Effect of Drying Schedules on the Drying Time and Quality of *Dendrocalamus barbatus* Bamboo Using Solar Energy Integrated with Steam Heated Source

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Bamboo is recognized as a promising material. It is widely distributed in Vietnam. Bamboo products are quite diverse. However, bamboo materials have been primarily air-dried in open locations. Thus, the bamboo does not achieve the required moisture contents for use in certain products. This can lead to easily being infected by fungi, especially molds that affect the quality of the bamboo's products. To date, bamboo drying using solar energy integrated with a steam-heated source has not been studied. This study investigated the effect of drying schedules on the drying time and quality of *Dendrocalamus barbatus* bamboos in "culm" and "strip" forms using solar energy integrated with steam-heated source. Higher temperatures yielded faster drying times, but they also created more drying defects in the bamboo because of the drying gradient being higher. However, depending on the manufacturer's requirements, the drying schedule No. 1 (40 °C to 60 °C) or No. 2 (50 °C to 70 °C) can be used for drying the bamboo culms. In relation to the bamboo strips, drying schedule No. 3 (60 to 80 °C) is recommended because it was the shortest drying time and had a low defect rate (9%).

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Keywords: Drying schedule; Dendrocalamus barbatus; Solar energy; Bamboo culm; Bamboo strip

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INTRODUCTION

Raw bamboo and bamboo products contain high levels of sugar and moisture, so they are prone to mold fungi, decay fungi, and insects, causing color change and loss of value and usability (Tang 2013). One of the important stages in bamboo product production is to dry the raw materials. The moisture content of raw materials greatly affects subsequent processing, such as machining, gluing, and painting (Tang *et al*. 2013). In fact, bamboo is often seasonally harvested and after that, mold quickly occurs. Handicraft villages often buy a large amount of bamboo raw materials for year-round production. Currently, bamboo material in Vietnam is primarily open air-dried. This method has many disadvantages such as long drying time, dependency on climatic conditions, and uneven moisture in the materials, especially in the humid season in Vietnam. Hence, the bamboo and bamboo products do not meet the required moisture contents of specific applications and then they can be easily infected by mold. Furthermore, it is difficult to dry bamboo to a moisture content of below 15%, a large area is needed for drying (Gandhi 1998; Montoya Arango 2006).

Apart from air-drying, the kiln drying method has also been used to dry bamboo materials. However, this method only applies to medium sized or bigger enterprises (Sengdala *et al*. 1997). For some micro or small-sized enterprises that do not have drying kilns, workers have to stop their jobs during the rainy season. However, for the others, bamboo materials are dried using manual kilns; thus, the capacity and efficiency are low. In contrast, if bamboo is not dried in an appropriate way, the raw materials will still be moldy and damaged, and they will become unusable (Wu 1992).

Different types of dryers have been used for drying bamboo. These include the electrically-operated dryer, solar dryer, the dehumidifier dryer, and steam-heated drying kiln. The electric, solar drying, or steam-heated kilns depend only upon hot air for drying, while the dehumidifier dryer relies on hot dehumidified air (Tang *et al*. 2012; Bao Ngoc Nguyen 2023). However, one of the most sustainable solutions is to dry bamboo materials using solar energy (Ong 1996). A solar drying system operates on the principle of the greenhouse effect, which utilizes the radiant energy of the sun when it passes through a transparent surface (glass, polyester, *etc*.,) and then reaches a black object (heat-absorbing material). This black object, which has poor light reflection properties and is not able to reflect it back, is called a “heat trap”. Therefore, the solar radiation is absorbed and turned into heat energy (Bui Duy Ngoc 2021).

