International Journal of Design & Nature and Ecodynamics
Vol. 20, No. 5, May, 2025, pp. 1059-1068
Journal homepage: http://iieta.org/journals/ijdne

Effect of Drying Methods on Behaviour and Quality of Tamiang Bamboo (*Schizostachyum blumei*) for Drinking Straw Application

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https://doi.org/10.18280/ijdne.200511

Received: 18 January 2025
Revised: 17 April 2025
Accepted: 9 May 2025
Available online: 31 May 2025

Keywords:
air drying, color change, defects, dimension shrinkage, drying rate, drying time, hot-steam air drying, oven drying

ABSTRACT

Tamiang bamboo (*Schizostachyum blumei*) has slender physical characteristics, making it a suitable raw material for drinking straws. It must be dried before being used as a drinking straw. Until now, local industries have air-dried tamiang bamboo, which takes a long time to dry. In order to obtain a suitable drying process for tamiang bamboo, this study was carried out to compare the drying behaviour and quality of tamiang bamboo using air-drying (AD), oven-drying (OD), and hot-steam air-drying (HSD). A constant temperature of 60°C was used for both OD and HSD. The sample length and diameter range were 220 mm and 10–20 mm, respectively. The parameters observed were drying rate, drying time, defects, shrinkage, and color change. The results showed that OD tamiang had the highest drying rate (-5.4×10^{-4} %/min), the shortest drying period (432 minutes), the lowest wall thickness shrinkage (5.71%), and the highest number of straws with cross-section deformation (9 samples). AD tamiang had the lowest diameter shrinkage rate (1.33%), the most prominent color change (ΔE value of 21.05), and the lowest number of straws with cross-section deformation (3 samples). However, more than 50% of the AD samples were attacked by powder beetles and mold. HSD tamiang had the darkest color after drying and showed approximately 4 samples with cross-section deformation. Drying methods significantly affected the drying rate, color changes, diameter shrinkage rate, and wall thickness shrinkage rate of tamiang straws. The findings recommend drying tamiang straws using artificial methods instead of air drying.

1. INTRODUCTION

Bamboo falls under the category of non-timber forest products and belongs to the Poaceae or Gramineae family [1]. It has rapid growth, good mechanical properties, is environmentally friendly, and easy to cultivate [2-4]. This material can be used for furniture, buildings, bridges, etc. [3]. Bamboo can also be utilized as a raw material for musical instruments or drinking straws, such as tamiang bamboo.

Tamiang (*Schizostachyum blumei*) is a species from the *Schizostachyum* genus, which is distributed across various Asian countries, including Indonesia, Myanmar, China, and Thailand [5-7]. The ranges of its culm diameter and length are 10–40 mm and 750–900 mm, respectively [8-11]. This slender physical structure makes tamiang bamboo a suitable raw material for a drinking straw.

Before its use as a drinking straw, the tamiang culm needs to be dried. Fresh bamboo generally has a moisture content range of about 45%–90% [12]. Due to its high moisture content, combined with high starch and sugar content, bamboo is vulnerable to mold and fungal attacks [13]. Natural bamboo also generally has low resistance to insects [3, 4, 14]. It has been reported that tamiang bamboo has moderate natural resistance toward termites' attack (*Coptotermes curvignathus*) [15].

Drying is an important stage required to reduce the moisture content of any biomaterial. This process helps improve the quality of bamboo [16]. Besides reducing the moisture content, drying can also prevent organism attacks and inhibit the growth of microorganisms, thus minimizing deterioration in the biomaterial [2, 16, 17].

Various methods can be used to dry bamboo, from traditional air-drying practice to advanced technology such as kiln drying or microwave drying [18]. Among all methods, air drying remains the simplest and most easily adopted by communities. It utilizes direct sunlight, which keeps operational costs relatively low [10]. Nevertheless, air drying of bamboo generally takes a long time (around 6–12 weeks) and often results in poor quality [19]. Based on the experience of a local small enterprise of bamboo-straw in Yogyakarta province, air-drying of tamiang bamboo can take up to a month to dry, depending on the weather [20].

Since air drying lacks control over drying conditions, excessive drying that leads to cracking may occur, as observed in 6-meter-long, 4-year-old moso bamboos (*Phyllostachys edulis*) [21]. Air drying is also usually carried out in an open field, which could invite unexpected fungal and insect colonization. Considering the weaknesses of air drying and the intended use of tamiang bamboo as a drinking straw, which requires a good level of hygiene, alternative drying techniques need to be explored.

Artificial drying of tamiang bamboo in a dryer, i.e., an oven, offers a potential solution. Convective drying in an oven uses electrical energy, which is converted into heat energy through its heating elements. Therefore, oven drying usually runs faster than air drying [10, 22].

Another potential artificial drying method for tamiang is hot-steam air drying. This particular method uses hot steam as its heat source and has been successfully applied for drying dragon blood's resin and silkworm's cocoon [23, 24]. Hot steam has a long success history as a drying medium in super-heated steam drying practice for food products [25, 26].

Using the hot-steam air drying process can potentially minimize the tendency of bamboo to get cracked/damaged due to excessive drying stress. Due to anisotropic shrinkage and special structural properties of bamboo, inappropriate drying methods may cause many defects such as cracking, charring, or cross-section deformation in bamboo [19]. The use of hot steam in super-heated steam drying has been reported to reduce the development of brown stain and drying stress in radiata pine [27].

Potential application of both oven- and hot-steam air drying for tamiang bamboo has not been studied yet. Therefore, this research was carried out to investigate and compare the drying behaviour and post-drying quality of tamiang bamboo from air, oven, and hot-steam air drying. The results obtained are useful as a basis for determining the most suitable drying method to obtain high-quality dry tamiang bamboo.

2. MATERIALS AND METHODS

2.1 Material and equipment

The materials used were tamiang bamboo, plastic clips, 90% alcohol, aluminum foil, and plastic tubes (10 ml) to store organisms, i.e., insects or fungi/mold, attacking bamboo during the drying process, in particular, air drying. The equipment method and tools used were laboratory oven (Heraeus), hot-steam air dryer (EB-2005D), table saw (Stanley SST 1801-B1), colourimeter (Konica Minolta CR-10+), digital caliper (Mitutoyo), ruler, analytical balance (Galaxy 400), microscope 50-150X camera for microorganism analysis, fan, and writing tools.

