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The Influence of Treatment Methods on Bending Mechanical Properties of Bamboo Strips

Shiyu Cao [1], Jiagui Ji [2], Haowei Yin [1] and Xuehua Wang [1,*]

[1] College of Furnishings and Industrial Design, Nanjing Forestry University, Nanjing 210037, China; shuyu@njfu.edu.cn (S.C.)
[2] Zhejiang Sanjian Industry & Trade Co., Ltd., Lishui 323800, China
* Correspondence: wangxuehua@njfu.edu.cn

Abstract: This study aimed to obtain a comprehensive understanding on bamboo as a curve-member manufacturing material by comparative analysis of how different treatment methods on bending properties improve the effect on bamboo strips. In order to achieve this purpose, bamboo strips were subjected to water boiling, 15% NaOH, and 25% NH_3 impregnation; the impact of physical, mechanical and chemical properties were explored. The results revealed that: (1) Water boiling significantly affected crystallinity, cellulose, and lignin content, with a treatment duration of 10 h showing the most favorable results for flexibility and plasticity, greatly improving bending performance. (2) An amount of 15% NaOH treatment significantly increased bending MOE and plastic displacement by 73% and 122.7%. However, it led to a noticeable decrease in bending strength (MOR). A treatment above 8 h could cause irreversible damage to bamboo strips. (3) The improvement of 25% NH_3 on bamboo bending ability was lower than water boiling. The effects of chemical composition were obvious in the initial five days and changed little after five days. Generally, water boiling for over 10 h is suitable for applications with significant bending requirements. While for maintaining bamboo color, original strength, and bending performance, 25% NH_3 for five days was recommended, and 15% NaOH was not advised for improving bamboo bending performance and its applications.

Keywords: bamboo bending ability; treatment methods; comparison; toughness enhancement; chemical composition

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1. Introduction

China produces bamboo resources which are widely distributed. Bamboo has short growth cycles, and possesses high strength and bending ability. Bamboo has extensive applications in various fields such as construction, furniture, and handicraft production. Despite the extensive research dedicated to the bending applications of wood [1], the utilization of bamboo in bending modification and application are relatively constrained [2], necessitating further exploration and investigation.

The bending performance of bamboo strips is influenced by treatment methods, such as heat treatment and chemical treatment, which significantly alter the mechanical properties of bamboo strips [3]. In recent years, scholars have conducted preliminary studies on the chemical composition changes of bamboo strips under different treatment temperatures and conditions [4]. Fang et al. found that alkali water boiling not only removes extractives but also affects the color of bamboo, thereby influencing its utilization [5]. Chu et al. investigated the structural changes of bamboo under different heat treatment temperatures and acid-base or glycerol treatment media. An increase in crystallinity was found at a hydrothermal temperature of 135 °C [6]. An et al. proposed that high crystallinity and oriented structure are crucial factors leading to poor bamboo bending performance, suggesting a reduction in crystallinity obtained through alkali treatment [7]. Xu suggested that bamboo color darkens, MOE and flexural strength decreases, and weight loss increases after heat treatment [8]. Zhang et al. discovered a decrease in cellulose and hemicellulose content in bamboo after heat treatment, accompanied by an increase in lignin and extractives content [9]. The aforementioned studies mainly focused on the influences of single variations by infrared spectroscopy, XRD changes, surface properties, or changes in chemical composition, and were mostly about raw bamboo or bamboo fiber; therefore, there is a lack of multidimensional comparison about bamboo strips [10].

Bamboo strips are the most widely used bamboo material in industrial applications. A comprehensive understanding of the different treatment methods holds significant importance for bamboo processing, offering insights that can be translated into practical industrial considerations. In order to meet the demand for high flexibility in bending applications, emphasizing the universality and versatility of bamboo, bamboo strips of *Phyllostachys edulis* (Carrière) J. Houz., which is known as moso bamboo, were obtained as the research object. Three different treatment methods, that is, water boiling, 15% NaOH impregnation, and 25% NH_3 impregnation, were used to enhance bending performance and the processing advantages of bamboo in this study. The bamboo strips underwent treatments of varying durations, and their physical and mechanical properties were tested. The changes in cellulose, hemicellulose, and lignin content before and after treatment were determined. Furthermore, X-ray diffraction (XRD) and Fourier-transform infrared spectroscopy (FTIR) were employed to confirm the influence of different treatment methods on the chemical composition and mechanical properties of bamboo [11]. The aim of this study was to provide a theoretical foundation for toughness enhancement in bamboo bending processing.

