

Review Article

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A review of thermal treatment for bamboo and its composites

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Abstract: Bamboo, one of the richest non-timber resources, thrives in vast tropical and subtropical regions around the world. The surge of interest in bamboo materials stems from their profound contributions to polymer matrix composites, lauded for their environmental sustainability, mechanical properties, and recyclability. However, the inherent hydrophilicity of bamboo poses a challenge to achieve optimal compatibility with hydrophobic polymer matrices, impede interfacial bonding, and reduce the effectiveness of fiber-reinforced composites. To address these hurdles, economical and environmentally sustainable heat treatment methods have emerged as pivotal tools for enhancing the surface properties of bamboo. Delving into the depths of thermal treatment research, this article meticulously summarizes the influences of varying temperatures, time, and medium on the structure of bamboo. Moreover, it reviews the mechanical properties and surface moisture content of bamboo after heat treatment, providing insights crucial for advancing the frontier of bamboo-based materials.

Keywords: bamboo materials, heat treatment, polymer matrix composites

1 Introduction

Composites have been applied in a wide range of experimental and industrial fields on account of their interesting mechanical properties and ease of production. These applications include aerospace, automotive, marine, packaging,

and construction fields. Composites have various features including low density, high chemical resistance, high specific strength, and modulus. However, due to the use of inorganic fibers, composites tend to exacerbate environmental pollution. Especially in recent years, China's consumption of various packaging materials has rapid growth. If effective measures are not taken to control this growth, it will bring a huge burden on resources and environmental pressure [1–8]. Therefore, people have begun to pay attention to developing and using green packaging materials. The development of green packaging should pay attention to the selection of green materials first. Natural fiber composites are widely used in diverse fields, from light industries like packaging to medical science. These factors include biodegradability, recyclability, strong mechanical properties, low toxicity, effective barrier capabilities, ease of processing, and outstanding attributes [9,10].

Bamboo fiber is one of the most natural and highly utilized materials. Bamboo has a lower density, lower cost, higher mechanical strength, better stiffness, excellent growth rate and the ability to fix atmospheric carbon dioxide. Its specific strength is almost equivalent to that of glass fiber. These advantages of bamboo have attracted more and more interest [11–17]. The benefit of bamboo fiber's mechanical properties lies in the longitudinal alignment of cellulose fibers within bamboo. Cellulose plays a key role in the structure of bamboo fibers. The content of cellulose contributes to higher tensile strength and elastic modulus. Bamboo's microfiber angle is relatively small ($2\text{--}10^\circ$) and it has a moderate lignin content of about 32% in various lignocellulosic fibers. The longitudinal modulus of their elasticity brings maximum elasticity to the fiber wall of the bamboo cellulose fibers, as well as their lignification improves the transverse rigidity. Bamboo is known as a significant plant fiber with great potential for application in the polymer composites industry [18]. Bamboo fibers have been utilized to enhance the performance of various composite materials [19]. They have been used to manufacture biodegradable packaging materials and to reinforce materials' mechanical strength and antimicrobial properties. A comparison of bamboo fibers with other fibers is shown in Table 1.

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Table 1: Comparison between bamboo fiber and other fibers [19–27]

Fiber	World production (10 ³ Ton per Year)	Diameter of fiber (μm)	Density (g·cm ⁻³)	Tensile strength (MPa)	Young modulus (GPa)	Elongation at break (%)
Bamboo	30,000	14	0.8–1.1	140–800	48–89	1.4
Hemp	214	10–51	1.5	690	30–70	1.6
Cotton	25,000	12–35	1.5	287–597	6–12.6	7–8
Jute	2,300	5–25	1.3–1.46	200–773	26.5	1.5–1.8
Kenaf	970	12–36	1.2	930	21–60	1.5
E-glass	—	13	2.5	2,000–3,500	70	2.5

In addition to the above advantages, bamboo is a renewable biological resource with more than 40 million hectares globally. Additionally, bamboo produces year-round, meaning that it is not a seasonal crop. It is recognized as the second most important forest resource and an important part of the world's plant resources. Bamboo is not only abundant but also has a short growth cycle. It can reach its optimal strength within three years. Therefore, bamboo is a suitable choice to investigate and develop in artificial fiber composites [2,24].

2 Characteristics of bamboo fibers and heat treatments

The mechanical characteristics of bamboo fibers are on par with those of synthetic fibers. Bamboo, as a lignocellulosic material, exhibits high hygroscopicity, which, in turn, affects the mechanical properties of composites reinforced with bamboo fibers due to their inherent weaknesses, including low wettability, hydrophilicity, poor moisture resistance of bamboo fibers, insufficient adhesion properties at the fiber–matrix interface, and the high content of starch and sugar in bamboo that may lead to biodegradation problems [28–33].

To enhance adhesion with different matrix materials as well as improve their surface properties, bamboo fibers must undergo treatment to reduce water absorption and improve mechanical characteristics. The interaction between bamboo fibers and the substrate can be enhanced through both physical and chemical approaches. Physical methods focus on altering surface properties without changing the fibers' structural composition, thereby improving the interfacial characteristics between the fiber and the matrix. On the other hand, chemical methods, including alkaline treatment, bleaching, acetylation, benzylation, vinyl grafting, peroxide treatment, and various coupling agent treatments, are commonly employed to modify the fiber structure and enhance bonding between the fibers and the matrix [34–38].