2.2 Sample preparation

Approximately 60 fresh culms were obtained from a 10-year-old tamiang bamboo plantation in Semin village, Wonosari subdistrict, Gunung Kidul district, Province of Yogyakarta. These bamboo culms had a diameter range of 10-20 mm and a length range of 600-800 mm. Each fresh culm was cut using a table saw to a length of 220 mm in the middle of the culm. Each drying sample was sandwiched between 20 mm-long samples, which were used for moisture content testing (Figure 1). To obtain the density value of tamiang straws, approximately 3 straws were randomly selected from each drying method. The density specimens were cut according to the cutting pattern shown in Figure 1. Using the method proposed by Nugroho et al. [28], the density range of tamiang straws used for this study was 0.38 ± 0.06 g/cm^3.

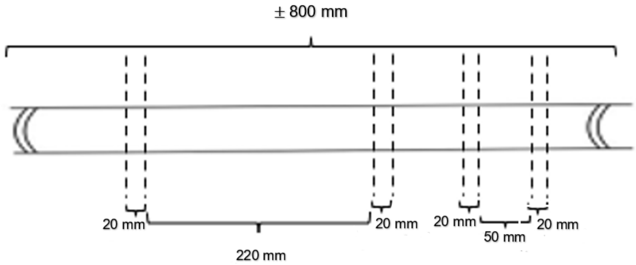


Figure 1. The cutting pattern of the tamiang sample: 220-mm-long drying samples, 20-mm-long moisture content samples, and 50-mm-long density samples

2.3 Initial moisture content determination

The initial moisture content of drying samples during the drying process was determined according to the procedures below:

(i) The initial weight of drying and moisture content (MC) samples was first determined using a balance.
(ii) The MC samples were oven-dried at a temperature of 103 ± 2°C for 24 hours, and reweighed after 24 hours.
(iii) The moisture content of MC samples was calculated using Eq. (1), and the oven-dry weight (ODW) of drying samples was calculated using Eq. (2) [29]:

$$MCs\ (\%) = \frac{b-c}{c} \times 100 \tag{1}$$

$$ODW\ (g) = \frac{a}{1+MC\%} \tag{2}$$

where,

MCs: moisture content of MC samples.
a: initial weight of drying samples (220-mm long samples).
b: initial weight of MC samples (20-mm long samples).
c: weight of MC samples after 24-hour oven drying at 103 ± 2°C.

2.4 Drying test

Three methods, oven drying, hot-steam-air drying, and air drying, were used to dry tamiang straws (Table 1). Each drying method used approximately 20 drying samples. Both oven- and hot-steam-air drying were carried out at a constant temperature of 60°C. The temperature selection was based on the results of past drying studies for *Gigantochloa apus* Kurts [30]. The hot-steam-air drying process was performed using the EB-2005D equipment (Figure 2) [23]. Before the start of the hot-steam-air drying process, water was filled into the equipment tank up to the specified level. The equipment was then turned on, and the temperature was set to 60°C. The heating flame was ignited and subsequently extinguished once the target temperature was reached.

The air-drying process was performed from December 2023 to February 2024 at IPB University, Bogor Regency. The samples were dried under sunlight during the day (morning to afternoon) and subsequently stored indoors at night. In the event of rainfall, the samples were relocated to a sheltered area to ensure they remained unaffected by rain exposure. The samples were then returned to the same location for air drying after the rain finished. The average temperature during the experiment was 27.2°C, whilst the average humidity level was 81% [31, 32]. All drying processes were stopped when the samples reached a moisture content of 8% or below.

Table 1. Specific experimental conditions for the three drying methods

No.	Method	Temp.	RH*	Observation Period
1.	Oven drying	60°C	-	Every 3 hours
2.	Hot steam air drying	60°C	-	Every 3 hours
3.	Air-drying	27.2°C	81%	Twice daily

Remarks: *RH= relative humidity, setting was not available for oven- and hot-steam air dryer

Figure 2. Hot-steam-air dryer (EB-2005D) used for the study

2.5 Drying behaviour

The drying samples were weighed regularly during the drying process. Sample reweighing was carried out every 3 hours for oven drying and hot-air-steam drying, and twice daily for air drying. The moisture content of drying samples during the drying process was calculated using Eq. (3).

$$MC_d\ (\%) = \frac{d - ODW}{ODW} \times 100 \tag{3}$$

where,

MC_d: moisture content of drying samples at t-time

d: weight of drying samples at t-time

ODW: calculated oven dry weight of drying samples (from Eq. (2))

The drying rate of tamiang bamboo straws was determined according to the following method [33]. For each drying sample, the data on the reduction of moisture content from every sample were first transformed into logarithmic values (base 10). The transformed data from each sample was then plotted in Cartesian coordinates with time (X) as the independent variable and moisture content (Y) as the dependent variable. The linear regression equation was then extracted from each graph. The slope from each regression equation was further divided by the drying duration to obtain the drying rate for the corresponding sample, as in Eq. (4). This step was repeated for all samples. All obtained drying rate values were averaged.

$$drying\ rate\ \left(DR, \frac{\%}{mins}\right) = \frac{b}{t} \tag{4}$$

with *b* is the slope of regression equation for each graph and t is drying time for corresponding sample.

2.6 Post drying qualities

2.6.1 Dimension shrinkage

The diameter and thickness of drying samples were measured before and after drying (Figure 3). Each sample was measured for both diameter and thickness using a digital caliper. Thickness measurements were taken on four sides, while diameter measurements were taken on two sides. A sketch illustrating the dimensional measurements was shown in Figure 3. The determination of dimensional and thickness shrinkage was based on Eq. (5), as follows [18]:

$$S_{d,t}(\%) = \frac{a_1\ (mm) - a_2(mm)}{a_1\ (mm)} \times 100 \tag{5}$$

where,

$S_{d,t}$: diameter shrinkage (S_d) or thickness shrinkage (S_t)

a_1: diameter/thickness before drying

a_2: diameter/thickness after drying

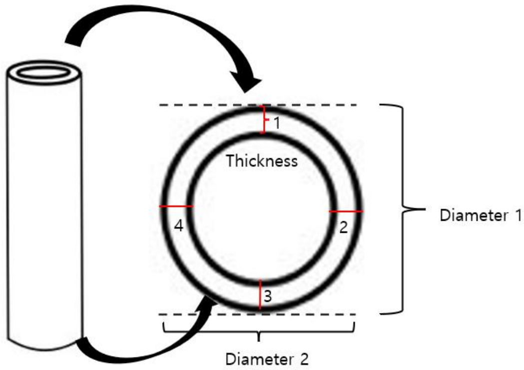


Figure 3. Measurement of the diameter and thickness of tamiang straws

2.6.2 Color change

Color testing was conducted to assess the changes in color and brightness of tamiang bamboo. Color difference before and after drying was observed. All samples were initially marked at 3 points (Figure 4). A colorimeter was used to obtain the L, a, and b values for each point in the sample. Eq. (6) was used to obtain the sample's color values before and after drying. Each sample's colour change was then calculated based on Eq. (7) [34]:

$$E = \sqrt{L^2 + a^2 + b^2} \tag{6}$$

$$\Delta E^* = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \tag{7}$$

where,

E = Initial color or post-drying color

L = Brightness of the color

a = Color between green and red

b = Color between blue and yellow

ΔL* = Difference in L* value initial and after treatment

Δa* = Difference in a* value initial and after treatment

Δb* = Difference in b* value initial and after treatment

ΔE* = Color change after treatment

Figure 4. Test point for color change in the sample

2.6.3 Drying defects

The drying defects observed were cross-section/diameter deformation and the presence of attack by lignocellulosic-destroying organisms, in particular, for the air-drying method. Diameter or cross-section deformation was evaluated for all drying samples. The sample's diameter from each end was measured in two directions (D1-D2), before (A) and after drying (A1), as illustrated in Figure 5. A digital caliper was used for this purpose. The diameter differences before and after drying were calculated based on Eq. (8) for each measurement direction. Negative values indicate diameter widening in one measurement direction. If the measurement in one direction has shown an increase in diameter, then the diameter from the 2nd measurement direction usually decreases (indicated by positive values).

$$\text{Diameter/cross-section deformation (mm)} = A - A_1 \qquad (8)$$

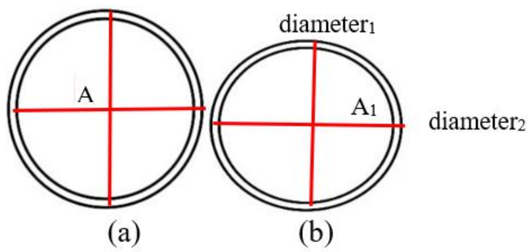


Figure 5. (a) Initial diameter and (b) after drying

The presence of the organisms' attack was observed mainly for air-drying samples. Observations were carried out twice daily from the initial point of the drying process. Samples of destroying organisms encountered during the air-drying process were collected and stored in plastic tubes containing 70% alcohol. The destroying organisms were identified using a microscope camera with 50x magnification.

2.7 Data collection and analysis

Data on drying rate, color changes, and shrinkage were tabulated using Microsoft Excel 2013 software. Data were averaged, and their standard deviations were determined. The effects of various drying methods on drying rate, diameter shrinkage, thickness shrinkage, and color change were analysed using one-way ANOVA with IBM SPSS 27.0 software at a 95% confidence level. Data on drying defects was presented in the form of a table and image, and analyzed descriptively.

3. RESULTS AND DISCUSSION

3.1 Drying behaviour

Oven drying provided the fastest drying rate ($-5.4 \times 10^{-4} \pm -5.4 \times 10^{-3}$ %/mins) and the shortest drying duration (432 mins) of tamiang straws. On the other hand, air-dried tamiang had the slowest drying rate $-1.9 \times 10^{-7} \pm -3.7 \times 10^{-6}$ %/mins (Table 2). According to a past study, a higher drying temperature leads to faster drying rates [18]. Drying duration is influenced by the drying rate; the faster the drying rate, the shorter the drying duration. Statistical analysis confirms that the drying method significantly influences the drying rate at a 5% significance level (Table 3).

Table 2. Drying rate and duration for each method

Drying Method	Drying Rate (%/mins)	Drying Duration (mins)
Oven drying	$-5.4 \times 10^{-4} \pm -5.4 \times 10^{-3}$	432 ± 257
Hot-steam air drying	$-2.6 \times 10^{-4} \pm -3.4 \times 10^{-3}$	729 ± 487
Air drying	$-1.9 \times 10^{-7} \pm -3.7 \times 10^{-6}$	22872 ± 11897

Note: The sign (-) indicates the declining trend of the moisture content value

Table 3. The effect of drying methods on the drying rate

	Sum of Squares	df	Mean Square	F	Sig.
Between groups	.000	2	.000	50.240	.000
Within groups	.000	57	.000		
Total	.000	59			

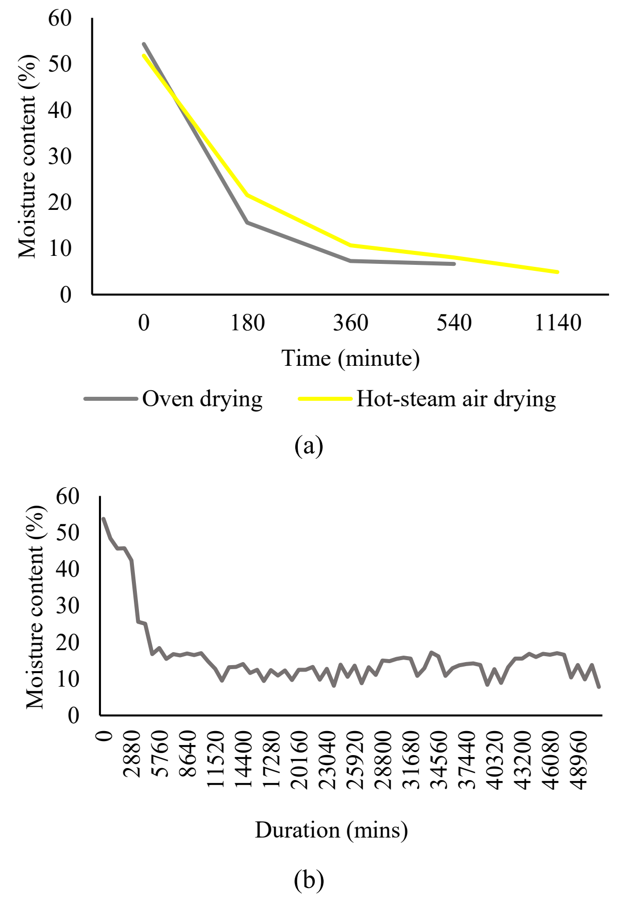


Figure 6. Moisture content changes of tamiang bamboo from (a) oven drying and hot-steam air drying, and (b) air drying

Figure 6 depicts that both oven and hot-steam-air-dried samples dried faster than air-dried ones. At the same temperature (60°C), oven-dried tamiang also had a faster drying rate than the hot-steam air-dried ones (Figure 6(a)). This could happen since oven drying utilizes direct heat generated by electricity. On the other way around, the hot-steam air drying in this study uses heat from steam, which results from the water boiling process. It also did not involve pressure, as in superheated steam drying [35]. Therefore, it is possible that the hot-steam air drying process in this study has less heat transfer capacity than the hot-air drying in the oven.