2. Materials and Methods

2.1. Materials

Moso bamboo strips were obtained from Zhejiang Sanjian Industrial & Trade Co., Ltd., Zhejiang province, Lishui, China. The selected bamboo strips were free from mold, discoloration, and were of uniform greenish-yellow color. Three-year-old bamboo tubes were obtained through a systematic sampling approach. In order to guarantee uniformity of the specimens, the green and yellow layers of the bamboo tube were eliminated, and the middle of the bamboo was selected and processed into bamboo strips (Figure 1). The bamboo strips were prepared according to the Chinese standard of GB/T 15780-1995 [12] testing methods for physical and mechanical properties of bamboo, with dimensions of 160 mm × 20 mm × 5 mm (longitudinal × tangential × radial).

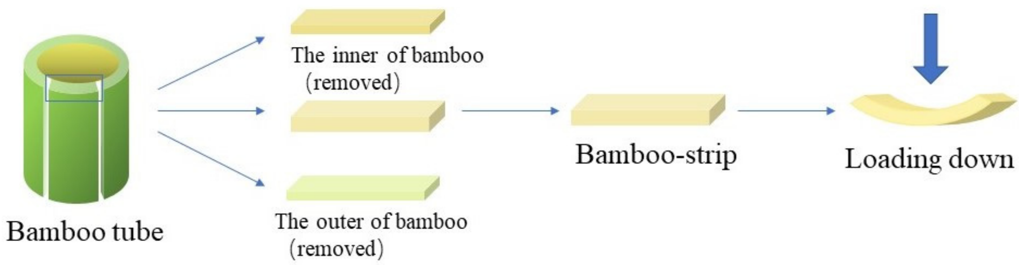

Figure 1. Diagram of the sampling location.

2.2. Sample Treatment

Three different treatment methods were applied to the bamboo strips and different treatment durations were used for each method (Table 1). The three treatment methods were hydrothermal boiling, 15% NaOH (mass content), and 25% NH_3 (mass content) solution impregnation. Following the water boiling treatment, the bamboo strips were immediately prepared for mechanical property testing. While after 15% NaOH and 25% NH_3 solution impregnation, the samples' surfaces were cleaned using water before mechanical performance testing.

Table 1. Treatment methods for bamboo strips.

Treatment Method	Treatment Duration	Other Information
Control	-	Room temperature
Water boiling	2 h, 4 h, 6 h, 8 h, 10 h	135 °C
15% NaOH	2 h, 4 h, 6 h, 8 h, 10 h	Room temperature
25% NH_3	5 days(d), 7 d, 9 d, 11 d, 13 d	Room temperature

2.3. Testing Methods

The bamboo strips were first subjected to bending mechanical property testing, and the destruction status after testing was recorded. Subsequently, their density was determined after drying. The dried bamboo was then ground into powder, and subjected to chemical composition testing (cellulose, hemicellulose, lignin), Fourier-transform infrared spectroscopy (FTIR), and X-ray diffraction (XRD) analysis.

A mechanical testing machine, MMW-50, Jinan Nair Testing Machine Co., Ltd., Shandong province, Jinan, China, was utilized for mechanical property testing. The mechanical property, modulus of rupture (MOR), and modulus of elasticity (MOE), were tested using the three bending method, according to Chinese standard GB/T 15780-1995 [12], and loading was at a rate of 10 mm/min. The elastic displacement (De) and plastic displacement (Dp) were obtained from the load-displacement curve by the equivalent elasto-plastic energy method (Figure 2). Each set of experiments was repeated 5 times, and the standard deviation was set as error.

