Effects of Different Drying Methods on Bamboo's Physical and Mechanical Properties

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Abstract

In this work, a comparative study on microwave–vacuum-drying (MVD) and hot-air-drying (HAD) of bamboo culms was conducted. Related physical and mechanical properties of bamboo culms were investigated. MVD results showed no drying defects of bamboo culms. Compared with that of the HAD method, the drying time of MVD was reduced. The shrinkage of both bamboo culm diameter and wall thickness increased with drying time. The crystallinity was changed with drying time between MVD and HAD. The CIELAB color system (L*, a*, b*) was used for analyzing bamboo color changes. All the values of L*, a*, and b* were increased after MVD, which caused the bamboo culms to become golden yellow. However, after HAD, L*, a*, and b* decreased and samples became brown. The mechanical properties of samples were improved after MVD, and did not show any significant changes after HAD. The pore structure after MVD showed higher adsorption capacity, higher specific surface area, and greater volume compared with HAD. Therefore, taking into consideration the dried product quality and short drying time, MVD provides a potential method for drying bamboo.

Bamboo, an important forest resource, is a very fast-growing plant with high levels of strength that can be used as a structural material (Jiang 2007). Freshly harvested bamboo has a high moisture content (MC), making it susceptible to being attacked by fungi. Thus, bamboo must be dried as soon as possible after being harvested. The current drying technologies, like air-drying and kiln-drying, usually require high energy and are time-consuming processes (Prasad and Krishna 2012). In addition to the high cost, inappropriate drying methods may cause many defects such as cracking and charring because of the anisotropy and special structural properties of bamboo. Currently, the hot-air-drying (HAD) method is widely used, not only on bamboo and wood materials, but also on many other materials (Seremet et al. 2016, Tian et al. 2016). However, HAD requires a relatively long processing time and it may damage bamboo culms, giving them an unattractive color. Therefore, new drying methods, which can shorten drying time and improve product quality, would be worthy of investigation.

Microwave drying provides a novel alternative. Heat is generated when microwaves interact with the polar water molecules in materials; a significantly high drying rate is achieved compared with HAD. Moreover, microwave drying can increase material permeability and help relax growth and drying stress (Torgovnikov and Vinden 2009, Vinden et al. 2011). Microwave-drying in the wood industry was first reported by Geoffrey (1966). It greatly reduced drying time with the proper control of drying conditions, allowing dried products with high quality to be obtained. Water molecules located in the material absorb the energy given off by the microwaves. This creates a large vapor pressure inside the material, allowing a rapid transfer of moisture from the inner to outer layers (Lin et al. 1998). The drying rate is considerably higher than that of traditional drying methods. A positive factor enhancing drying rate is the wattage of microwaves (Andrés et al. 2004). In addition,

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applying microwave energy under vacuum could improve energy efficiency and product quality (Yongsawatdigul and Gunasekaran 1996). Microwave-vacuum-drying (MVD) has already been satisfactorily applied to reduce MC on many materials. Microwaves supply energy for rapid heat transfer, and vacuum lowers the boiling point of water in the material (Mui et al. 2002), accelerating the vaporization of moisture. Accordingly, microwave-drying combined with vacuum could simultaneously improve drying rate and shorten drying time. Gunasekaran (1999) demonstrated the advantages of MVD both in terms of energy efficiency and quality of the dried product regarding its color and texture. In addition, the bamboo treatment inhibited oxidation and preserved color and also improved physical–chemical properties, such as shrinkage (Sun and Gu 2004), crystallinity (Fu et al. 2016), and mechanical properties (Shupe et al. 2015).

MVD provides a novel choice and improves drying rate, requires lower temperatures, and offers a more uniform and efficient distribution of energy compared with other drying methods. However, there has yet to be a systematic investigation regarding the effects of MVD on bamboo properties. As such, a comparative study was conducted in this work to investigate the effects of MVD and HAD on some important properties of bamboo. Shrinkage, crystallinity, mechanical properties, color, porosity, and microstructure characteristics were observed, measured, and compared between MVD and HAD.