2.1 Significance of heating treatment

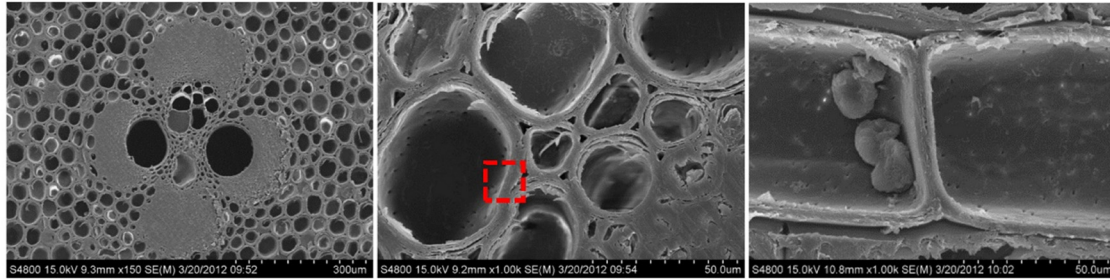
The heat treatment process is simple, environmentally friendly, and widely employed in wood modification. Currently, thermal treatment is also receiving more and more attention in the modification of the bamboo industry. It is also reported that a rapid heat treatment of bamboo at 160–220°C results in a variety of chemical reactions, including a certain degree of pyrolysis and condensation. Throughout this treatment, bamboo transforms its structure and chemical makeup, primarily due to the breakdown of hemicellulose and subsequent cellulose crystallization. The thermal processing notably decreases the levels of hemicellulose and hydroxyl groups within the bamboo's cell walls. These changes enhance the bamboo's physicochemical characteristics, notably reducing its tendency to absorb moisture and water.

This results in enhanced surface qualities, greater dimensional stability, and improved resistance to biological degradation [39,40]. Different heat treatment processes significantly impact on the chemical constituent and mechanical performance of bamboo, and the use of thermal treatment processes can be utilized to manufacture bamboo products with different properties, thus meeting the needs of products with different ranges of use. Heat treatment of bamboo is of great significance for environmental protection, expanding the application of bamboo-based fiber composites, realizing the efficient use of bamboo, and alleviating the contradiction between the supply and demand of wood.

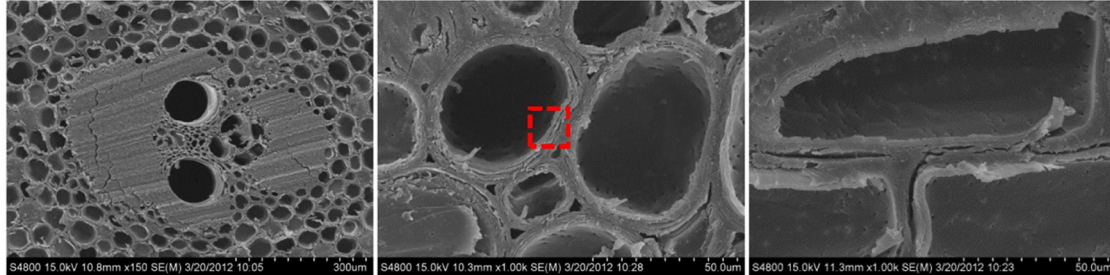
2.2 Methods of heat treatment

The impact of thermal processing on bamboo characteristics is highly dependent on factors like the heat intensity (temperature and duration) and the medium used for treatment, such as vacuum, gas, vapor pressure, and oil, which also has a certain influence on the results of heat

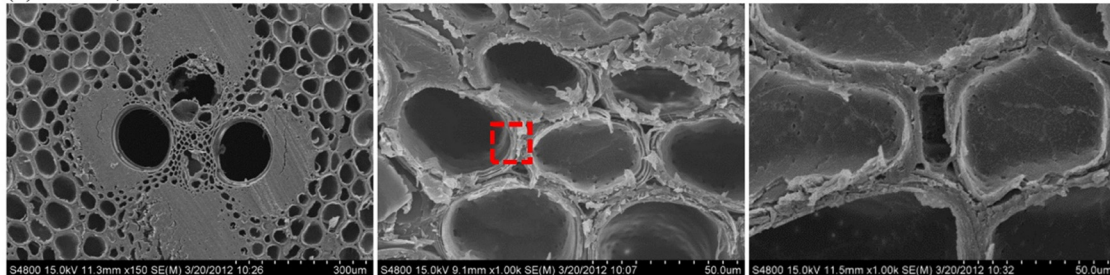
(a) Untreated



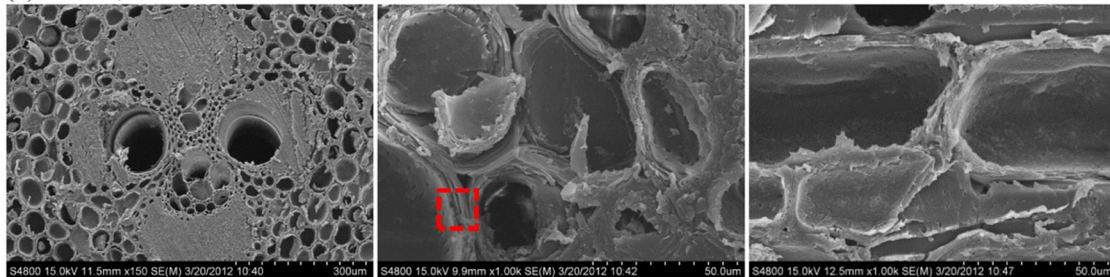
(b) 150 °C, 2 h



(c) 170 °C, 2 h



(d) 190 °C, 2 h



Vascular bundle (CS)

Parenchyma cells (CS)

Parenchyma cells (TS)

Figure 1: SEM images of bamboo specimens after treatment in the air for 2 h at different temperatures. Vascular bundles (transverse section, CS), parenchyma cells (transverse section, CS), and parenchyma cells (tangential section, TS) [31]. (a) Untreated, (b) 150 °C, 2 h, (c) 170 °C, 2 h, and (d) 190 °C, 2 h.

treatment, and these factors determine the final behaviors of bamboo after being heated.