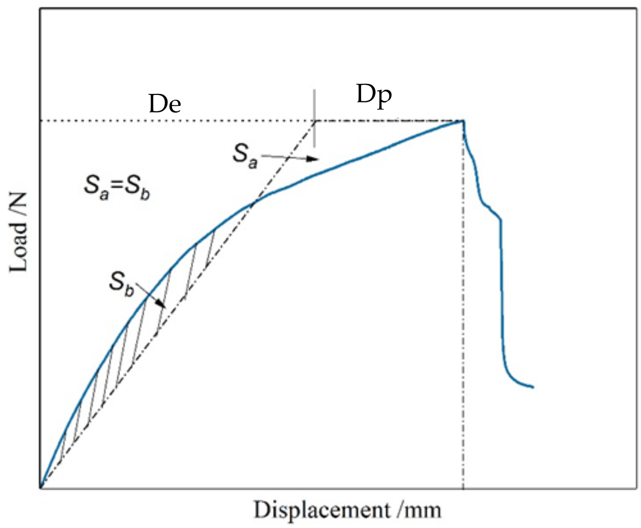

Figure 2. Testing method for De and Dp.

Chemical composition determination followed the methods of the National Renewable Energy Laboratory (NREL) in the United States. The treated bamboo strips were of the same specifications, thoroughly dried in a dry oven (DHG-9070A, Shanghai Jinghong Experiment Co., Ltd., Shanghai, China), and the content of cellulose, acid-insoluble lignin (AIL), and hemicellulose was determined, with each sample undergoing six parallel tests.

Infrared spectroscopy analysis utilized a Fourier-transform infrared spectrometer (VERTEX 80V, Bruker, Luken, Germany) and adopted the KBr pellet method. The powder, sieved through a 200-mesh sieve, was dried and made into KBr pellets (the ratio of bamboo power to KBr was 1:100). Infrared spectroscopy scanning was performed in transmission mode, ranging from 400 cm^{-1} to 4000 cm^{-1}, at a resolution of 4 cm^{-1} with 32 scans.

X-ray diffraction analysis utilized an X-ray diffractometer (AXIS UltraDLD, Shimadzu, Milton Keynes, UK). The powder, sieved through a 200-mesh sieve, was dried, placed on a test slide, and the crystallinity of the sample was analyzed using X-ray diffraction. The

X-ray source was CuKa, with a voltage of 40 kV, and a current of 40 mA. The scanning rate was 5°/min, and the diffraction angle ranged from 5° to 80°.

3. Results

3.1. Physical and Mechanical Properties

As water boiling time increased, the bamboo strips gradually changed from light yellow to reddish-brown (Figure 3a). As treatment time increased, the color deepened. Additionally, after drying, the volume and mass of the bamboo strips decreased. Mechanical testing revealed a small amount of bamboo fiber fracture on the surface, with the main body of bamboo strips remaining intact and maintaining relatively high strength.