Materials and Methods

Sample preparation

Samples of 5-year-old Hong bamboo (*Phyllostachys iridescens* C.Y.Yao & S.Y.Chen) were taken from Guangde, Anhui Province, China. The samples were about five nodes long (1 m in length, with an average diameter of 30 to 40 mm) and collected from bamboo culms at a height of 1.5 to 2.5 m distance from the ground. The samples were selected with a circular cross section and were marked at the ends for the experiment. They were stored at a temperature of 4°C ± 0.5°C in a refrigerator with 95 percent relative humidity. All samples used for drying (MVD and HAD) were collected from the same location. Figure 1 shows the preparation of the samples. The initial MC of samples was measured by oven-drying according to the GB/T standard 15780-1995 (Standardization Administration of China 1995), a Chinese standard for testing physical and mechanical properties of bamboo.

Drying methods

Microwave–vacuum-drying.—MVD was performed in a customized device fabricated by Boda Microwave Equipment Co., Ltd., Henan Province, China. The MVD drier had a cylindrical chamber (150 cm in diameter and 150 cm in height) with an exhaust fan on the top and a tray on the bottom. Microwave energy was generated by water-cooled magnetrons (frequency 2,450 MHz). Bamboo culms were placed on the tray. The tray rotated in the chamber during drying to keep heating uniform. The tray was connected to a load cell with a precision of 0.03 percent. The MC change during drying could be monitored by the weight change (the initial MC and initial weight of the samples were measured in advance). The interval was 10 minutes for every test in the experiment. Once MC reached 10 percent, the drying process was terminated. The microwave radiations were generated perpendicular to the longitudinal direction of the bamboo culms. The equipment was operated at the powers of 2, 4, and 6 kW and temperatures of 70°C, 80°C, and 90°C, respectively. The vacuum level was –0.02 MPa. Ten specimens were tested for each treatment and the averages were reported. The MC was calculated as follows:

$$\mathrm{MC\%} = \frac{W_t - W_0}{W_0} \times 100\% \qquad (1)$$

where W_t and W_0 are, respectively, the weight at each interval during drying and ovendry weight of samples.

Hot-air-drying.—HAD was conducted in an electric thermal static drying oven (DHG-9240A; Shanghai Jinghong Experiment Instrument Co., Shanghai China) at temperatures of 70°C, 80°C, and 90°C. The samples were dried from an MC of 53 percent until approximately 10 percent MC. The final MC of each sample was recorded to calculate the MC at each weight interval. The calculation of MC can be given as Equation 1. Drying tests were replicated 10 times at each condition. The interval was 30 minutes for each measurement.

Shrinkage

Shrinkage is an important physical parameter of bamboo, and occurs during drying as a result of water evaporation. It is the basic cause of many problems during the service life (such as cracking). Unlike in most wood species, the shrinkage of bamboo starts to become apparent in a decrease of both cell wall thickness and cell diameter, which is attributable to the capillary forces leading to cell collapse as

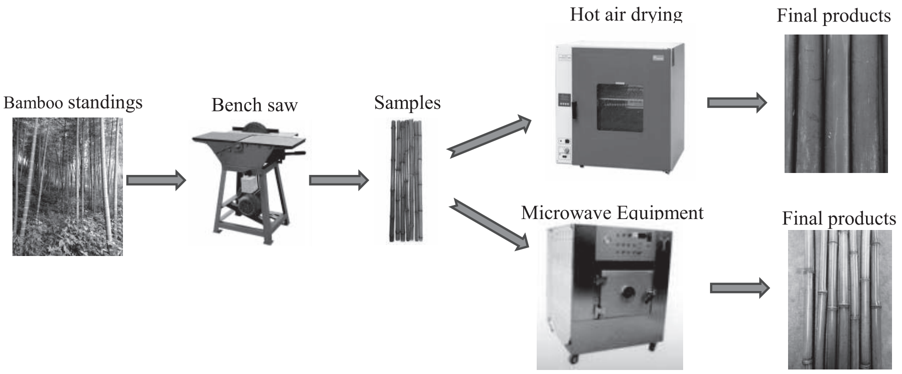

Figure 1.—Sample preparation.

soon as MC begins to decrease (Liese and Köhl 2015). In our study, the outer diameter and wall thickness of the bamboo culms were measured on both ends of each specimen before and after drying. The shrinkage was calculated as follows:

$$S_D = \frac{D_b - D_a}{D_b} \tag{2}$$

$$S_W = \frac{W_b - W_a}{W_b} \tag{3}$$

where S_D is diameter shrinkage; D_b and D_a are, respectively, the diameter before and after drying; S_W is wall thickness shrinkage; and W_b and W_a are, respectively, wall thickness before and after drying.