The primary methods of high-temperature heat treatment for bamboo include oil, water, and vapor phase treatments. The first two methods have seen limited industrial

application globally, appreciated for their effectiveness in enhancing bamboo's physical and chemical attributes.

However, these hydrothermal and oil heat treatments are complex and time-consuming. During the process, bamboo tends to absorb significant amounts of oil and water, which

hampers further processing and utilization. Additionally, these methods pose challenges such as high operational costs and more complicated waste management [28,39].

3 Effects of heat treatment on the structure of bamboo

Bamboo is a natural fiber composite material with a multi-scale microstructure. Bamboo fiber bundles are distributed along a radial gradient, and the density of their numbers progressively rises from the inner side of the wall toward the outer side. Natural bamboo features a radial gradient structure, comprising vascular bundles encased by thin-walled cells. These are made up of blood vessels, phloem, and an abundance of bamboo fibers [41]. The vascular bundles are encircled by basic tissues, and the closer to the bamboo green, the denser the vascular bundles are; the less basic tissues there are, the denser they are.

Bamboo is mainly a complex natural polymer compound consisting of cellulose, hemicellulose, lignin, and extractives. Hemicellulose is the cell wall with cellulose tightly linked to the material which plays a role in bonding and it is the matrix material. Lignin permeates the fibers and contributes to the reinforcement and hardening of the cell wall. Changes in hemicellulose and cellulose content during thermal treatment influence the internal microstructure of bamboo [31,38,41]. Differences between the microstructures of bamboo under different thermal conditions by scanning electron microscope (SEM) have also been widely investigated.

3.1 Effect of heat treatment temperature and time on the structure of bamboo

During the heat treatment, the microstructure of bamboo changes. Lee's research focused on how different temperatures affect bamboo's structure [31], as depicted in Figure 1. In this study, bamboo samples were heat-treated using air as the medium. For those treated at 150°C, the examination revealed no significant damage to the structure of the cell walls, and the microstructure of the bamboo samples was almost unchanged compared with the untreated samples, which indicated that no significant compositional degradation had occurred.

As the temperature of the heat treatment increased, particularly when it exceeded 150°C, the thin-walled cells gradually showed shrinkage, cracks, and delamination of the fiber wall, indicating that the bamboo had begun to

chemically degrade. Yet, the architecture of the cell wall and the linkage between the vascular bundles and thin-walled cells suffered minimal damage. At temperatures close to 200°C, bamboo composition underwent significant degradation, resulting in substantial changes in the architecture of thin-walled cells, which became nearly detached from the vascular bundles. Fragility was observed in the denser fiber cells within the vascular bundles [31,32].

Wang et al. [39] used saturated water vapor for heat treatment of bamboo, and in the temperature interval of 150–200°C, the thin-walled cells in the bamboo stems began to shrink with the increase in temperature, the cell volume became smaller, and the structure of the thin-walled cell wall gradually changed. Zhang et al. [42] found in the study that when the temperature reached 160–200°C, as the temperature rose, the thin-walled cells of the bamboo stems, hemicellulose as the matrix material, degraded rapidly and the structure of bamboo changed thus affecting the mechanical performance of bamboo.

During the bamboo heat treatment process, the duration of heat exposure significantly impacts the bamboo's structure. Lee et al. [31] employed SEM imagery of samples treated at 210°C for varying durations to study the impact of treatment time on the anatomical structure of bamboo, with the findings presented in Figure 2. At a treatment time of 1 h, cracks became evident in the cell walls surrounding the vascular bundles. With the increase in treatment time, the cracks gradually increased. Upon reaching 4 h, significant warping and harm to the bundle sheath cells were evident. Wang et al. [39] also found in the study that after prolonged heat at 180°C, the structure of the thin-walled cell walls changed considerably, and the thin-walled cells became nearly detached from the vascular bundles, likely resulting not just from external high pressure but also from the decomposition of hemicellulose in the cell wall material, causing alterations in the bamboo's structure.

3.2 Effect of heat treatment medium on the structure of bamboo

When investigating the thermal treatment process of bamboo, the researchers successively used air, nitrogen (N₂), saturated steam, tung oil, and linseed oil, as thermally conductive media to study the effect of thermal treatment on the structure of bamboo. Heat-treated samples exhibited varied responses in distinct treatment environments. The presence of oxygen in the air hastened bamboo's thermal decomposition, whereas inert gases, such as nitrogen, shielded the bamboo from oxygen exposure and thus resulted in a more moderate reaction. Oil heat treatment prevented the bamboo from being