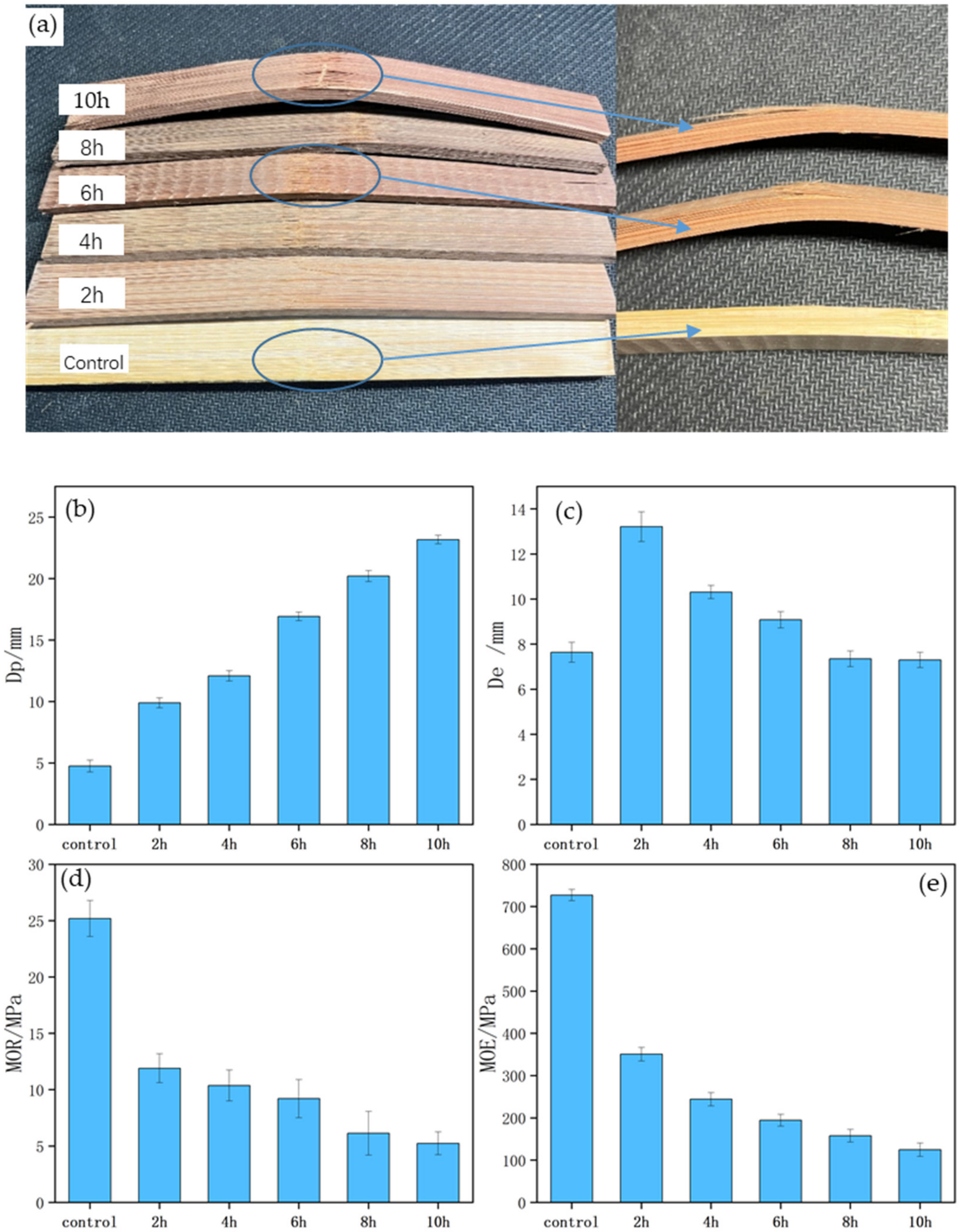

Figure 3. Mechanical and physical properties of bamboo strips using water boiling: (**a**) color and failure status, (**b**) plastic displacement (Dp), (**c**) elastic displacement (De), (**d**) bending strength (MOR), and (**e**) modulus of elasticity (MOE).

As water boiling time increased, both the modulus of rupture (MOR) (Figure 3d) and modulus of elasticity (MOE) (Figure 3e) significantly decreased. After 10 h, the MOR decreased by approximately 50% compared to 2 h, representing a reduction of 79.2% compared to the control, while the bending MOE also decreased significantly, showing an 82.5% reduction compared to the control. The change in elastic displacement was evident. At 10 h, elastic displacement increased by 387.9%, compared to the control (Figure 3b). The density decreased as water boiling time increased (Figure 4a). Compared to the control, the density decreased from 0.75 g/cm^3 to 0.56 g/cm^3 after 2 h of treatment. For 6 h and 8 h, there was a further significant decrease in density, MOR, and MOE. The density and mechanical performance reached minimum values after 8 h of treatment, with a 48% reduction in density compared to the control.

