.00–(3.99)	1.34–16.10

Table 3 *(Continue)*

Condition	Height position		Shrinkage (%)		
			Wall thickness	Circumference	Diameter
	Middle	Mean	8.18	3.33	4.14
			(1.33)	(1.69)	(2.85)
		Range	6.30–9.17	1.89–5.69	1.20–8.00
	Top	Mean	11.18	4.28	2.34
			(5.32)	(0.44)	(1.86)
		Range	4.40–(17.39)	3.92– 4.90	0.00–(4.55)
	Overall	Mean	8.12	3.22	4.29
			(2.91)	(1.25)	(3.86)
		Range	2.38–17.39	0.00–5.69	0.00–16.10

Values in parentheses are standard deviations

The culm wall thickness and circumferences shrinkage tend to increase from the bottom to the top part of the culms for both drying methods. Meanwhile, the diameter shrinkage shows an opposite trend. The bottom part reported the highest diameter shrinkage value compared to other parts. Meanwhile, the top part showed the highest wall thickness and circumference shrinkage value, followed by the middle and bottom parts (Figure 7). Based on the statistical analysis, shrinkage variation within the culm height was not significantly different ($p > 0.05$).



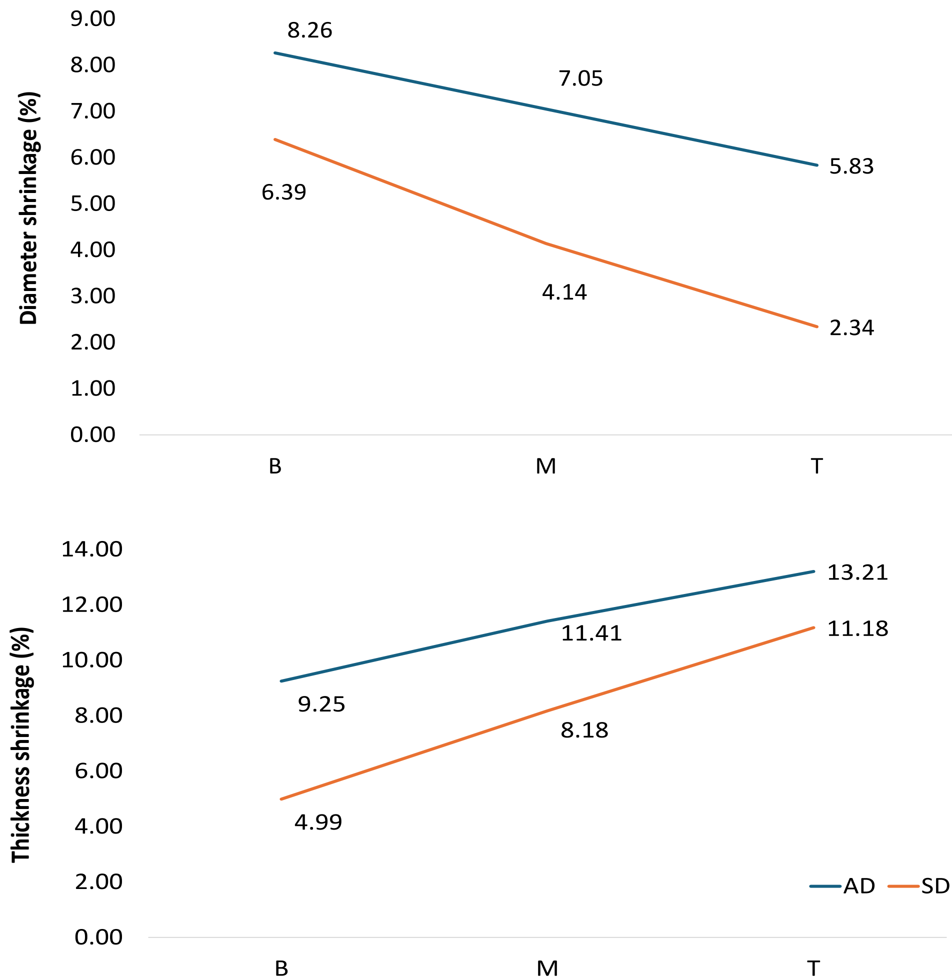


Figure 7. Variation of shrinkage of air-dried (AD) and solar-dried (SD) *Gigantochloa levis* culms at different height positions (B = bottom, M = middle, T = top)