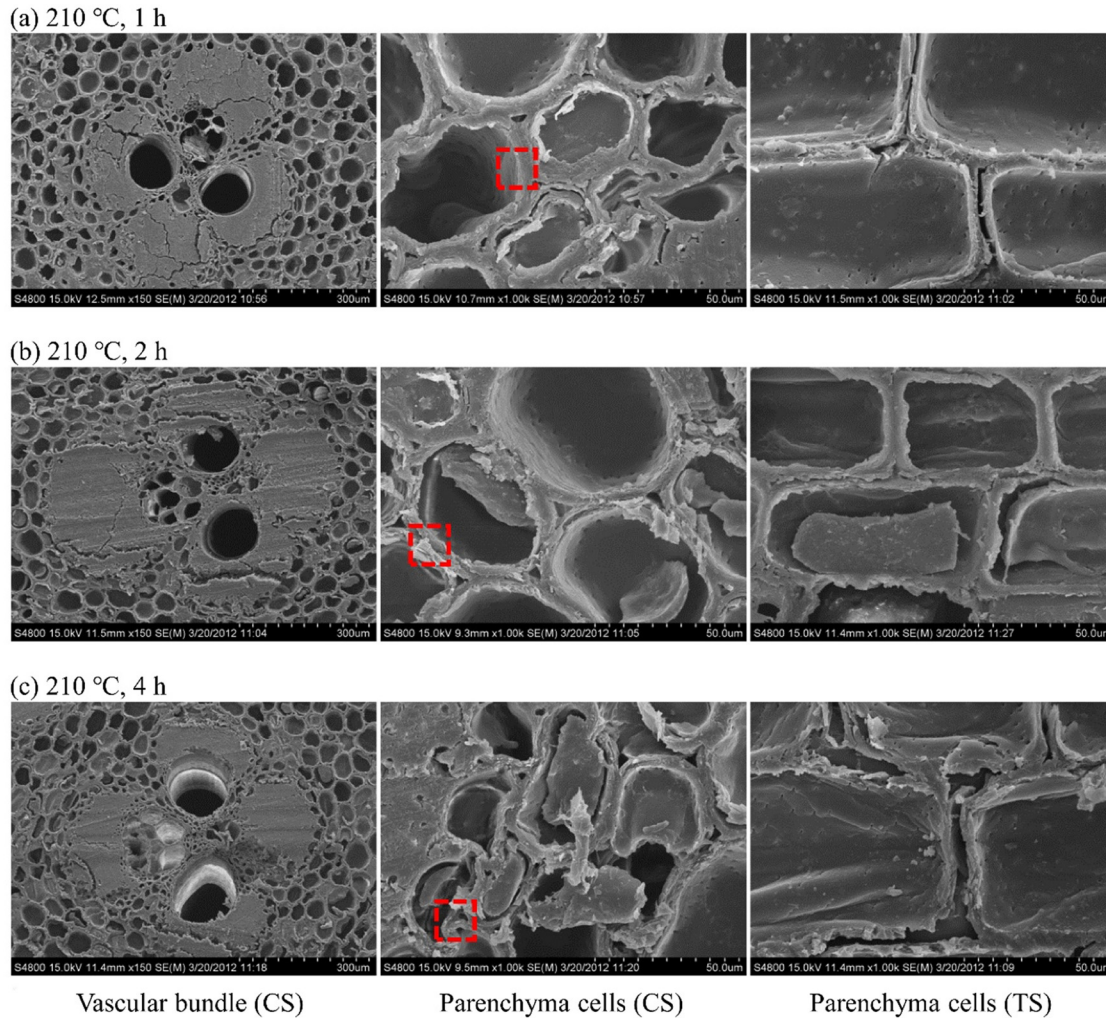


Figure 2: SEM images of vascular bundles (transverse section), parenchymal cells (transverse section, CS), and thin-walled cells (tangential section, TS) of bamboo specimens treated at different times in air at 210°C [31]. (a) 210°C, 1 h, (b) 210°C, 2 h, and (c) 210°C, 3 h.

exposed to oxygen and promoted a rapid and uniform heating effect by penetrating the internal structure of the bamboo, making the reaction more vigorous.

Oil is always utilized as a medium in the process of heat treatment, researchers have employed various oils, including palm, motor, and tung oil, to thermally treat bamboo at temperatures of 140–220°C for different durations, to explore its impact on bamboo's structure [43,44]. Lee et al. [31] found that based on the SEM results of heat-treated bamboo at 150°C and 170°C, despite the existence of the oil film on the surface of samples, the anatomical structure of the specimen was almost intact. The intact anatomical structure indicated that the bamboo did not have substantial compositional degradation. On the contrary, in the specimen treated at 190°C, the thin-walled cells were severely ruptured and delaminated due to intense compositional degradation. Elevated temperature oil-based heating processes can alter

bamboo's structural composition, increase its density, reduce dry shrinkage, and increase fiber crystallinity. However, in the process of high-temperature oil heating, the oil medium infiltrates the bamboo, leading to the formation of a slender oil film on the surfaces of the thin-walled cells and vessels' walls, as shown in Figure 3 [44].

In the study of the thermal processing of bamboo utilizing water vapor as a medium, different periods in the range of 140–180°C have been utilized to heat-treat bamboo [34,39–41,45,46]. Wang et al. [47] showed that the structure of thin-walled cell walls changed considerably when bamboo was heat-treated using water vapor for a long period at 180°C. The thin-walled cells were almost separated from the vascular bundles, which might be owing to the deterioration of the cell wall composition. Wang et al. [39] found that the saturated steam heat was effectively propagated within the wet bamboo slices, leading to the hydrolysis of a large amount

of hemicellulose. During saturated steam heat treatment, bamboo has a high initial moisture level and experienced significant water evaporation, resulting in some disruption of the bamboo's cellulose microcrystalline structure.

In the study of the thermal processing of bamboo utilizing gas as a medium, the influence of thermal treatment on the chemical composition, surface performance, microstructure, and thermal stability of bamboo was also explored at 140–200°C [30,38,48,49]. These studies reported changes in the microstructure of bamboo, reduced water absorption, and decreased shear strength due to high temperatures. Yang *et al.* [50] found that under identical temperature settings, N₂ could insulate the bamboo from oxygen interaction, thereby reducing internal thermal decomposition. As an example, the strength retention of heat-treated in three media at a temperature of 210°C was: N₂ (82.81%) > air (74.86%) > oil (70.57%). Lee *et al.* [31] heat-treated bamboo at 170°C using air and linseed oil, analyzed SEM photographs, and found that microstructural disruption of bamboo was

more severe after heat treatment under air conditions. These study findings suggest that various media impact the chemical makeup and architecture of bamboo differently, even under identical conditions of heat treatment intensity. The temperature, time, medium, and research results used by different researchers in the heat treatment of bamboo are shown in Table 2.