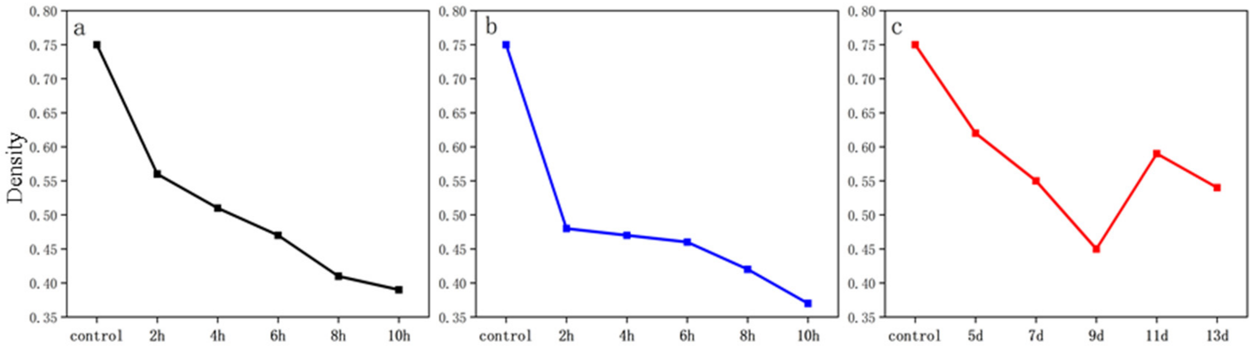

Figure 4. Density changes of bamboo strips for different treatments: (**a**) water boiling, (**b**) 15% NaOH, and (**c**) 25% NH_3.

The results aligned with previous studies about the impact of different treatments on bamboo properties. Furuta et al. [13–15] found that the MOE of bamboo slices decreased with increasing water temperature. When the temperature was 160 °C and time was 6 min, the softening effect on bamboo was better. As the temperature and duration increased, the hemicellulose structure changed obviously, which facilitated the softening of the bamboo. Similar to previous research, this study showed that a temperature of 135 °C and heating time adjusted from 2 to 10 h would be a suitable method for bamboo strips. The water boiling process provided reliable guidance for the batch processing and production of thick bamboo strips.

With an increased duration of 15% NaOH treatment, the bamboo strips gradually changed from light yellow to yellow-brown, which was darker than for the water boiling treatment (Figure 5a). The sample surface exhibited a large area of alkali attachment and residue. Moreover, the bamboo fiber damage was significant. As treatment time increased, the yellow-brown color deepened, the area of alkali attachment increased, and bamboo fiber damage intensified. After the mechanical test, bamboo fibers showed a brittle fracture at the force application site. The number and extent of fractures increased with the prolonged treatment duration. However, the volume and mass change after drying were relatively small.

The MOR and MOE of bamboo strips decreased after 15% NaOH treatment and exhibited an initial decrease followed by an increase between 2 and 8 h (Figure 5c–e). At 4 h, the MOR and MOE showed little change compared with 2 h. However, the MOR significantly decreased after 6 h, and the MOE experienced a precipitous drop after 8 h. Compared to the control, the MOR decreased by 57.3% and MOE decreased by 73% at 10 h. Elastic and plastic displacements (Figure 5b) decreased with the increasing treatment duration, ultimately reducing by 52.2% and 122.7%, respectively. Density exhibited a noticeable decline after treatment (Figure 4b). All mechanical properties reached their minimum values at 10 h.