Like wood, bamboo starts to shrink and change in dimension when it reaches its fibre saturation point (FSP). The shrinkage in diameter is higher at the bottom parts, probably due to higher initial moisture content (Rehman & Ishaq, 1947). Thus, proper drying practices must be implemented to avoid excessive shrinkage of bamboo culm, which may lead to severe warping, such as bowing and splits. The top part experiences a higher wall thickness and circumference shrinkage due to the higher number of vascular bundles in the top section compared to the bottom and middle sections. The condition is further compounded by the distribution of fibre that increases from the inner layer towards the outer layer of the bamboo culm wall (Azedah & Ghavami, 2018). Due to the different volume fractions of fibres at the internal and external sides of bamboo at the transversal cross-section, the trend of non-uniform shrinkage of the wall thickness and circumference was observed along the culm's height.

Mechanical Properties

Table 4 shows the mechanical properties of solar-dried *G. levis* culms. Three-point static bending test results showed the mean values of modulus of rupture (MOR) and modulus of elasticity (MOE) were 63.75 and 12567.99 N mm^{-2}, respectively. The mean values for compression and shear parallel to fibre were 45.87 and 10.01 N mm^{-2} under the required test condition.

Table 4
Mechanical properties of solar-dried G. levis *bamboo culms*

Mechanical properties	Bottom	Middle	Top	Overall	*p*-value
MOR (N/mm^2)	66.89	51.62	72.75	63.75	0.082
	(18.82)	(22.41)	(28.94)	(23.39)	ns
MOE (N/mm^2)	12896.08	10248.24	14559.66	12567.99	0.037
	(2298.03)	(3707.01)	(5570.77)	(3858.60)	s
Compression (without nodes)	49.69	41.04	45.89	45.54	0.079
(N/mm^2)	(9.04)	(13.50)	(8.54)	(10.36)	ns
Compression (with nodes)	50.52	40.87	47.20	46.20	0.095
(N/mm^2)	(9.23)	(11.98)	(9.97)	(10.39)	ns
Shear (without nodes)	10.35	8.23	9.22	9.27	0.077
(N/mm^2)	(2.44)	(2.08)	(2.15)	(2.22)	ns
Shear (with nodes)	11.48	9.83	10.94	10.75	0.341
(N/mm^2)	(3.72)	(2.71)	(1.84)	(2.76)	ns

Figures in parentheses are standard deviations. MOR = modulus of rupture; MOE: modulus of elasticity; ns = not significant; s = significant at $p < 0.05$

The analysis showed the MOR and MOE value of solar-dried *G. levis* was highest at the top, followed by the bottom and middle sections of the culms. Meanwhile, the compression and shear values were highest at the bottom, followed by the top and middle sections due to the variation of density, physical dimension, and size and the number of vascular bundles along the culm height and across the culm wall (Liese & Köhl, 2015). Awalluddin et al. (2017) and Daud et al. (2018) reported that the compression and shear values of round betung bamboo (*Dendrocalamus asper*), minyak bamboo (*Bambusa vulgaris*), semantan bamboo (*Gigantochloa scortechinii*) and semeliang bamboo (*Schizostachyum grande*) was highest at the top section followed by middle and bottom parts of the culms. The MOR, compression, and shear values did not vary significantly ($p > 0.05$) between the bottom, middle, and top sections except for MOE. The sample tested with nodes showed a higher compression and shear value than those without nodes. However, the result was not significantly different. The presence of nodes can influence the tensile strength of bamboo and engineered bamboo lumber by preventing the propagation of splits and buckling during services (Liu et al., 2021).