XRD measurements

X-ray diffraction (XRD) measurements (Philips X'Pert PRO) were performed to assess the crystalline properties after HAD and MVD. All XRD measurements were performed with a reflection technique. The incident X-ray radiation was the characteristic Cu Kα X-ray passing through a nickel filter with a power of 30 kV and 30 mA. The width of the detection slit was 0.1 mm, and the scanning speed and integration time for crystallinity measurements were 2.0°/min and 2.0 seconds, respectively. Scanning range of the 2θ angle was 5.0° to 40.0°. Specimens were ground into powder after drying (0.15 to 0.18 mm). The crystallinity of the crystalline cellulose in the bamboo cell wall was calculated as follows, using the Segal method (Segal et al. 1959, Sun and Li 2010):

$$C_rI = \frac{I_{002} - I_{am}}{I_{002}} \times 100\% \tag{4}$$

where C_rI is relative crystalline degree, namely the percentage of crystallinity; I_{002} is the maximum intensity (002) of the crystal lattice diffraction angle (arbitrary unit), appearing in the scan curve when 2θ was near 22°; and I_{am} is the scattering intensity of background diffraction in amorphous region when 2θ was near 18°, whose unit is the same as that of I_{002}.

Mechanical properties

Bamboo exhibits excellent flexural behavior, which can mainly be attributed to the distribution of fibers and parenchyma cells along bamboo culm radial direction. In this study, the bending property was tested, and the loading direction was tangential. The samples, with measurements of 80 by 4 by 4 mm, were tested in a three-point bending with a span of 64 mm and testing speed of 3 mm/min by using the Instron Material Testing System. The modulus of rupture (MOR) and modulus of elasticity (MOE) were determined by the following equations:

$$\text{MOR (MPa)} = \frac{3P_{\max}L}{2\delta bh^2} \tag{5}$$

$$\text{MOE (MPa)} = \frac{P_P L^3}{4\delta bh^3} \tag{6}$$

where $P_{\max}$ is the maximum load (N), L is the span of the specimen (mm), b is the width of the samples (mm), h is the thickness of the specimen (mm), P_p is the load difference between the upper and lower boundary loads within the proportional limit, and δ is the midspan deflection of the specimen under P_p.

Color measurement

The color of samples before and after drying was determined using a colorimeter (BYK-Gardner, made in Germany), referring to the CIELAB color system, CIE L*a*b*, in which L* is lightness along the lightness axis (100 = white or brightness; 0 = black or darkness); a* is redness (a* $>$ 0) or greenness (a* $<$ 0); and b* is yellowness (b* $>$ 0) or blueness (b* $<$ 0). Color was measured using a wide range of spectrophotometers according to ISO 11664-4 (International Organization for Standardization 2008). The color coordinates of the samples were determined using a D65 standard light source and a 10° observation angle. The mean values were reported in this study.

Pore structure

The pore characteristics of bamboo, such as pore diameter, pore volume, and pore distribution, were investigated by the Brunauer-Emmett-Teller method (Zhou et al. 2017) using a nitrogen adsorption/desorption analyzer (SSA-4200; Bulder, Beijing). Bamboo powders (0.15 to 0.18 mm in diameter) were used for the tests. Three replications were studied, and the mean values were listed.

Results and Discussions

Drying kinetics

Figure 2 shows MC changes for MVD and HAD. A much longer time (600 min) was required to reach 10 percent MC for HAD, compared with MVD (50 min). The main reason for this was that the heat transfer medium of HAD was only hot air, and there was not enough force for water to discharge in a short time to reach expected MC. In addition, with HAD, the heat was transferred from the outer to the

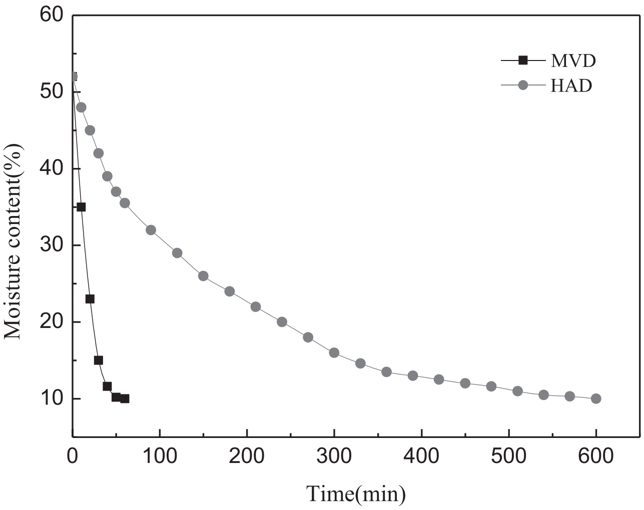

Figure 2.—Moisture content under different drying methods (MVD: 4 kW, 80°C; HAD: 80°C). MVD = microwave–vacuum-drying; HAD = hot-air-drying.