In comparison to hot-steamed air, hot air could maintain a lower relative humidity at the same drying temperature, which encourages evaporation and heat transfer to the surface of the object being dried [36, 37]. As a result, the application of hot air for the drying process may result in a more successful moisture removal process from the object than the use of hot-steamed air [37]. A previous study using *Pinus radiata* wood as the study's object informed that the whole stack of pine boards dried faster when being subjected to hot-air at 90℃ than when it was exposed to superheated steam under vacuum conditions and the same temperature [35]. They further explained that hot air possesses higher air density and heat capacity than superheated steam, resulting in more effective heat transfer [35]. While hot air may dry goods faster, hot-air steam can be useful in certain situations, such as when delicate materials require gentle drying to prevent damage, i.e., silk worm cocoons or dragon's blood resin [23, 24]. The decision between the use of hot-air and hot-steam air drying eventually depends on the precise drying requirements and material qualities.

3.2 Post-drying qualities

3.2.1 Dimension shrinkage

Table 4 shows that the highest thickness shrinkage occurred for air-dried samples (15.81 ± 5.28%). The largest diameter shrinkage is observed for the hot-steam air dried samples (3.68 ± 0.84%). The drying methods significantly affect the shrinkage of bamboo diameter and thickness at a 5% significance level (Tables 5 and 6).

Table 4. Dimensional shrinkage and number of diameter-deformed tamiang samples from all drying methods

No.	Method	Dimensional Shrinkage (%)		Number of Samples with Deformed Diameter
		Diameter	Thickness	
1.	Oven drying	3.50 ± 0.93	5.71 ± 2.69	9
2.	Hot steam air drying	3.68 ± 0.84	7.16 ± 5.20	4
3.	Air drying	1.33 ± 0.58	15.81 ± 5.28	3

Table 5. The effect of drying methods on bamboo diameter shrinkage

	Sum of Squares	df	Mean Square	F	Sig.
Between groups	68.274	2	34.137	53.599	.000
Within groups	36.303	57	.637		
Total	104.577	59			

Table 6. The effect of drying methods on bamboo thickness shrinkage

	Sum of Squares	df	Mean Square	F	Sig.
Between groups	1192.303	2	596.152	3.840	.027
Within groups	8849.291	57	155.251		
Total	10041.594	59			

The results obtained contradict previous findings on the thickness shrinkage of oven-dried mayan (*Gigantochloa robusta* Kurz.), ater (*Gigantochloa atter* (Hassk) Kurz. ex. Munro), ampel kuning (*Bambusa vulgaris* var *striata*), and wulung bamboo (*Gigantochloa atroviolacea* Widjaja), which was greater than that of the air-dried samples due to a higher drying temperature in the oven [38]. In general, oven drying reduces moisture content faster, which could lead to a higher shrinkage rate than air drying [39, 40]. The results of this study show that the shrinkage diameter in air drying is lower than that of oven drying and hot steam air drying. However, drying at high temperature could also reduce the equilibrium moisture content of the dried object and improve its dimensional stability, which further contributes to less shrinkage compared to air drying [41, 42]. A study's results showed that the highest thickness shrinkage of air drying can also be caused by gradual moisture removal, which may result in higher shrinkage rates [21].

In addition to the above discussion, a factor that might contribute to the thickness shrinkage of bamboo during the drying process is differences in the physical properties of the basal, tip, and middle parts of bamboo as observed in sero bamboo (*Schizostachyum brachycladum*) [43]. Bamboo shrinkage is also influenced by the composition of parenchyma and vascular bundles [29]. Bamboo with less parenchyma tends to have smaller shrinkage than those with more. Parenchyma undergoes deformation with increasing moisture content and weight loss, leading to defects or damage in bamboo [21].

3.2.2 Color change

Oven-dried samples had color change (ΔE) of 12.49 ± 4.57 and brightness of 17.98 ± 3.72, hot-steam-air-dried samples had color change of 10.80±4.19 and brightness of 16.03 ± 3.11, and air-dried samples had color change of 21.05 ± 7.33 and brightness of 35.58 ± 5.22 (Table 7). Drying method significantly affects the color change and brightness of tamiang straws at a 5% significance level (Tables 8 and 9). According to a previous study [34], bamboo exposed to higher temperatures undergoes more pronounced color changes.

Table 7. Color change and brightness of tamiang straws from various drying methods

Method	Color Change (ΔE)	Brightness (L)
Oven drying	12.49 ± 4.57	17.98 ± 3.72
Hot-steam air drying	10.80 ± 4.19	16.03 ± 3.11
Air drying	21.05 ± 7.33	35.58 ± 5.22

Air-dried tamiang samples possessed the largest color change and brightness among others. According to a previous study on the drying process of birch wood [44], the air-dried birch wood had enhanced brightness and color changes more than the steam-dried samples. Daytime heat provides UV radiation, resulting in brighter colors of birch wood compared to winter and spring seasons. Oxygen content also affects the color changes of birch wood, hong bamboo, and shiitake mushrooms during the drying process [2, 45, 46].

Table 8. The effect of drying methods on bamboo color changes

	Sum of Squares	df	Mean Square	F	Sig.
Between groups	1208.383	2	604.191	19.650	.000
Within groups	1752.581	57	30.747		
Total	2960.963	59			

Table 9. The effect of drying methods on bamboo brightness changes

	Sum of Squares	df	Mean Square	F	Sig.
Between groups	4640.051	2	2320.007	137.195	.000
Within groups	963.886	57	16.910		
Total	5603.901	59			

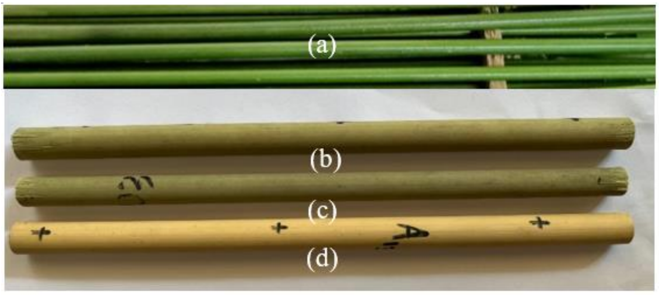


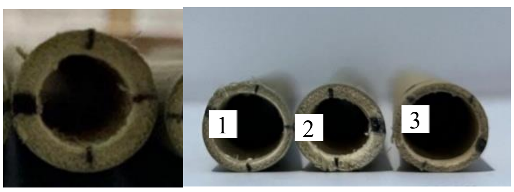
Figure 7. Tamiang color (a) before drying and after (b) oven drying, (c) hot-steam air drying, and (d) air drying

Hot-steam-air-dried samples had the smallest color changes among other samples. Figure 7 shows that hot-steam air-dried samples exhibit a darker color than oven- and air-dried samples. According to a previous study [46], the steam process utilizes saturated steam, which induces dark color changes in samples. Another study [2] has also noted that hot-steam air-dried hong bamboo (*Phyllostachys iridencens*) had a darker color than the microwave–vacuum-dried ones. This limitation could potentially restrict the use of the hot-steam-air drying method due to the market preference for bright bamboo color.