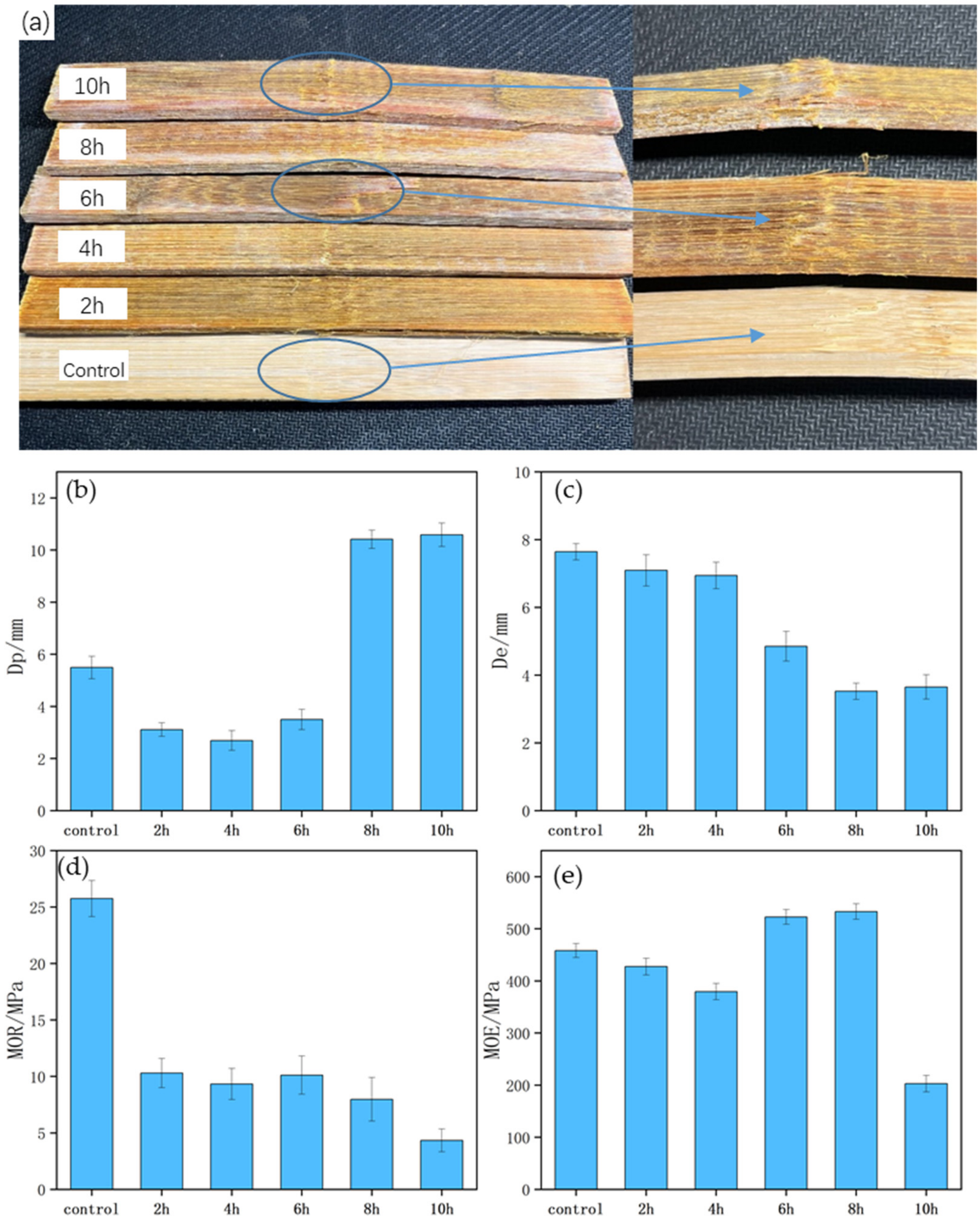

Figure 5. Mechanical and physical properties of bamboo strips using 15% NaOH treatment: (**a**) color and failure status, (**b**) Dp, (**c**) De, (**d**) MOR, and (**e**) MOE.

As 25% NH_3 treatment time increases, bamboo strips gradually changed from light yellow to reddish-brown, and the deepening of the reddish-brown color was relatively small (Figure 6a). After the mechanical test, bamboo fibers on the surface at 9 days(d) showed little fractures. A small amount of NH_3 solution residue was easily wiped clean. At 13 d, there were noticeable fiber fractures on the sample surface, while the change in volume and mass after drying was relatively small.