inner side of bamboo culms. The outer temperature was higher than the inner one. The movement of water vapor from the inner to outer side was hindered and more time was needed to dry. The HAD drying curve behaved similarly to a reported 40°C oven-drying of *Bambusa vulgaris 'Vittata'* (Vetter et al. 2015).

Compared with HAD, the MVD method had an efficient drying rate. It only took less than 1 hour to achieve the target MC. The drying rate of MVD (1.06%/min) was much higher than that of HAD (0.09%/min). Furthermore, it was found that MVD did not cause any defects such as cracking or splitting. During the MVD process, the samples were exposed to an electromagnetic field with high-frequency microwave radiation. The molecules rotated with this high frequency and increased the temperature of the samples (Fansson and Antti 2006). The heating method was rapid, integral, and uniform. In addition, the vacuum in the chamber increased the pressure gradient between the samples and the cavity, therefore accelerating the movement of water.

Shrinkage

During the drying process, samples underwent changes in bamboo culm diameter and wall thickness along with water loss. The shrinkage of bamboo caused by MVD and HAD was calculated based on the dimensions of initial fresh samples. Figure 3 shows the shrinkage changing along with drying time under different drying conditions.

The shrinkage increased with drying time under the two drying methods. It should be noted that there was no obvious difference in diameter shrinkage between the two methods. However, HAD showed higher shrinkage in wall thickness than MVD. MVD showed smaller and more uniform shrinkage than HAD. Drying involves a complicated process related to the mass and heat, because multiple phases are present in form of solids, liquid water, and gas. Therefore, shrinkage had a relationship with MC and heating transfer mode. HAD shrinkage was moderate with the long drying time, which gave more time for the samples to shrink. During the MVD process, the microwave energy and vacuum created more force and facilitated the transport of water. Evaporation of water in the samples was accelerated by the preferential absorption of microwave energy. Hence, the shrinkage of wall thickness with MVD was less than that with HAD. Moreover, studies (e.g., Meisam et al. 2015) showed that the vascular bundles of bamboo are horizontal and in an intricate arrangement at the nodes. This could suppress the shrinkage during drying; the shrinkage in diameter was very small.

Crystallinity measurement

The crystallinity was the crystalline area accounting for the percentage of the whole cellulose, potentially affecting mechanical properties. Figure 4 depicts the crystallinity after drying.

After MVD, the values of crystallinity were 48.97, 52.53, and 50.28 percent, corresponding to the temperatures of 70°C, 80°C, and 90°C, respectively, at 4 kW; and 51.74, 52.53, and 50.28 percent, respectively, corresponding to the powers of 2, 4, and 6 kW at 80°C.

The values of crystallinity were 47.52, 47.44, and 47.34 percent after HAD at 70°C, 80°C, and 90°C, respectively. There was no significant difference in these values. The main reason was that the HAD treatment was relatively moderate and might not cause any changes to the chemical properties of the samples.

After drying, the crystallinity changed in varying degrees. Under relatively mild conditions (70°C, 80°C and 2, 4 kW) the crystallinity was improved in different levels. The main reason could be attributed to the microwave special heating mechanism. This mechanism promoted the hydroxyl condensation reaction, allowing it to occur in the amorphous area (Sun et al. 2013). It produced a certain amount of ether bond, making the arrangement of microfibrils more orderly and merging them into the crystallization zone. Therefore, the degree of crystallinity increased.

At a high temperature (90°C) and high power (6 kW), the drying conditions were relatively intense, leading to some thermal degradation of hemicellulose and producing acetic acid. In these conditions, the sample appeared slightly charred. The acetic acid promoted the degradation of microfibrils in the amorphous regions or even in the crystalline regions (Sun and Li 2010). Therefore, the crystallinity decreased at high temperature and high power.