Although the intensity of solar energy in all regions in Vietnam is quite high, especially in the Southern region (Hoang and Tang 2007). The weather changes erratically, thus requiring an additional heat source to support the solar kiln. Drying uses only solar energy during periods of plentiful sunshine. The alternative source is employed when encountering cloudy weather or prolonged rain. If a solar source were to be used without integrating it with another heat source, the drying process would still depend on the weather. This will interrupt the drying process and affect the required moisture content of the raw materials. Therefore, solar energy system integrated with a steam-heated source was developed with the aim of supplying heat at times when insufficient heat is being generated by absorption of solar energy to reach the required temperature. Depending on weather conditions, if it is sunny and the solar energy is high, the materials can be completely dried by solar energy (do not need to use the steam-heated source). If the solar energy is low, the steam-heated source will be automatically opened to supply heat to maintain the required temperature. The drying parameters of temperature and relative humidity are automatically adjusted to ensure the drying schedules, as installed.

Therefore, a detailed study is required to investigate the effect of drying schedules on the drying time and quality of bamboo materials using solar energy integrated with a steam-heated source. In this study, *Dendrocalamus barbatus* bamboo in “culm” and “strip” forms was dried to a moisture content of 10 ± 2% to meet the requirements of production.

EXPERIMENTAL

Materials

The selected *Dendrocalamus barbatus* bamboos were between 3 and 5 years old. The bamboo was grown in Quan Hoa, Thanh Hoa Province, Vietnam.

Bamboo culms were harvested within 10 days, the moisture content was 100 ± 5%, and there were no harmful molds or fungus in the culms. The diameter of a bamboo culm was 100 to 120 mm; the length was 3.00 m (suitable for the length of the kiln); internodes were 30 ± 3 cm; and the culm wall thickness was 1.5 ± 0.5 cm.

Bamboo strips were manufactured from bamboo culms. They had dimensions of 12 mm × 24 mm × 3,000 mm (thickness × width × length) and were prepared at a moisture content of 70 ± 5%.

The capacity of each drying batch was 3 tons.

Drying Process

The experiments were performed in a solar kiln of 6.2 m length, 4.5 m height, and 5.4 m width, which was made by the Research Institute of Forest Industry, Vietnamese Academy of Forest Sciences. Its heating system could generate temperatures up to 90 °C *via* solar energy integrated with a steam heating source. The kiln was operated automatically using a PLC-controller, ensuring control and monitoring of the drying protocol, temperature, and relative humidity in the chamber in real time. Some principal specifications of the kiln are as follows:

- Maximum drying capacity: 10 ton/batch
- Heat source: Solar + steam heating
- Use the solar energy absorber with an absorption coefficient of more than 85%

Drying Schedules

The following drying schedules were used for the drying experiments (Table 1). All experiments were conducted at the Bamboo Vina Company Limited, Thanh Hoa province, Vietnam during the summer season from July and September in 2022. The air velocity was maintained at a constant speed of 3.0 m/s, reflecting current industrial standards.

Table 1. Experimental Framework Used for the Drying Study of Bamboo Culms

Moisture Content (%)	Drying Schedule 1			Drying Schedule 2			Drying Schedule 3		
	T (°C)	RH (%)	*U*	*T* (°C)	RH (%)	*U*	*T* (°C)	RH (%)	*U*
> 100 - 90	40	100	3.6	50	100	3.7	60	100	3.8
90 - 70	40	96	3.8	50	96	3.9	60	96	4.1
70 - 50	45	85	4.2	55	85	4.4	65	85	4.7
50 - 40	45	66	4.5	55	66	4.8	65	66	5.1
40 - 30	50	50	4.9	60	50	5.2	70	50	5.6
30 - 20	55	32	5.5	65	32	5.9	75	32	6.4
20 - 10	60	20	5.9	70	20	6.7	80	20	7.2

T: Temperature; RH: Relative humidity; *U*: Drying gradient

Table 2. Experimental Framework Used for the Drying Study of Bamboo Strips

Moisture Content (%)	Drying Schedule 1			Drying Schedule 2			Drying Schedule 3		
	T (ºC)	RH (%)	*U*	*T* (ºC)	RH (%)	*U*	T (ºC)	RH (%)	*U*
> 70 - 65	40	100	2.5	50	100	2.6	60	100	2.7
65 - 50	40	85	3.9	50	85	4.0	60	85	4.2
50 - 40	45	66	4.5	55	66	4.8	65	66	5.1
40 - 30	50	50	4.9	60	50	5.2	70	50	5.6
30 - 20	55	32	5.5	65	32	5.9	75	32	6.4
20 - 10	60	20	5.9	70	20	6.7	80	20	7.2

T: Temperature; RH: Relative humidity; *U*: Drying gradient

Three different drying schedules were tested for both bamboo culms and bamboo strips (Schedule No. 1 with mild drying intensity, Schedule No. 2 with medium drying intensity, and schedule No. 3 with severe drying intensity).