The mechanical properties of solar-dried *G. levis* bamboo culms were compared with previously published data on air-dried bamboo culms. The mean values of MOR, compression, and shear parallel to the fibres of solar-dried samples obtained in this study were slightly higher compared to other Malaysian bamboo species in air-dried conditions (Awalluddin et al., 2020; Awalluddin et al., 2017; Daud et al., 2018). Furthermore, the mean shear value of solar-dried culms obtained in this study is higher by approximately 20% compared to air-dried *G. levis* culms reported by Mohd Tamizi (2010). The finding showed that solar-dried *G. levis* had better mechanical properties than air-dried bamboo. This improvement could be due to the densification and chemical modification of the bamboo during the solar drying process. Studies on wood dried under controlled environments such as kiln drying and solar drying also revealed better mechanical properties than wood dried using air drying (Jacket et al., 2014; Samson et al., 2021; Uetimane, 2020). Overall, the solar-dried bamboo culms reported in this study have good mechanical properties and are suitable to be fabricated into furniture components and laminated bamboo products.

CONCLUSION

The solar-assisted kiln dryer used in this study reduced the drying time of *G. levis* culms by approximately 40% compared to the air-drying method. The drying time of *G. levis* culms has been reduced to 40 days compared to the conventional air-drying time of about 70 days. Solar-dried culms have a lower final moisture content of 20% compared to air-dried culms, which are suitable for indoor applications. Overall, the solar drying method enhances the quality of *G. levis* culms. The incidence of significant drying defects, such as cupping, surface checking, and twisting, as well as a sign of fungal and insect attacks, were not observed in all culms. Solar-dried bamboo has a significantly lower shrinkage value of approximately 10 to 40% compared to air-dried culms. The solar-dried *G. levis* culms have mechanical properties comparable to those of the air-dried sample in terms of static bending, compression, and shear parallel to the fibre. The quality of solar-dried bamboo culms produced in this study indicates the viability of using solar-assisted kiln dryers to produce quality bamboo materials for further fabrication into value-added products.

ACKNOWLEDGEMENT

The authors express their gratitude to the Ministry of Natural Resources, Environment and Climate Change (NRECC) Malaysia for funding this project.

REFERENCES

Abdullah Siam, N., Uyup, M. K. A., Husain, H., Mohmod, A. L., & Awalludin, M. F. (2019). Anatomical, physical and mechanical properties of thirteen malaysian bamboo species. *Bioresources*, *14*(2), 3925-3943. https://doi.org/10.15376/biores.14.2.3925-3943

Anonymous. (1976). *Indian standard methods of tests for split bamboos*. Indian StandardsInstitution, New Delhi, India.

Anonymous. (2019). *ISO 22157:2019 (E). Bamboo structures – Determination of physical and mechanical properties of bamboo culms-test methods.* International Organisation for Standardisation, Geneva.

Awalluddin, D., Ariffin, M. A. M., Osman, M. H., Hussin, M. W., Ismail, M. A., Lee, H. -S., & Lim, N. H. A. S. (2017). Mechanical properties of different bamboo species. *MATEC Web of Conferences*, *138*, 1-10. https://doi.org/10.1051/matecconf/201713801024

Awalluddin, D., Ariffin, M. A., Zamri, N.F., Ahmad, Y., Ibrahim, I. S., Osman, M. H., & Lee, H. -S., & Lim, N. H. A. S. (2020). Tensile and shear strength of four species of bamboo in Malaysia*. IOP Conference Series: Materials Science and Engineering*, *849*(1), 012041. https://doi.org/10.1088/1757-899X/849/1/012041

Azadeh, A., & Ghavami, K. (2018). The influence of heat on shrinkage and water absorption of *Dendrocalamus giganteus* bamboo as a functionally graded material. *Construction and Building Materials, 186*,145-154. https://doi.org/10.1016/j.conbuildmat.2018.07.011.

Azmy, H. M., & Appanah, S. (1995). *Bamboo resources conservation and utilization in Malaysia* (pp. 1-13). Forest Research Institute Malaysia (FRIM).

Azreena, A. K., Parid, M., Hazmira, M., Mukrimah, A., Hamdan, H., Lim, H. F., Izani, I.,Othman, D., & Norliyana, A. (2016, September 27-29). Potential of bamboo based industry in Peninsular Malaysia. *Proceeding of the Asean Bamboo Symposium 2016* (pp.20). Kuala Lumpur, Malaysia.