3.2.3 Drying defects

Defects observed in tamiang bamboo from all drying methods were diameter/cross-section deformation of one or both bamboo straws' ends and organism's attack. Diameter/ cross-section deformation occurred in 9 samples from oven drying, 4 samples from hot-steam-air drying, and 3 samples from air drying (Table 4 and Figure 8). Table 10 shows details of diameter change values for both ends of oven-dried, hot-steamed air-dried, and air-dried tamiang samples. As can be seen in Table 10, the diameter deformation generally occurs at one end of the tamiang sample, rarely at both ends.

Bamboo cross-section deformation during drying is caused by the relationship between moisture content and drying shrinkage. The moisture movement in the radial direction of round bamboo during drying is an asymmetric one and is dominated by the outer surface migration under the moisture gradient [47]. As moisture evaporates, uneven shrinkage creates internal tensions, causing cracking and distortion of the bamboo structure [21]. Oven drying quickly reduces the moisture content of the sample, resulting in a large internal moisture gradient of the sample [20]. On the other hand, hot steam air drying can reduce the risk of drying defects due to slower moisture content decrease than oven drying [26]. Therefore, bamboo exposed to oven drying has a higher risk of deformation than that dried using hot steam air drying, even at the same temperature.



(a) (b)

Figure 8. (a) bamboo diameter before drying (round-shaped); (b) diameter deformation in tamiang bamboo samples from (1) oven drying, (2) hot-steam air drying, and (3) air drying

Air-dried tamiang straws had poor quality due to traces of beetle infestation and fungal growth (Figure 9). Approximately 17 and 16 air-dried samples were affected by beetle infestation and fungal attack, respectively. It has been reported that bamboo is generally susceptible to mold and powder beetle attacks due to its high moisture content and nutrient-rich composition [48].

Air-dried tamiang straws started to be susceptible to the attack of powder post beetle (*Dinoderus minutus*) on the 2nd, 3rd, and 4th days of observation. This beetle is a common insect that usually attacks many bamboo species during their drying process (Figure 10) [49-53]. Further data observation revealed that the moisture content of tamiang bamboo from day 2 to day 4 ranged from approximately 45% to 25%. This aligns with a previous study informing beetles can survive in bamboo with a moisture content of 30% in adulthood, but larvae do not develop into pupae [51]. A past study reported that dry bamboo with a moisture content of 12% is not susceptible to beetle attacks [54].

Table 10. Diameter change of each end of the tamiang straws from all drying methods

Sample	Observation Direction		Air Drying	Oven Drying	Hot-Steam Air
1	End 1	D1	0.17	-0.34	0.40
		D2	0.05	0.51	0.41
	End 2	D1	-0.40	0.05	-0.11
		D2	0.64	0.42	0.34
2	End 1	D1	0.22	0.42	0.14
		D2	0.12	0.41	0.34
	End 2	D1	0.19	0.32	-0.59
		D2	-0.31	-0.16	0.18
3	End 1	D1	0.56	-0.06	0.60
		D2	-0.19	0.28	-0.23
	End 2	D1	0.20	0.28	0.38
		D2	0.50	0.25	0.09
4	End 1	D1		0.34	0.45
		D2		0.27	0.40
	End 2	D1		1.43	-0.30
		D2		-1.29	0.41
5	End 1	D1		-0.11	
		D2		0.61	
	End 2	D1		0.34	
		D2		0.39	
6	End 1	D1		0.56	
		D2		-0.32	
	End 2	D1		0.40	
		D2		0.57	
7	End 1	D1		0.39	
		D2		-0.09	
	End 2	D1		0.46	
		D2		0.34	
8	End 1	D1		0.42	
		D2		0.44	
	End 2	D1		-0.06	
		D2		0.40	
9	End 1	D1		-0.23	
		D2		0.48	
	End 2	D1		0.43	
		D2		0.33	

Remark: D1 = diameter 1 (mm) and D2 = diameter 2 (mm) from each end of the tamiang straw sample, as referred to Figure 2. The sign (-) indicates a diameter increase after drying.

It is considered that beetle infestation also contributed to thickness shrinkage during air drying of tamiang straws. Air-dried tamiang straws, which were attacked by the beetle, had greater weight loss (3.45 ± 3.45 grams) than the hot-steam air-dried samples (3.4 ± 1.21 grams) and oven-dried samples (3.38

± 1.34 grams). The powder post beetles can create boreholes up to 1.16 mm in diameter in bamboo [51]. This has the potential to affect the reduction of bamboo weight.

(a) (b)

Figure 9. Damaged air-dried tamiang straws due to the attacks of: (a) powder beetles, (b) mold/fungus

Figure 10. The powder beetle (*Dinoderus minutus*) was found during the air-drying of tamiang straw (microscope observation at 50 × magnification)

The presence of mold at the ends of several air-dried tamiang straws was observed after the drying process finished (Figure 8(b)). However, this mold was easily removed by hand. This result is in line with previous research informing the easy removal of mold's presence on moso bamboo after the drying process without leaving significant effects on the attacked surface [55].

Bamboo is more susceptible to mold than other materials, such as wood [13]. While the mold type found on air-dried tamiang straws is not confirmed yet, several previous studies have reported the general vulnerability of bamboo to different types of mold and other fungi attacks. *Aspergillus niger*, *Trichoderma viride, Penicillum citrinum,* and *Botryodiplodia theobromae* are types of molds often found in various bamboo products [56-58]. Other fungi include a white rot fungus, such as *Lentinus edodes*, which infects *Phyllostachys edulis* bamboo [59] and *Aciculosporium take* that infects shoot tissue of *Phyllostachys bambusoides* and *Phyllostachys pubescens* [60]. Both white and soft rot fungi have also been observed to colonize and degrade *Gigantochloa scortechinii* bamboo [61].