Mechanical properties

Table 1 presents the bending properties of bamboo samples after MVD and HAD. Both MOE and MOR were the highest after MVD at 80°C, and the lowest at 90°C. No significant difference was found after HAD among the three temperatures. After HAD treatment, the specimens may undergo drying without obvious compound degradation. Therefore, the strength did not change. In addition, the results of the crystallinity research showed that there was no significant alteration in physical and chemical properties. Accordingly, the mechanical strength did not substantially change after HAD.

On the contrary, the bending properties were improved after MVD until 80°C and decreased above 80°C. There might have been some changes in the chemical property, such as crystallinity (Wang et al. 2014b). In the crystalline region, segment motion of the cellulose chains was

Table 1.—Mechanical properties after microwave–vacuum-drying and hot-air-drying.[a]

Conditions	MOE (GPa)	SD	MOR (MPa)	SD
MVD				
4 kW, 70°C	12.19	0.5	150.66	4.5
4 kW, 80°C	12.70	1.2	158.24	5.1
4 kW, 90°C	10.99	0.8	154.41	5.0
2 kW, 80°C	11.09	0.6	150.12	7.2
4 kW, 80°C	11.70	1.2	158.24	6.1
6 kW, 80°C	10.34	0.9	149.99	5.1
HAD				
70°C	10.45	0.5	155.21	5.2
80°C	10.74	1.2	155.68	6.3
90°C	10.71	0.8	155.29	5.5

[a] MOE = modulus of elasticity; MOR = modulus of rupture; MVD = microwave–vacuum-drying; HAD = hot-air-drying; SD = standard deviation.