Correal, J. F., & Arbelaez, C. J. (2010). Influence of age and height position on Colombian *Guadua angustifolia* bamboo mechanical properties. *Maderas. Cienciay Tecnología, 12*(2), 105-113. https://doi.org/10.4067/S0718-221X2010000200005

Daud, N. M., Nor, N. M., Yusof, M. A., Al Bakhri, A. A. M., & Shaari, A. A. (2018). The physical and mechanical properties of treated and untreated *Gigantochloa scortechinii* bamboo. *AIP Conference Proceedings*, *1930*(1), 020016. https://doi.org/10.1063/1.5022910

Haifaa, K., Helwa, N. H., Enayet, M. M., & Hashish, M. I. (2004). Optimization of solar kiln for drying wood. *Drying Technology, 4*(4), 677-701. https://doi.org/10.1081/DRT-120034257

Jacket, B., Machet, W., & Aleksandra, K. (2014). The change of mechanical properties of selected wood species after the drying process under various conditions. *Forestry and Wood Technology*, *86*, 13-17.

Kamaruzaman, O., Mahpar, A., & Mohamad Zamakhsary, M. (2016, September 27-29). Credit opportunity for bamboo plantation in Malaysia. *Proceeding of the Asean Bamboo Symposium 2016* (pp.5). Kuala Lumpur, Malaysia.

Li, W., & He, S. (2019). Research on the utilization and development of bamboo resources through problem analysis and assessment. *IOP Conference Series: Earth and Environmental Science*, *300*(5), 052028. https://doi.org/10.1088/1755-1315/300/5/052028

Liese, W., & Tang, T. K. H. (2015). Preservation and drying of bamboo. In W. Liese, & M. Köhl (Eds.), *Bamboo, Tropical Forestry 10* (pp. 257-297). Springer International Publishing Switzerland. https://doi.org/10.1007/978-3-319-14133-6_9

Liese, W., & Köhl, M. (Eds.). (2015). *Bamboo - The plant and its uses. Tropical forestry.* Springer International Publishing Switzerland. https://doi.org/10.1007/978-3-319-14133-6

Liu, P. C., Zhou, Q. S., Fu, F. Y., & Li, W. (2021). Effect of bamboo nodes on the mechanical properties of P. edulis (*Phyllostachys edulis*) bamboo. *Forests, 12*(10), 1309. https://doi.org/10.3390/f12101309

Mohamad Omar, M. K., & Mohd Jamil, A. W. (2011). Mechanical properties. In S. C. Lim, K. S. Gan & Y. E. Tan (Eds.), *Properties of Acacia Mangium planted in Peninsular Malaysia*. *ITTO Project on Improving Utilisation and Value adding of Plantation Timbers from Sustainable Sources in Malaysia Project No. PD 306/04 (1)* (pp. 23-45). Forest Research Institute Malaysia.

Mohamad Omar, M. K., & Khairul, M. (2020). Mechanical properties. In A. S. Nordahlia (Eds.), *Wood properties and uses of planted Hopea odorata in Peninsular Malaysia* (pp. 41-48). FRIM Research Pamphlet No. 1*45*. ISBN 978-967-2149-71-2.

Mohd Tamizi. (2010). *Fundamental and characteristic study of cultivated Malaysian bamboo*.[Doctoral dissertation]. Universiti Sains Malaysia.

Rehman, M. A., & Ishaq, S. M. (1947). Seasoning and shrinkage of bamboo. *Indian Forest Records, 4*, 1-22.