4. CONCLUSIONS

The study compared the air-, oven-, and hot-steamed air-drying processes of tamiang bamboo. Oven drying method resulted in the highest drying rate ($-5.4 \times 10^{-4} \pm -5.4 \times 10^{-3}$ %/mins) and fastest drying time (432 mins). The smallest diameter shrinkage (1.33 ± 0.58) occurred in samples during air drying, while the smallest thickness shrinkage (5.71 ± 2.69) occurred for oven-dried samples. Air-dried samples had the greatest color ΔE (21.05 ± 7.33) and brightness changes (35.58 ± 5.22), but were vulnerable to powder beetle and fungal attacks. Several samples from all drying methods tended to show cross-section deformation. Statistical tests confirmed the significant effect of various drying methods on drying rates, drying times, diameter shrinkage, thickness shrinkage, color changes, and bamboo brightness at a 5% significance level. Based on the study results, although air drying is low-cost, the quality of tamiang bamboo could be reduced due to the powder beetle's attack. Therefore, the use of artificial drying in an oven or hot-steam air dryer is recommended to obtain mold/fungi-free dry tamiang straws. Nevertheless, the use of hot-steam air drying should be carefully conducted as it might lead to the deepest bamboo color hue, which is less preferred by consumers.

ACKNOWLEDGMENT

The authors convey their gratitude to National Research and Innovation Agency of Indonesia (BRIN) for the research grant, the Laboratory of Wood Quality Improvement Technology, Faculty of Forestry and Environment, IPB University and Standardization Center for Sustainable Forest Management Instruments, Ministry of Environment and Forestry for the research facilities and technical assistances provided for this study.

REFERENCES

[1] Akinlabi, E.T., Anane-Fenin, K., Richard, D. (2017). Bamboo: The Multipurpose Plant. Spinger, Germany.

[2] Lv, H.F., Chen, M.L., Ma, X.X., Li, J.H., Zhang, B., Fang, C.H., Fei, B.H. (2018). Effects of different drying methods on bamboo's physical and mechanical properties. Forest Products Journal, 68(4): 445-451. https://doi.org/10.13073/FPJ-D-18-00009

[3] Du, J., Yang, K., Yuan, Z., Liu, Z., Li, X., Liu, S., Li, C., Meng, S., Wu, R. (2023). Effect of physical treatment methods on the properties of natural bamboo materials. Construction and Building Materials, 394: 132170. https://doi.org/10.1016/j.conbuildmat.2023.132170

[4] Leo, M.D.A., Conrado, D.S.R., Flávia, S.J.P. (2023). Assessment of physical, mechanical, and chemical properties of *Dendrocalamus asper* bamboo after application of wetting and drying cycles. Advances in Bamboo Science, 2: 1-11. https://doi.org/10.1016/j.bamboo.2022.100014

[5] Andriani, L.R., Ngabekti, S., Partaya. (2020). Species richness, distribution, and phenotype relationship of bamboos in Kecubung Ulolanang Nature Reserve (KUNR) on Batang. Journal of Physics: Conference Series, 1918: 052010. https://doi.org/10.1088/1742-6596/1918/5/052010

[6] Thang, T.H. (2023). Bamboos in Myanmar. Myanmar Ecological Society, Nay Pyi Taw, the Republic of the Union of Myanmar.

[7] Goh, W.L., Sungkaew, S., Teerawatananon, A., Ohrnberger, D., Widjaja, E.A., Sabu, K.K., Goparkumar, B., Koshy, K.C., Xia, N., Wong, K.M. (2020). The phylogenetic position and taxonomic status of the Southeast and South Asian bamboo genera Neohouzeaua and Ochlandra (Poaceae: Bambusoideae). Phytotaxa, 472(2): 107-122. https://doi.org/10.11646/phytotaxa.472.2.2

[8] Dransfield, S., Widjaja, E.A. (1995). Plant Resources of South-East Asia. Backhuys, Belanda.

[9] Liana, A., Purnomo., Sumardi, I., Daryono, B.S. (2017). Bamboo species (Poaceae: Bambusoideae) from Selayar island. Flouribunda, 5(6): 185-191. https://doi.org/10.32556/floribunda.v5i6.2017.136