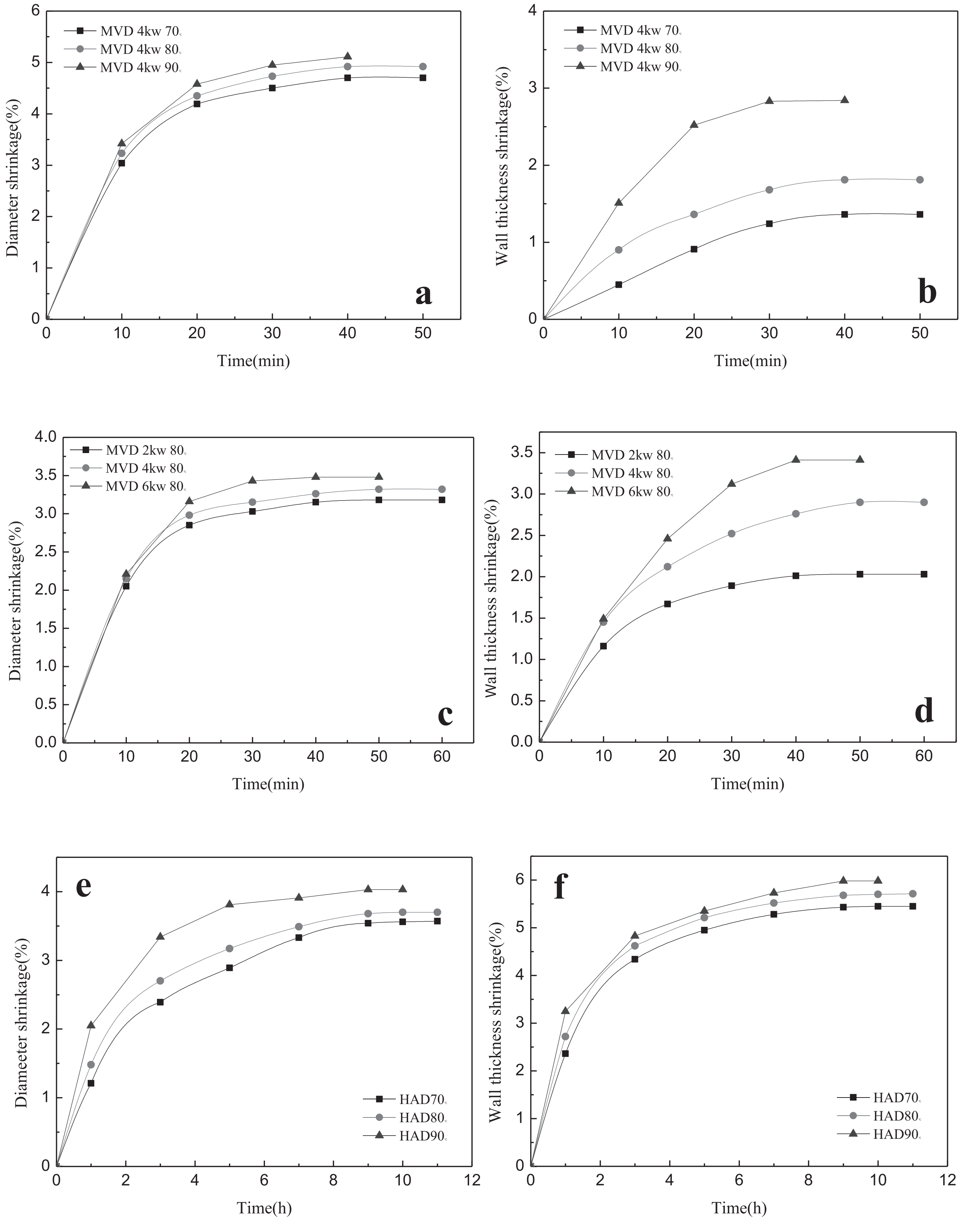

Figure 3.—Bamboo culms shrinkage variations with drying time (a, b, c, d: MVD; e and f: HAD). MVD = microwave–vacuum-drying; HAD = hot-air-drying.

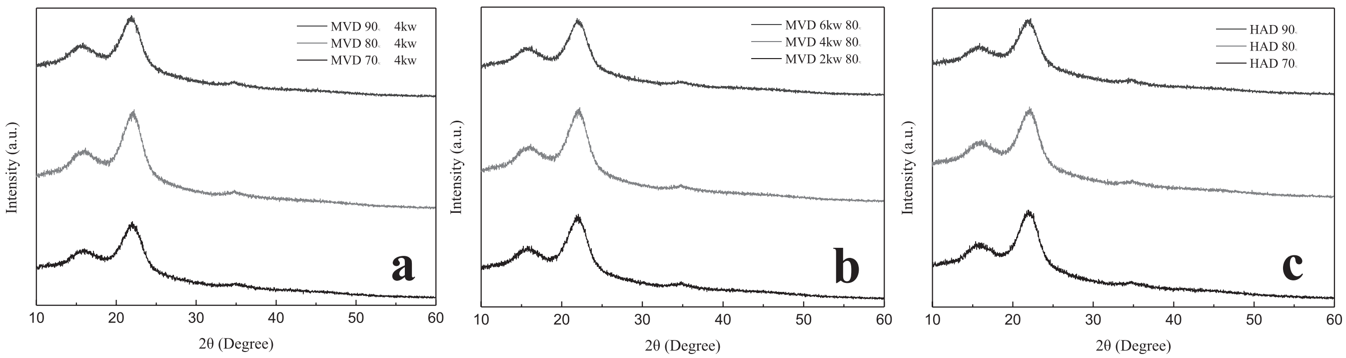

Figure 4.—X-ray diffraction spectra of bamboo under different drying methods (a, b: MVD; c: HAD). MVD = microwave–vacuum-drying; HAD = hot-air-drying.

enhanced as the temperature increased, causing part of the space between cellulose chains to decrease and allowing a new hydrogen bond to form, enhancing the crystallinity to a certain extent. Therefore, MVD could improve bamboo bending properties within a certain range.

When the samples were treated under a temperature of 90°C and power of 6 kW, crystallinity of samples decreased again, This may be because when the heat temperature increased over 80°C, the segment motion was so acute that the hydrogen bond was destroyed, the intermolecular force between cellulose chains was reduced, wood crystallinity decreased, and the mechanical property dropped on the macroscopic view.

Color parameters of samples

Color was one of the critical quality parameters influencing consumer acceptance and the market value of products. Table 2 displays the results of color changing before and after drying. The initial color of samples was green, but they significantly changed after drying. The samples obtained the lower values of lightness after HAD. Theander et al. (1993) showed that a long drying time induced enzymatic discoloration, evoking the brown appearance. It clearly indicated that more browning occurred because of nonenzymatic browning. The organic acid and reduced saccharides during drying might be responsible for the formation of brown compounds. In addition, when the moisture moved from the inner to outer side of the bamboo, the extract was driven to move and accumulate on the surface. This resulted in discoloration at the surface after hydrothermal action (Bekhta and Niemz 2003), such as having the visual characteristics of being brown and dark.