4 Effects of heat treatment on bamboo properties

4.1 Effect of heat treatment on mechanical properties of bamboo

The characteristics of fiber composites are contingent on the fiber concentration, interfacial properties, and so on.

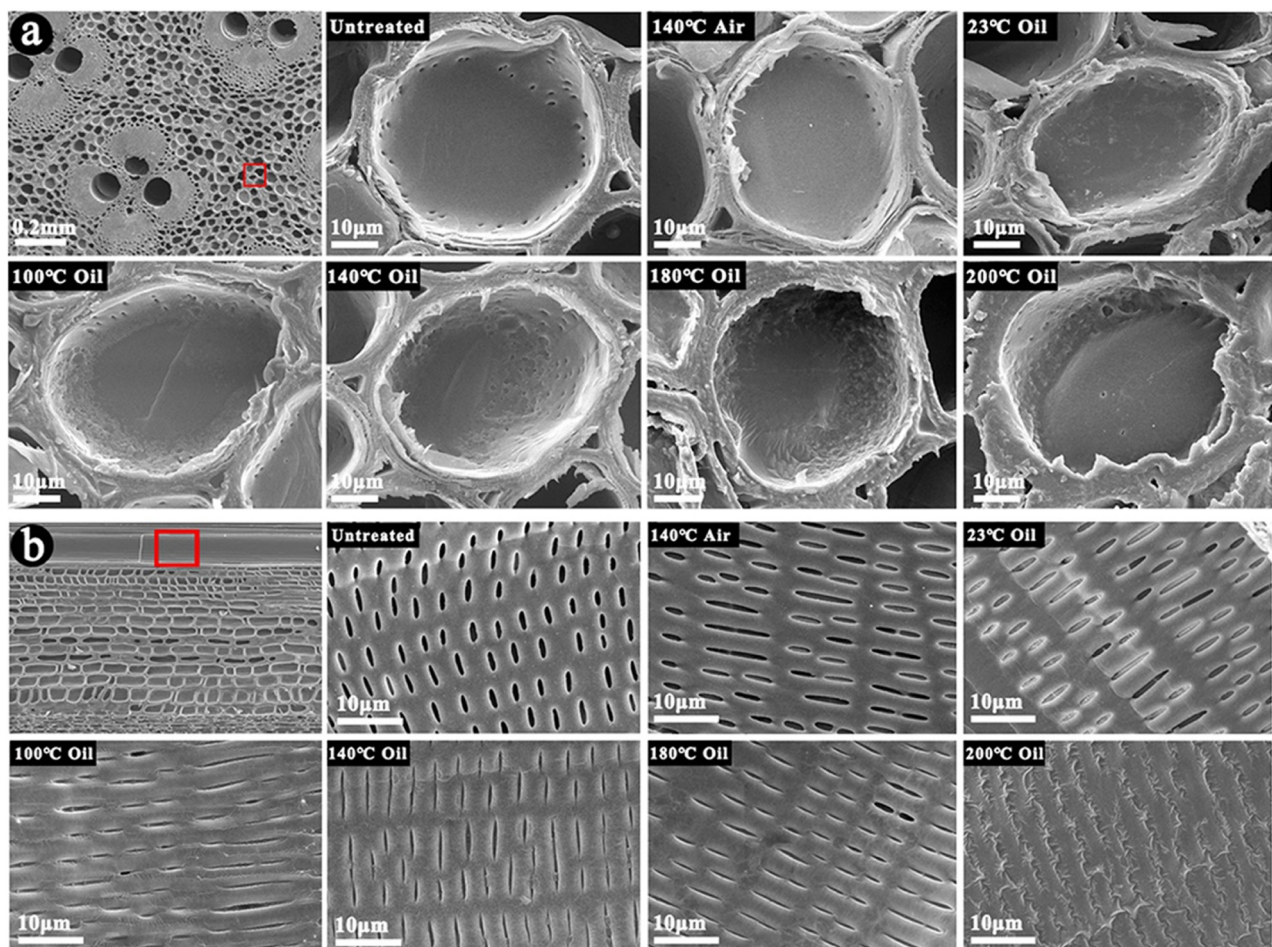


Figure 3: SEM images of different bamboo samples. Transverse section with (a) thin-walled cells and (b) pits in the radial wall of the meso-xylem conduit [44].