[10] Ediwar, Minawati, R., Yulika, F., Hanefi. (2019). Kajian

organologi pembuatan alat musik daluang darek berbasis teknologi tradisional (Study of organology in the making of traditional musical instruments 'daluang darek' based on traditional technology). Jurnal Seni Budaya (Journal of Arts and Culture), 29(2): 117-130.
[11] Ilhami, A., Sriyati, S., Liliawati, W., Handrianto, C. (2024). The potential of local wisdom in Dadio as source for biology learning. Journal of Biology Education Research, 5(2): 99-144. https://doi.org/10.32332/al-jahiz.v5i2.9427
[12] Huangfei, L., Caiping, L., Bin, X., Xin, S., Jian, Y., Benhuang, F. (2022). Effects of microwave-assisted drying on the drying shrinkage and chemical properties of bamboo stems. Industrial Crops and Products, 187: 115-122. https://doi.org/10.1016/j.indcrop.2022.115547
[13] Yu, Z., Zhang, X., Zhang, R., Yu, Y., Sun, F. (2022). Improving the mould and blue-stain-resistance of bamboo through acidic hydrolysis. Polymers, 14(2): 244. https://doi.org/10.3390/polym1402024
[14] Li, Z., Luan, Y., Hu, J., Fang, C., Liu, L., Ma, Y., Liu, Y., Fei, B. (2022). Bamboo heat treatment and their effects on bamboo properties. Construction and Building Materials, 331: 127320. https://doi.org/10.1016/j.conbuildmat.2022.127320
[15] Jasni, Damayanti, R., Sulastiningsih, I.M. (2017). Resistance classification of 20 bamboo species against dry-wood termites. Journal of Forest Products Research, 35(3): 171-183. https://doi.org/10.20886/jphh.2017.35.3.171-183
[16] Pei, Y., Vidyarthi, S., Wang, J., Deng, L., Wang, H., Li, G., Zheng, Z., Wu, M., Xiao, H. (2021). Effect of vacuum-steam pulsed blanching (VSPB) on drying characteristics and quality properties of garlic slices. Drying Technology, 40(6): 1232-1246. https://doi.org/10.1080/07373937.2020.1861620
[17] Putri, A.H., Dewi, O.C. (2020). Overview of bamboo preservation methods for construction use in hot humid climate. International Journal of Built Environment and Scientific Research, 4(1): 1-10. https://doi.org/10.24853/ijbesr.4.1.1-10
[18] Lv, H.F., Ma, X.X., Zhang, B., Chen, X.F., Liu, X.M., Fang, C.H., Fei, B.H. (2019). Microwave-vacuum drying of round bamboo: A study of the physical properties. Construction and Building Materials, 211: 44-51. https://doi.org/10.1016/j.conbuildmat.2019.03.221
[19] Vetter, R.E., Ribeiro, R.A., Ribeiro, M.G.S., Miranda, I.P.A. (2015). Studies on drying of imperial bamboo. European Journal of Wood and Wood Products, 73: 411-414. https://doi.org/10.1007/s00107-015-0900-6
[20] Yuniarti, K., Basri, E., Afifah, N., Priadi, T., Sofianto, I.A. (2023). Mutu dan performa pengeringan sedotan bambu pada beberapa teknik pengeringan buatan dengan penambahan media adsorben (*Drying quality and performance of bamboo drinking straws from sevreral artifical techniques with addition of adsorbent media)*. Research Program, Research Organization of Life Science and Environment. Report RP1TP3BSubTema2-9.
[21] Yan, Y., Fei, B.H., Liu, S.Q. (2020). The relationship between moisture content and shrinkage strain in the process of bamboo air seasoning and cracking, Drying Technology, 40(3): 571-580. https://doi.org/10.1080/07373937.2020.1819307
[22] Kuswardhani, N., Andriyani, I., Nasir, M.A., Alfarisy, F.K. (2023). Pengembangan ekonomi masyarakat secopangepok melalui produksi sedotan bambu sebagai upaya mengurangi sampah plastik dikabupaten jember (The development of the secopangepok community economy through bamboo straw production as an effort to reduce plastic waste in Jember Regency). Jurnal Pengabdian Masyarakat Berkemajuan (Journal of Progressive Community Service), 7(2): 1366-1372. https://doi.org/10.31764/jpmb.v7i2.15034
[23] Basri, E., Kaomini, Yuniarti, K. (2009). The quality of filament and silk thread produced from cocoon processed with p3hh-drying and storage equipment. Journal of Forest Products Research, 27(3): 213-222. https://doi.org/10.20886/jphh.2009.27.3.213-222
[24] Yuniarti, K., Batubara, I., Pasaribu, G., Waluyo, T.K., Efiyanti, L., Basri, E. (2023). Dracorhodin content and selected bioactivities of *Calamus ruber'* dragon blood resin from different drying conditions. Studies on Ethno-Medicine, 17(3-4): 140-154. https://doi.org/10.31901/24566772.2023/17.3-4.6759
[25] Adewumi, A.D., Ojediran, J.O., Oladele, S.O., Olumuyiwa, M., Okonkwo, C.E., Olayanju, T.A. (2021). Energy requisite and drying capacity of a superheated steam dryer. IOP Conference Series: Materials Science and Engineering, 1107(1): 1-7. https://doi.org/10.1088/1757-899X/1107/1/012045
[26] Sobulska, M., Wawrzyniak, P., Woo, M.W. (2022). Superheated steam spray drying as an energy-saving drying technique: A review. Energies, 15(22): 1-22. https://doi.org/10.3390/en15228546
[27] Pang, S., Pearson, H. (2004). Experimental investigation and practical application of superheated steam drying technology for softwood timber. Drying Technology, 22(9): 2079-2094. https://doi.org/10.1081/DRT-200034252
[28] Nugroho, N., Kartini., Bahtiar, E.T. (2021). Cross-species bamboo grading based on flexural properties. IOP Conference Series: Earth and Environmental Science, 891: 012008. https://doi.org/10.1088/1755-1315/891/1/012008.
[29] Hartono, R., Iswanto, A.H., Priadi, T., Herawati, E., Farizky, Sutiawan, J, Sumardi, I. (2022). Physical, chemical, and mechanical properties of six bamboo from Sumatera Island Indonesia and its potential applications for composite materials. Polymers, 14(22): 1-15. https://doi.org/10.3390/polym14224868
[30] Basri, E., Saefudin. (2006). Shrinkage-swelling properties and equilibrium moisture content of bamboo tali (*Gigantochloa apus* Kurtz) at various age and drying level. Journal of Forest Products Research, 24(3): 241-250. https://doi.org/10.20886/jphh.2006.24.3.241-250
[31] Bogor Regency Statistics Office. (2024). Average air temperature by month in Bogor Regency (°C), 2022-2023. Bogor Regency Statistics Office. Retrieved from https://bogorkab.bps.go.id/statistics-table/2/NzQjMg==/rata-rata-suhu-udara-menurut-bulan-di-kabupaten-bogor.html, accessed on Nov. 13, 2024.
[32] Bogor Regency Statistics Office. (2024). Average air humidity by month in Bogor Regency (%), 2022-2023. Bogor Regency Statistics Office. https://bogorkab.bps.go.id/id/statistics-table/2/NzUjMg%253D%253D/rata-rata-kelembaban-udara-menurut-bulan-di-kabupaten-bogor.html, accessed on Nov. 13, 2024.