Measurement of Moisture Content

Measurement of moisture content of the samples during the drying process

The moisture content of the samples was automatically determined from the three different positions of a bamboo batch in the chamber. The average moisture content was shown on the screen.

Measurement of moisture content of the samples after the drying process

The moisture content of the samples after drying was measured according to TCVN 8168 (2010) standard.

Measurement of the Drying Defects

All samples used for the drying experiments were visually inspected for defects such as collapse, cracking, and splitting that had occurred during drying. Drying defects were expressed as percentage of all samples in each kiln run.

RESULTS AND DISCUSSION

Evaluation of the Bamboo Culms

Effect of drying schedules on drying defects

In drying of bamboo culms, defects can appear at any time during and after the drying process. Common defects of bamboo culms were end checks, cracks on the top of bamboo internodes, and collapses. Results of the evaluation of the defects of bamboo culms at the 3 drying schedules are summarized in Table 3.

Table 3. Percentage of Damaged Bamboo Culms in Different Drying Schedules

Drying Schedules	Defects After Drying (%)
No 1: T = 40 to 60 °C	6
No 2: T = 50 to 70 °C	16
No 3: T = 60 to 80 °C	30

Defects of the bamboo culms after drying gradually increased as the drying temperature increased. In the drying schedule No. 1 with a temperature of 40 to 60 °C, only 6% (6 out of 100 samples randomly taken from the drying kiln) were damaged, of which 5 samples had end checks, and 1 sample had surface cracks. The number of the defected bamboo culms increased dramatically to 16% in the drying schedule No. 2, of which 3 samples were bent (curvature > 3%), while the other 11 samples were surface cracked. The rate of defects increased greatly (30%) at the drying temperature of 60 to 80 °C (Schedule No. 3), of which 21% had end checks, 2% had surface cracked, and 7% had cracks at the top of bamboo internodes.

Effect of drying schedules on drying time

The obtained results of the drying time and moisture loss at various drying schedules are given in Fig. 1.