Table 2: Bamboo heat treatment process

Thermal conductive medium	Heat treatment process		Research result	Bibliography
	Temperature	Time		
Saturated vapor	180°C	10, 20, 30, 40, and 50 min	Throughout the thermal processing phase, the color of bamboo becomes darker and the overall color change is uniform. The initial water content and duration of thermal treatment of bamboo had a large effect on a^* , b^* , and L^* co-ordinates in CIELAB color space. [46]	
Vapor	180–220°C	1 and 3 h	The heat treatment's temperature and duration markedly influenced bamboo's surface wettability. Post-heat treatment alterations in bamboo's cell wall constituents led to a decrease in its surface wettability. [51]	
Air	160–220°C	2, 3, and 4 h	The color of the bamboo slices deepened uniformly after thermal process. The influence on the color index was more significant than that of heat treatment time. [52]	
Air	150–210°C	2, 3, and 4 h	As the temperature of heat treatment rose and the duration extended, there was a diminishing trend in both the dry shrinkage and wet expansion rate of bamboo. [53]	
Air	160–200°C	4 h	Simultaneously, the primary mechanical properties of bamboo progressively declined. The lignin content tends to increase as the heat treatment temperature increases, and elevated temperatures can enhance bamboo's dimensional stability but may diminish its mechanical characteristics. [54]	
Tung oil	23–200°C	0–180 min	Bamboo subjected to tung oil heat treatment exhibits enhanced hydrophobicity and dimensional stability, increased resistance to fungi, and maintains good mechanical properties. [44]	
Saturated vapor	140–180°C	10–30 min	The equilibrium moisture content of the bamboo gradually decreased after thermal process saturated steam treatment. Both the temperature and time affected the mechanical performance of bamboo. Compared with the modulus of rupture (MOR), the modulus of elasticity (MOE) of bamboo was susceptible to the saturated steam heat treatment. [47]	
Air, N ₂ , and linseed oil	150–210°C	1, 2, and 4 h	The treatment temperature and time had significant influences on the surface color and contact angle of bamboo. Higher temperature resulted in a darker color and increased contact angle. Bamboo treated with tung oil demonstrates improved hydrophobicity, dimensional stability, enhanced resistance to fungi, and sustained good mechanical properties. [50]	
Air	100–220°C	6 h	The microstructures of fiber cells and thin-walled cells were gradually changed with the increase of treatment temperature. The heat treatment notably enhanced the thermal stability of the thin-walled cells. [38]	
Palm oil	140–220°C	30 min, 60 min	The degradation of cellulose and hemicellulose in heat-treated bamboo results from the softening of lignin under heating conditions, along with the hydrolysis of starch content. [43]	
Air	180°C	4 h	Heat-treated bamboo has a much lower moisture content in both fast and slow processes, especially at higher relative humidity. Also, after heat treatment, surface wettability is reduced and dimensional stability is increased. [30]	
N ₂	180–220°C	2 h	[28]	

(Continued)

Table 2: Continued

Thermal conductive medium	Heat treatment process		Research result	Bibliography
	Temperature	Time		
Hot water, air and saturated vapor	80°C (hot water), 180°C (air), 135°C (saturated vapor)	2 h	Cellulose has high thermal stability. In addition, heat-treated bamboo sheets have a high Poisson's ratio due to reduced ductility along the loading direction and increased transverse shrinkage. After thermal process, the surface color of bamboo darkens and the relative lignin content increases. Saturated steam treatment gives higher color stability during ultra violet radiation. Heat treatment delayed, but did not prevent, photodegradation of bamboo.	[55]
Fluids	160–190°C	2 h	Oil heat treatment effectively improved the moisture absorption and dimensional stability of bamboo. The MOR of oil-heat-treated bamboo increased at 165 and 175°C but declined when the temperature reached 190°C.	[56]
Air, N ₂ , and linseed oil	150–210°C	1, 2, and 4 h	Compared with the control samples, the MOE and MOR of bamboo did not decrease significantly at lower than 200°C, mainly owing to the absorption of tung oil, which stabilized the cellulose proportion as well as the increase of cellulose crystallization.	[50]

Being a natural fiber composite, bamboo undergoes high-temperature heat treatment that alters its chemical composition and microstructure, resulting in modifications to its mechanical properties. Researchers have investigated heat-treated bamboo [28,39,44,57] and its composites [45,48] with a particular emphasis on how the intensity of heat treatment influences bamboo's mechanical properties, including the modulus of elasticity (MOE) and modulus of rupture (MOR), among others, as shown in Figure 4.

For the thermal process of bamboo with tung oil, Tang [44] found that the MOE and MOR increased when the temperature remained under 140°C. Even when the temperature was increased to 200°C, the MOE and MOR were higher than those of the untreated samples. The findings indicated that heat treatment in tung oil at temperatures below 200°C preserved favorable mechanical properties.

In addition, the heat temperature was controlled at 100–220°C in the air for 1–4 h [42]. It indicated that the MOR first rose and then declined. When it reached higher than 160°C, the MOR decreased with the relatively increasing temperature and treatment time. And when the treatment temperature exceeded 200°C, the MOR decreased significantly. The influence of heat treatment on the MOE was less pronounced compared to its effect on MOR. The highest value was observed at 140°C, and an inflection point occurred at 200°C. The MOE experienced a notable decline when the samples underwent heat treatment above 200°C (Figure 4). At the beginning of heat treatment, the increase in the MOR and MOE may be due to higher density and cellulose crystallinity. When bamboo underwent heat treatment at 200–210°C, cellulose degradation emerged as the primary cause for the diminished mechanical properties, in contrast to untreated samples. As the temperature of the heat treatment escalated, there was a reduction in the hydroxyl group peak in bamboo. This treatment process led to cellulose degradation and a subsequent decrease in hydroxyl and other hygroscopic groups. Consequently, these changes under the influence of chemical composition resulted in reduced crystallinity in bamboo, thereby impacting its mechanical properties [24,42,44,50]. Despite the observed reduction in mechanical properties, it was noted that the extent of strength decline varied according to the different treatment media [50].

As the intensity of heat treatment escalated, a continuous decline in the MOR of bamboo fiber composites was observed, whereas the MOE experienced minimal changes, as depicted in Figure 5. This trend aligns with the alterations in bamboo's mechanical properties following heat treatment. Bamboo fiber composites consist of reinforcing material (bamboo fiber material) and matrix material (generally polymer). As the intensity of heat treatment increased, there was gradual degradation of hemicellulose.