[33] Yuniarti, K. (2015). Intermittent drying of *Eucalyptus saligna*. Ph.D. dissertation, The University of Melbourne, Australia.
[34] Lee, C., Yang, T., Cheng, Y., Lee, C. (2018). Effects of thermal modification on the surface and chemical properties of moso bamboo. Construction and Building Materials, 178: 59-71. https://doi.org/10.1016/j.conbuildmat.2018.05.099
[35] Pang, S., Dakin, M. (1999). Drying rate and temperature profile for superheated steam vacuum drying and moist air drying of softwood lumber. Drying Technology, 17(6): 1135-1147. https://doi.org/10.1080/07373939908917599
[36] Bond, J.F., Mujumdar, A.S., van Heiningen, A.R.P., Douglas, W.J.M. (1994). Drying paper by impinging jets of superheated steam. Part 2: Comparison of steam and air as drying fluids. Canadian Journal of Chemical Engineering, 72(3): 452-456. https://doi.org/10.1002/cjce.5450720310
[37] Parajia, J.S., Prabhu, M.R., Subrahmanyam, K. (1967). Hot-air drying: Effects of temperature and humidity. Journal of The Textile Institute, 58(9): 446. https://doi.org/10.1080/00405006708629890
[38] Bahanawan, A., Sugiyanto, K. (2020). The effect of drying on color changes, thickness shrinkage, and weight reduction of four bamboo species. Journal of Forest Products Research, 38(2): 69-80. https://doi.org/10.20886/jphh.2020.38.2.69-80
[39] Zhu, J., Yang, L. (2025). Progress in the study of dry shrinkage deformation and drying stress of raw bamboo. Bioresources, 20(1): 2304-2320. https://doi.org/10.15376/biores.20.1.zhu
[40] Singhal, P., Rudra, S.G., Singh, R., Satya, S., Naik, S.N. (2018). Impact of drying techniques on physical quality of bamboo shoots: Implications on tribal's livelihoods. Indian Journal of Traditional Knowledge, 17(2): 353-359.
[41] Coto, Z. (2005). Penurunan kadar air keseimbangan dan peningkatan stabilitas dimensi kayu dengan pemanasan dan pengekangan (*Reducing equilibrium moisture content and improving dimensional stability of wood through heating and restraining*). Jurnal Ilmu dan Teknologi Kayu Tropis (*Journal of Tropical Wood Science and Technology*), 3(1): 27-31. https://doi.org/10.51850/jitkt.v3i1.302.g275
[42] Wu, K.T. (1992). The effect of high-temperature drying on the antisplitting properties of makino bamboo culm (*Phyllostachys makinoi* Hay.). Wood Science and Technology, 26(4): 271-277. https://doi.org/10.1007/bf00200162
[43] Luanmasse, A.D., Liliefna, L.D., Fransz, J.J. (2023). Physical properties along the culm of sero bamboo (*Schizostachyum brachycladum* Kurz.). Journal Makila, 17(2): 149-162. https://doi.org/10.30598/makila.v17i2.10710
[44] Dudiak, M., Dzurenda, L. (2023). The effect of sunlight on the color change of steamed birch wood. Acta Facultaris Xylologie Zvolen, 65(1): 35-43. https://doi.org/10.17423/afx.2023.65.1.03
[45] Dudiak, M., Dzurenda, L., Kučerová, V. (2022). Effects of sunlight on the change in color of unstreamed and steamed beech wood with water steam. Polymers, 14(9): 1-12. https://doi.org/10.3390/polym14091697
[46] Tian, Y., Zhao, Y., Huang, J., Zeng, H., Zheng, B. (2016). Effects of different drying methods on the product quality and volatile compounds of whole shiitake mushrooms. Food Chemistry, 197: 714-722. https://doi.org/10.1016/j.foodchem.2015.11.029
[47] Cheng, A., Chen, F., Xu, K., Xiang, J., Wang, X., Hu, C., Zhou, Q., Tu, D. (2024). Moisture migration mechanism of round bamboo in the radial direction during drying. Construction and Building Materials, 435: 136819. https://doi.org/10.1016/j.conbuildmat.2024.136819
[48] Liu, Y.D., Liu, W.J. (2010). Research progress on the bamboo timber preservation. Advanced Materials Research, 159: 216-221. https://doi.org/10.4028/www.scientific.net/AMR.159.216
[49] Liu, L. (2021). An annotated synopsis of the powder post beetles (Coleoptera: Bostrichidae) of mainland China. Zootaxa, 3: 389-419. https://doi.org/10.11646/zootaxa.5081.3.5
[50] Liese, W., Tang, T.K.H. (2015). Bamboo: The Plant and Its Uses. Springer International Publishing, Switzerland.
[51] Norhisham, A.R., Faizah, A., Zaidon, A. (2015). Effects of moisture content on the bamboo borer *Dinoderus minutus*. Journal of Tropical Forest Science, 27(3): 334-341.
[52] Zhang, Y., Meng, L., Beaver, R. (2022). A review of the non-lyctine powder-post beetles of Yunnan (China) with a new genus and new species (Coleoptera: Bostrichidae). Zootaxa, 4: 501-545. https://doi.org/10.11646/zootaxa.5091.4.1
[53] Tripathy, M.K., Pradhan, B. (2021). Diversity of timber infesting beetles from Odisha. Indian Journal of Entomology, 83(2): 183-193. https://doi.org/10.5958/0974-8172.2021.00054.7
[54] Watanabe, H., Yanase, Y. (2015). Evaluation of larval growth process and bamboo consumption of the bamboo powder-post beetle *Dinoderus minutus* using X-ray computed tomography. Journal of Wood Science, 61: 171-177. https://doi.org/10.1007/s10086-014-1458-3
[55] He, L., Chen, L., Xiang, L., Lie, H., Shao, H., Qi, J., Jiang, Y., Xie, J. (2023). Improving the anti-mould property of moso bamboo surface by using a bamboo green colour preservation approach. Wood Material Science & Engineering, 18(1): 161-171. https://doi.org/10.1080/17480272.2021.2000023
[56] Chen, C.Q., Zhang, S.J., Kong, Y.B.H., Ji, T., Huang, W.W., Hu, Y.T., Zhang, D.W., Xiao, Y. (2023). Compressive strength degradation of engineered bamboo subjected to fungal attack. NPJ Materials Degradation, 7: 92. https://doi.org/10.1038/s41529-023-00407-9
[57] Kai, Y., Li, X., Wu, Y., Zheng, X. (2021). A simple, effective and inhibitor-free thermal treatment for enhancing mold-proof property of bamboo scrimber. European Journal of Wood and Wood Products, 79(5): 1049-1055. https://doi.org/10.1007/S00107-021-01655-9
[58] Ouyang, H., Hou, K., Ge, S., Deng, H., Peng, W. (2017). Antimicrobial activities of flavonoids against bamboo-destroying fungi and molds. Toxicological & Environmental Chemistry, 99(56): 892-899. https://doi.org/10.1080/02772248.2017.1320049
[59] Kim, S.K., Lee, K.H., Cho, C.H., Koch, G., Kim, S.K. (2008). Micromorphological characteristics and lignin distribution in bamboo (*Phyllostachys pubescens*) degraded by the white rot fungus *Lentinus edodes*.

Holzforschung, 62(4): 481-487. https://doi.org/10.1515/HF.2008.080
[60] Tanaka, E. (2009). Specific in situ visualization of the pathogenic endophytic fungus Aciculosporium take, the cause of witches' broom in bamboo. Applied and Environmental Microbiology, 75(14): 4829-4834. https://doi.org/10.1128/AEM.00635-09
[61] Wahab, R., Sudin, M., Samsi, H.W. (2005). Fungal colonisation and decay in tropical bamboo species. Journal of Applied Sciences, 5(5): 897-902. https://doi.org/10.3923/jas.2005.897.902