Table 2.—Color change under different drying conditions.

Drying condition	L*	a*	b*
Fresh			
—	46.34	−2.45	25.83
Microwave–vacuum-drying			
4 kW, 70°C	52.86	3.98	27.29
4 kW, 80°C	55.35	5.74	28.84
4 kW, 90°C	49.10	3.07	24.92
2 kW, 80°C	55.86	5.52	28.88
4 kW, 80°C	56.66	6.29	29.68
6 kW, 80°C	52.73	2.65	26.16
Hot-air-drying			
70°C	43.95	7.92	22.58
80°C	43.43	7.70	22.33
90°C	40.01	6.96	19.99

However, it is worth noting that the samples had a shorter drying time under MVD, increasing the obtained higher values of lightness. Compared with HAD, the L* and a* were clearly improved after MVD. For a* (redness/greenness) scale, the initial color of fresh samples was negative. After drying, a* values became positive and showed a reddish color. For b* (yellowness/blueness) scale, the yellowness of the samples increased after drying. The color changed initially from green to yellow in its final form. From these results, it could be understood that some modifications occurred in the color properties of bamboo during drying with the decrease of MC. In addition, less oxygen was present in a vacuum-drying chamber under negative pressure. This led to a less intense enzymatic browning reaction, which was the main cause of yellow color produced in dried samples (Tian et al. 2016).

Pore structure

The adsorption/desorption isotherm was obtained to characterize the pore structures (Fig. 5).

Figure 5a shows a typical isotherm classification. At the same relative pressure, the samples after MVD expressed higher adsorption than after HAD. These results imply that the microwave-treated samples obtained high specific surface area (2.802 m^2/g for MVD and 2.312 m^2/g for HAD) and pore volume (6.227×10^{-3} cm^3/g for MVD and 6.172×10^{-3} cm^3/g for HAD). This was probably attributable to the accelerated generation of water vapor under MVD. The vapor pressure was higher in a short time and increased the permeability of the pit membrane, which not only led to higher porosity, but also enlarged the pore (Wang et al. 2014a, Zhou et al. 2017).

Figure 5b shows the pore size distribution of samples after MVD and HAD. It was found that the distribution of pores was consistent after treated. However, microwave-treated samples exhibited higher pore volume than hot-air–treated samples. This was consistent with the proposed effect of enlarging pore size.

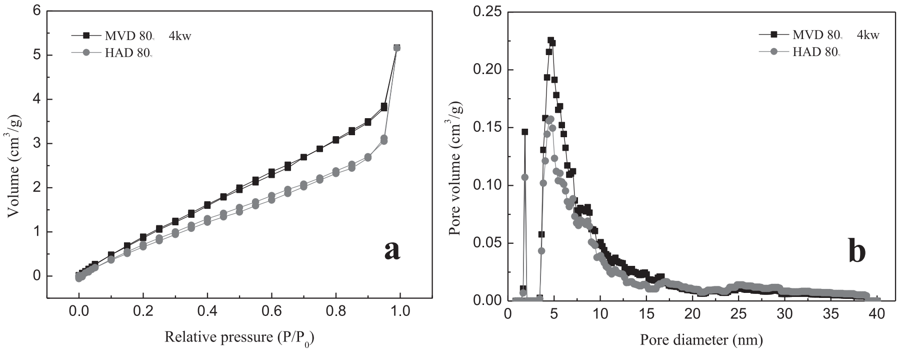

Figure 5.—(a) Nitrogen adsorption/desorption isotherms and (b) corresponding pore size distribution after drying at different conditions. MVD = microwave–vacuum-drying; HAD = hot-air-drying.

Conclusions

MVD was a good method for rapid drying of bamboo stems and drastically reduced the drying time compared with HAD. The shrinkage was gradually increased with the drying time. In MVD, according to Segal algorithm, the values of crystallinity were shown to have increased with drying time, though there was no significant change with HAD.

The MOE and MOR increased with 70°C and 80°C treatments, but tended to decline at a 90°C treatment with MVD, allowing higher values of the color parameters to be obtained. The lightness was higher than before treatment and the color changed from green to golden yellow. The microwave-treated samples expressed higher adsorption than hot-air–treated samples, obtaining high specific surface area and volume.

Acknowledgments

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