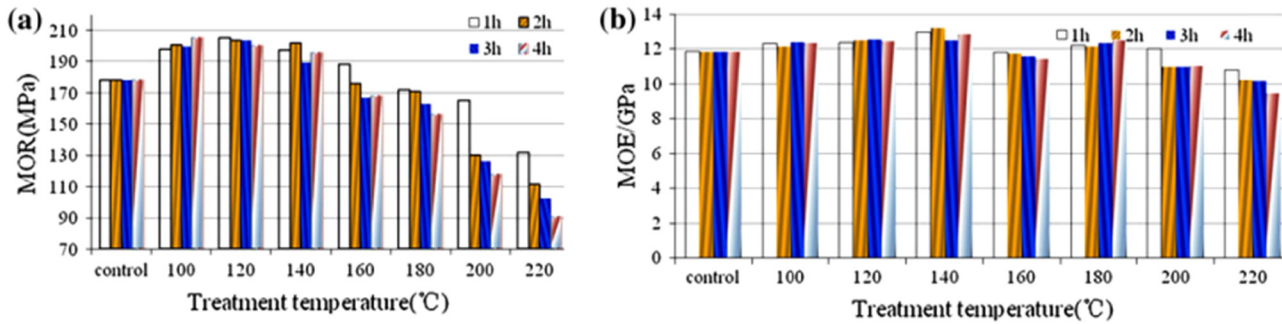


Figure 4: Effect of heat treatment Effect of thermal treatment on MOR (a) and MOE (b) [42].

Hemicellulose, a cell wall component tightly linked with cellulose, plays a bonding role. Its degradation leads to decreased performance of the reinforcing material, thereby affecting the overall composite behavior. The MOE characterizes the stiffness of the material, with lignin contributing to its hardness and stiffness. In the thermal process, the polysaccharide proportion decreased, resulting in lignin relative content increases and hence, the change in MOE is not significant [45,48]. A comparison of several mechanical properties of bamboo under several different heat treatment conditions is shown in Table 3.

4.2 Effect of heat treatment on surface wetting properties

The compositional and microstructural changes resulting from bamboo thermal processing impact the mechanical performance and the interface of bamboo. Lee et al. [31] observed an increase in the contact angle for bamboo samples across all treatment groups following heat treatment. Moreover, longer treatment durations and higher treatment

temperatures were associated with greater increases in the contact angle. The degradation of amorphous cellulose and increased crystallinity of bamboo may be one of the reasons for the above-mentioned changes in contact angle and enhanced water-repellent properties of the bamboo surface. Furthermore, the displacement and breakdown of fatty substances and waxes in bamboo under elevated temperature conditions further affected the surface hydrophobicity of bamboo.

For thermally processing bamboo, Tang et al. [44] selected tung oil as a medium. The result showed that both thermal treatment and tung oil alteration enhanced the short-term water resistance of bamboo. In contrast, bamboo samples with the simultaneous action of heat treatment and tung oil exhibited improved and more durable water repellency. The hydrophobicity of bamboo increased as the heating temperature rose (Figure 6).

For natural fiber polymers, the polymer matrix is hydrophobic. Fibers with lower hydrophilicity, i.e., smaller contact angles, have a higher affinity to the matrix, which aids in creating a strong interfacial bond between the matrix and the bamboo fibers.

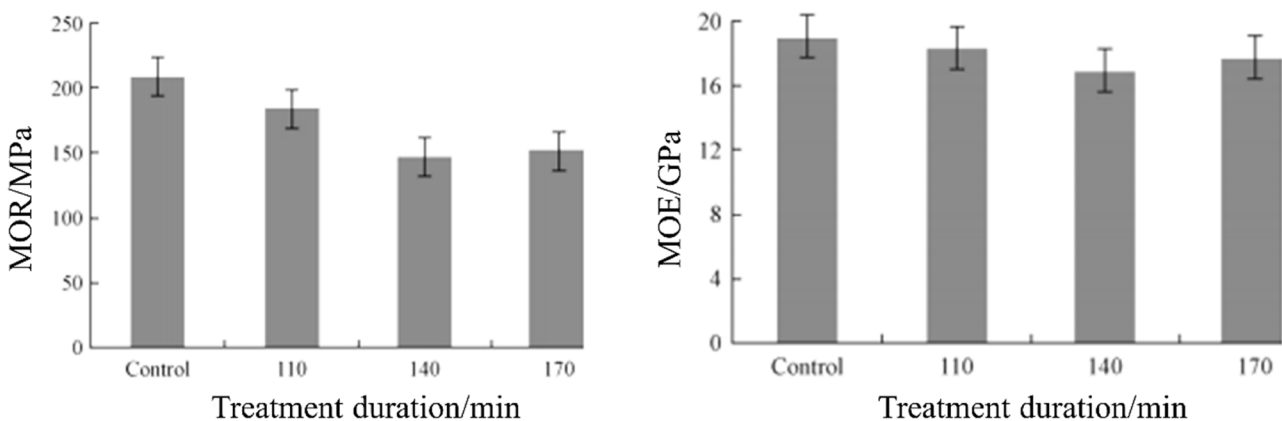


Figure 5: Impact of thermal processing on the mechanical characteristics of bamboo composites [45].