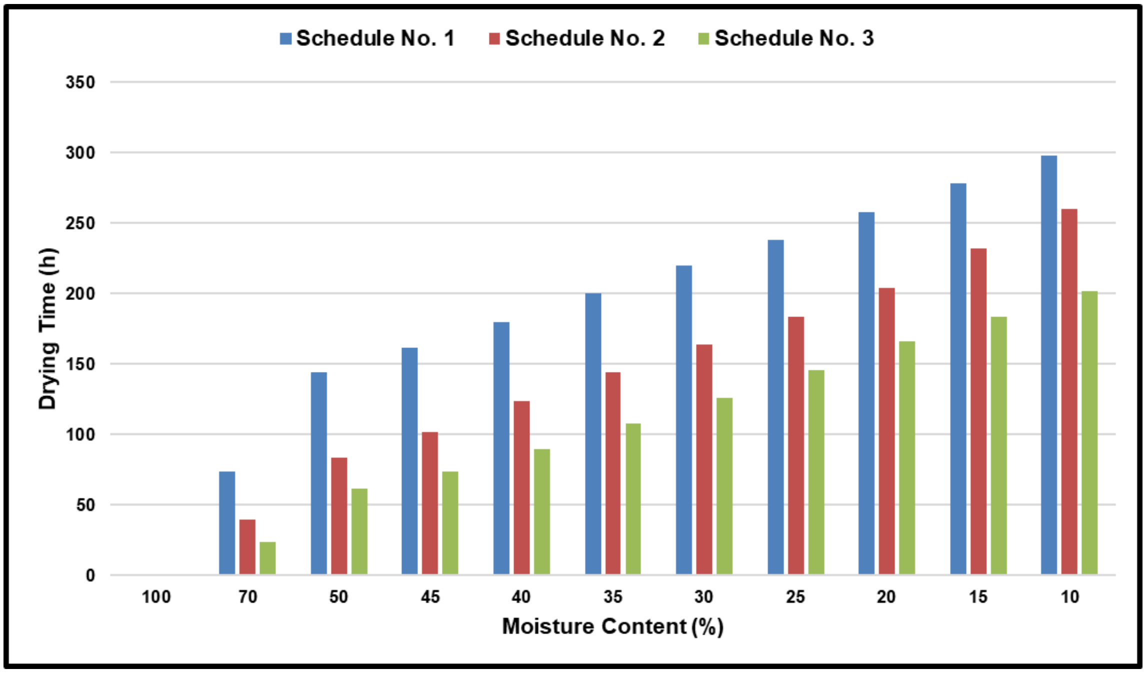

Fig. 1. Drying time and moisture loss at the different drying schedules

There was a remarkable difference in the drying rate of bamboo culms at the 3 different drying schedules. The drying time from a moisture content of approximately 100% to 10% in the drying schedule No. 1 was the longest, taking 298 h (12.42 days), corresponding to an average drying rate of 0.3% of moisture-loss/h. In schedule No. 2, the drying time was 260 h (10.83 days), which was 38 h faster than the drying time in schedule No. 1. In schedule No. 3, the drying time only took 202 h (8.42 days) – reducing the drying time by 96 h (4 days).

Although the schedule No. 3 with the highest temperature of 60 to 80 °C was the shortest drying time, the defect rate of the bamboo culms was relatively high (30%), thus it is not recommended to use this schedule for further experiments. The schedule No. 2 (T = 50 to 70 °C) had a lower defect rate (16%), therefore depending on the manufacturer's requirements for final products, this schedule No. 2 can be used. In addition, the drying schedule No. 1 can also be used to have a higher drying quality (6% defects) but longer drying time.

The drying parameters that were measured during the moisture reduction process of the bamboo culms are shown in Table. 1. The table shows the correlation between the two drying parameters: temperature (*T*) and relative humidity (RH), to the moisture reduction rate of the bamboo culms at the three drying schedules. The rate of RH reduction was the same (80%, 60%, 50%, 40%, 32%, and 20%) with the moisture reduction rate of the samples, but the temperature was gradually adjusted to increase from the drying schedule No. 1 to No. 3.

Evaluation of the Bamboo Strips

Effect of drying schedules on drying defects

The bamboo strips were less susceptible to defects in the drying compared to bamboo culms. Effect of the three different drying schedules on the drying defects of the bamboo strips and the results are shown in Table 5.

Table 5. Percentage of Damaged Bamboo Strips in Different Drying Schedules

Drying Schedules	Defects After Drying (%)
No 1: T = 40 to 60 °C	2
No 2: T = 50 to 70 °C	5
No 3: T = 60 to 80 °C	9

A similar trend was observed in the drying defect rate of bamboo culms and bamboo strips. However, the bamboo strips became less defect prone. In the drying schedule No. 1 at the temperature of 40 to 60 °C, only 2% of the samples were defective (end checks only). The percentage of defects slightly increased to 5% and 9% in the drying schedules No. 2 and No. 3, respectively. The main defects were end checks and curves.

Effect of drying schedules on drying time

The drying time required to reach moisture content of the bamboo strips for the different drying schedules is given in Fig. 2.