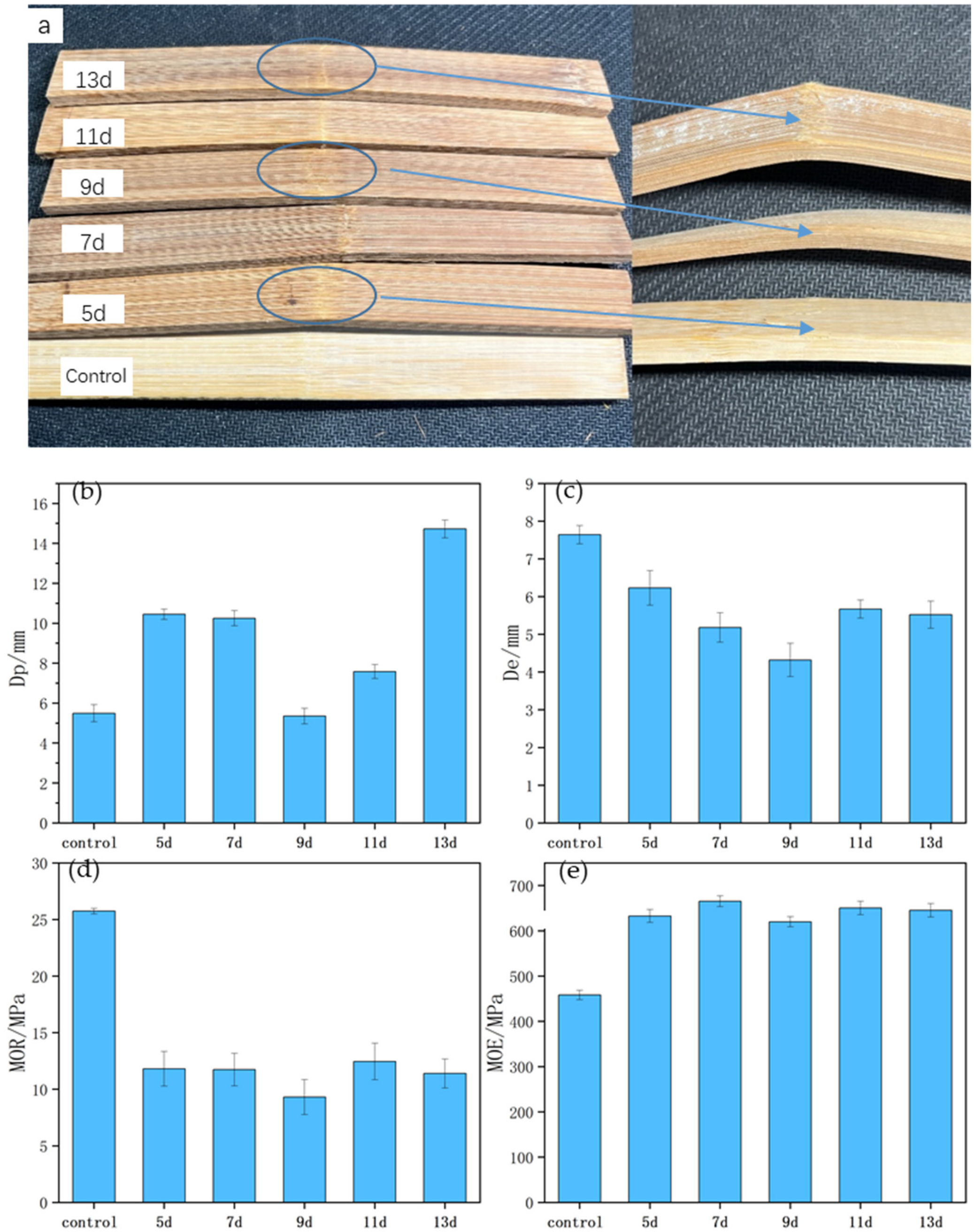

Figure 6. Mechanical and physical properties of bamboo strips using 25% NH3 treatment: (**a**) color and failure status, (**b**) Dp, (**c**) De, (**d**) MOR, and (**e**) MOE.

MOR of bamboo strips decreased, while the MOE increased after 25% NH_3 treatment. Between 5 d and 11 d, it exhibited an initial decrease then increase, and there was a slight decrease at 13 d compared to 11 d. The mechanical property was lowest at 9 d, elastic displacement, plastic displacement, density (Figure 6c), MOR, and MOE decreased by 43.4%, 12.6%, 63.8%, 40%, 66.8%, and 49.2%, respectively, compared to the control (Figure 6b–e).