Table 3: Mechanical properties of bamboo under different heat treatment conditions

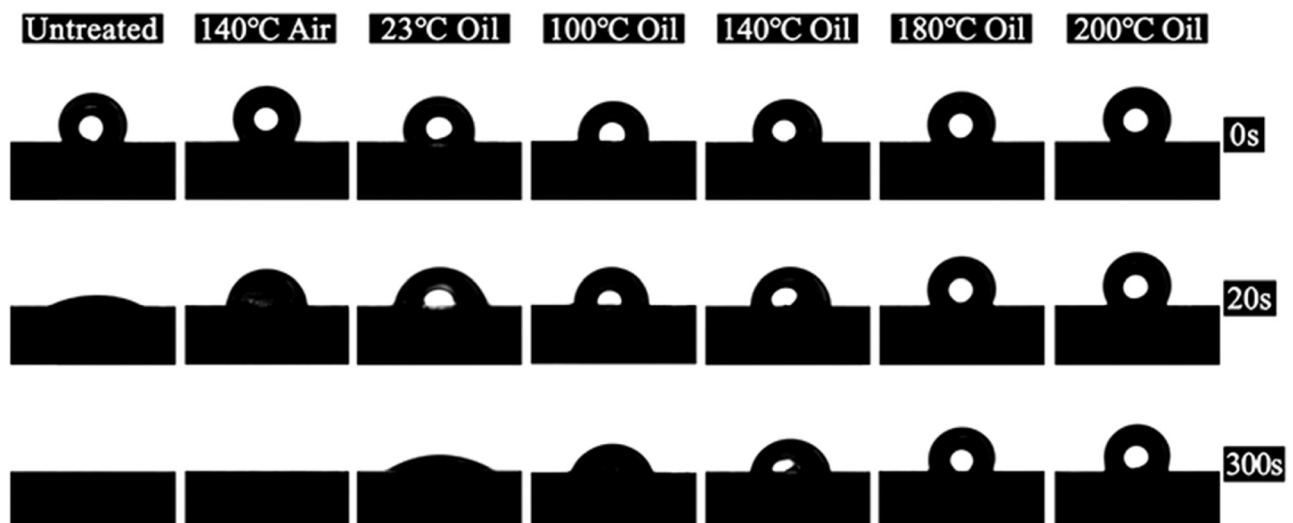
Treatment condition	MOE (GPa)	MOR (MPa)	Bibliography
Untreated	8.4	122.4	[58]
Hot water (140°C, 60 min)	7.7	104.6	
Hot water (140°C, 120 min)	7.8	92.5	
Hot air (150°C, 2 h)	12.4	157.1	[50]
Hot N ₂ (150°C, 2 h)	11.2	152.7	
Hot oil (150°C, 2 h)	12.0	158.3	
Hot air (170°C, 2 h)	11.4	132.4	
Hot N ₂ (170°C, 2 h)	11.6	149.9	
Hot oil (170°C, 2 h)	10.4	125.3	
Hot air (190°C, 2 h)	11.1	135.0	
Hot N ₂ (190°C, 2 h)	10.6	140.4	
Hot oil (190°C, 2 h)	10.3	121.3	
Hot air (210°C, 2 h)	11.2	100.7	
Hot N ₂ (210°C, 2 h)	10.4	109.2	
Hot oil (210°C, 2 h)	10.3	111.6	
Vacuum heating (120°C, 90 min)	20.8	186.5	[59]
Vacuum heating (140°C, 90 min)	21.2	196.2	
Vacuum heating (160°C, 90 min)	20.9	187.2	
Vacuum heating (180°C, 90 min)	21.4	211.0	
Microwave (4 kW, 70°C)	12.2	150.7	[60]
Microwave (4 kW, 80°C)	12.7	158.2	
Microwave (4 kW, 90°C)	11.0	154.4	
Hot air (70°C)	10.5	155.2	
Hot air (80°C)	10.7	155.7	
Hot air (90°C)	10.7	155.3	
Untreated	0.68	22.2	[61]
Hot air (100°C, 15 min)	0.41	13.0	
Hot air (120°C, 15 min)	0.31	10.2	
Hot air (140°C, 15 min)	0.25	10.9	
Hot air (160°C, 15 min)	0.22	9.7	
Hot air (200°C, 15 min)	0.23	11.7	

5 Conclusions and outlook

Bamboo stands out as a green and sustainable resource that emerges as a highly promising material owing to its unique attributes such as light-specific density and fast growth rate. Its perennial availability throughout the year further enhances its appeal for various applications, particularly in the realm of green and environmentally friendly packaging materials (e.g., antimicrobial food packaging, biodegradable packaging, and wrapping paper). This article extensively investigates the effects of temperature, time, and medium on the structural properties of bamboo subjected to heat treatment and reviews the resulting mechanical and surface-wetting properties.

The judicious application of heat treatment at specific temperature and time parameters has been shown to significantly alter the chemical composition and microstructure of bamboo. Such transformation not only enhances the interfacial compatibility between bamboo or its fibers and the polymer matrix but also augments the mechanical properties of both bamboo and bamboo-based composites. However, in spite of the progress made in bamboo heat treatment technology, there are still some avenues to be further explored and improved:

- (1) Scaling up heat treatment technology: Transitioning bamboo heat treatment from lab-scale to large-scale, batch applications poses a significant challenge. Addressing this issue requires innovative approaches and technologies to ensure the scalability, efficiency, and consistency of the treatment process.
- (2) Optimizing compatibility with matrix materials: Achieving the optimal match between the degree of bamboo heat treatment and various matrix materials is essential to maximizing the performance and durability of bamboo-based composites. Further research is needed to delineate

**Figure 6:** Influences of thermal process intensity on the contact angle of bamboo [44].

the ideal combination that balances structural integrity with environmental sustainability.

- (3) Exploring form factors for bamboo matrix composites: Investigating the most effective form of bamboo application in green packaging composites is of paramount importance. Whether in powder form, bamboo fibers, strips, or blocks, determining the optimal form factor can significantly improve the overall performance and applicability of bamboo-based composites in packaging materials.

As the demand for natural fiber composites continues to rise, the focus on bamboo heat treatment technology is poised for further growth. Through concerted efforts to address the above-mentioned areas, bamboo-based composites are primed to witness broader adoption, thereby contributing to the proliferation of sustainable solutions across diverse industries.

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Data availability statement: All data generated or analyzed during this study are included in this published article.

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