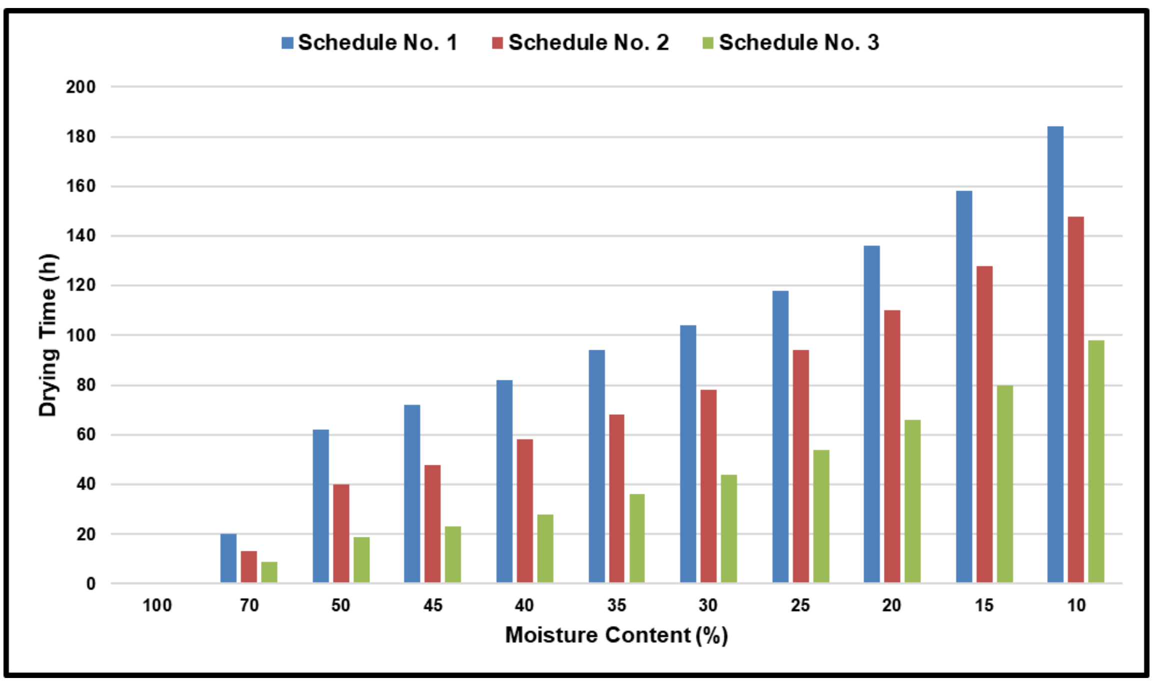

Fig. 2. Drying time and moisture loss at the different drying schedules

The results of drying bamboo strips also showed a noticeable difference in the drying time at the different drying schedules. The drying time for bamboo strips at a moisture content of approximately 90% to 10% in the schedule No. 1 was the longest, 184 h (7.67 days) needed, which was equivalent to an average drying rate of 0.43% of moisture loss/h, which was faster than the drying of bamboo culms (0.30%). In the drying schedule

No. 2, 148 h (6.17 days) was needed to dry the bamboo strips to a moisture content of 10%. However, the drying time took 98 h (4.08 days) in the drying schedule 3, which was 96 h shorter than the drying schedule No. 1. Overall, the drying time of the bamboo strips was also clearly different in the drying schedules as the drying of bamboo culms but was nearly half the amount shorter.

The drying time of schedule No. 3 was the shortest, but the defect rate was not really high (9%). Moreover, this temperature range is completely applicable with a solar dryer integrated into other heat sources. Therefore, this drying schedule was selected when developing the drying process for bamboo strips, a common bamboo material in Vietnam.

The drying parameters that were measured during the moisture reduction process of the bamboo strips are shown in Table. 2. It was found that the rate of RH reduction was similar (80%, 60%, 50%, 40%, 32%, and 20%) with the moisture loss rate of the bamboo strips, but the temperature gradually increased from the drying schedule No. 1 to No. 3. The moisture reduction line also gradually increased. The MC in the drying schedule No. 3 was dramatically decreased, but the defect rate of the bamboo strips was low. Thus, this drying schedule was selected to save drying time.

CONCLUSIONS

1. At a higher drying temperature, the defect rate of both bamboo culms and bamboo strips increased.
2. The drying schedule No. 1 or No. 2 of bamboo culms can be used depending on the manufacturer's requirements.
3. It is recommended to use the drying schedule No. 3 for drying bamboo strips because it had the shortest drying time and low defect rate (9%).

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