Samson, N. U., Zimuzo U., Oji, A. N., Emmanuel, A. E., & Boniface, O. U. (2021). Engineering properties of wood under different drying methods. *Global Journal of Engineering and Technology Advances*, *07*(03), 118-124. https://doi.org/10.30574/gjeta.2021.7.3.0082

Santhoshkumar, R., & Bhat, K. V. (2014). Variation in density and its relation to anatomical properties in bamboo culms, *Bambusa bambos* (L.) Voss. *Journal of Plant Sciences (Science Publishing Group)*, *2*(3), 108. https://doi.org/10.11648/j.jps.20140203.12

Sattar, M. A., Kabir, M. F., & Bhattacharjee, D. K. (1992). Physical and mechanical properties of six important bamboo species of Bangladesh. In S. Zhu, W. Li, X. Zhang, & Z. Wang. (Eds.), *Proceedings of the International Symposium on Industrial Use of Bamboo* (pp. 112-117). Beijing, China.

Sattar, M. A. (1994). Major energy saving by use of solar timber drying in developing countries. *Renewable Energy*, *5*(Part 1), 457-464. https://doi.org/10.1016/0960-1481(94)90414-6

Simo-Tagne, M., Zoulalian, A., Romain Rémond, R., & Rogaume, Y. (2018). Mathematical modeling and numerical simulation of a simple solar dryer for tropical wood using a collector. *Applied Thermal Engineering, 131*,356-369. https://doi.org/10.1016/j.applthermaleng.2017.12.014

Singhal, P., Rudra, S. G., Singh, R. K., Satya, S., & Naik, S. N. (2018). Impact of drying techniques on the physical quality of bamboo shoots: Implications on tribal's livelihoods. *Indian Journal of Traditional Knowledge*, *17*(2), 353-359.

Sosongka, S. B., Hadiyanto, H., & Djaeni, M. (2020). Effects of drying temperature and relative humidity on the quality of dried onion slice. *Heliyon, 6*(7), e04338. https://doi.org/10.1016/j.heliyon.2020.e04338

Tang, T. K. H., Welling, J., & Liese, W. (2013). Kiln drying for bamboo culm parts of the species Bambusa stenostachya, *Dendrocalamus asper* and *Thyrsostachys siamensis*. *Journal of the Indian Academy of Wood Science, 10*(1), 26-31. https://doi.org/10.1007/s13196-013-0089-4

Teussingka, T., Simo-Tagne, M., Njankouo, J. M., Betchewe, G., Ndukwu, M. C., Nwakuba, N. R., Bekkioui, N., & Zoulalian, A. (2023). An experimental and theoretical analysis of the dynamic response of solar drying in natural convection under rainy month of Maroua (Cameroon) of three tropical wood species. *Wood Material Science & Engineering*, *18*(5), 1685-1705. https://doi.org/10.1080/17480272.2023.2178030

Uetimane, E. (2020). *Anatomy, drying behaviour and mechanical properties of lesser used wood species from Mozambique* [Doctoral thesis, The Swedish University of Agricultural Sciences]. https://pub.epsilon.slu.se/2356/1/Uetimane_Junior_E_100928.pdf

Vetter, R. E., S á Ribeiro, R. A., S á Ribeiro, M. G., & Miranda, I., P. A (2015). Studies on drying of imperial bamboo. *European Journal of Wood Product*, *73*, 411-414. https://doi.org/ 10.1007/s007/s00107-015-0900-6

Wakchaure, M. R., & Kute, S. Y. (2012). Effect of moisture content on physical and mechanical properties of bamboo. *Asian Journal of Civil Engineering*, *13*(6), 753-763.

Wang, Y., Hui, Z., Yulong, D., Shuguang, W., & Shuyan, L. (2016). Variability of anatomical and chemical properties with age and height in *Dendrocalamus brandisii*. *BioResources, 11*(1), 1202-1213. https://doi.org/ 10.15376/biores.11.1.1202-1213

Xu, Q. F., Liang, C. F., Chen, J. H., Li, Y. C., Qin, H., & Fuhrmann, J. J. (2020). Rapid bamboo invasion (expansion) and its effects on biodiversity and soil processes. *Global Ecology and Conservation*, *21*, e00787. https://doi.org/10.1016/j.gecco.2019.e00787

Zakikhani, P., Zahari, R., Sultan, M. T. H., & Dayang, L. M. (2017). Morphological, mechanical, and physical properties of four bamboo species. *BioResources, 12*(2), 2479-2495. https://doi.org/10.15376/biores.12.2.2479-2495