Li et al. [15] found that the concentration of ammonia solution was 25%, while the sodium hydroxide solution between 10% and 15% was more suitable for the softening treatment of bamboo strips. Based on the previous research, the processing time was optimized and refined in this study, and the results of the alkali treatment were roughly the same as previous studies in terms of ammonia treatment. However, in the sodium hydroxide treatment, this research found that it was more destructive to bamboo, which might be due to the extended concentration and soaking time.

3.2. X-ray Diffraction (XRD)

The 2θ positions of the XRD diffraction peaks for bamboo were observed at 15.8° and 22°, representing characteristic peaks of the cellulose structure [16]. Throughout the treatment process, there was no significant change in the crystalline structure of cellulose [17], while the crystal plane angles and crystallinity changed with treatment duration (Figure 7, Table 2).

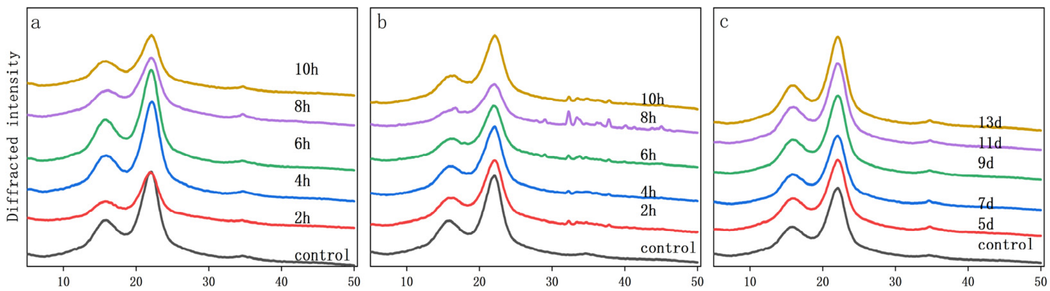

Figure 7. X-ray diffraction of bamboo strips for different treatment methods: (**a**) water boiling, (**b**) 15% NaOH, and (**c**) 25% NH_3 treatment.

Table 2. Crystallization characteristics of bamboo strips using different treatment methods.

Treatment Method		2θ/°	RC/%	Treatment Method		2θ/°	RC/%	Treatment Method		2θ/°	RC/%
Control	-	21.65	51.45	-	-	-	-	-	-	-	-
Water boiling	2 h	22.15	59.66	15% NaOH	2 h	22.02	61.32	25% NH_3	5d	21.85	53.32
	4 h	22.42	61.89		4 h	21.96	59.45		7d	21.86	52.45
	6 h	22.56	62.22		6 h	21.65	58.62		9d	22.02	52.43
	8 h	22.64	63.34		8 h	21.45	57.78		11d	22.04	52.23
	10 h	22.78	64.75		10 h	21.19	54.45		13d	22.03	51.89

Note: 2θ—002 crystal plane angle, RC—Relative crystallinity.

The diffraction peaks of the crystal plane were concentrated at a range of 21° to 22.7°, which indicates that the 101 crystal plane angle (2θ) of bamboo strips did not show significant changes after processing [18]. The treatment could only reach the noncrystalline region of cellulose and could not penetrate the crystalline region. It did not alter the results in the crystalline region [19], and there was no change in the crystalline layer distance [20]. This result was consistent with the research findings of Sun.

As to the crystallinity, the crystallinity gradually increased as water boiling treatment time increased. The crystallinity noticeably decreased with increasing treatment time in 15% NaOH immersion, and the decrease in crystallinity was not significant, showing a relatively small change in 25% NH_3 immersion. The decrease in crystallinity after alkali treatment indicated an irregular molecular arrangement inside the material, weakening its stability, which was related to the degradation of cellulose in the crystalline region [21]. Additionally, alkali treatment changed the microcrystal width of the bamboo microfibers, leading to decreased stability. After water boiling treatment, the crystallinity of the bamboo strips increased, causing changes in thermal stability [22]. Under the influence of heat, hydroxyl groups between cellulose molecular chains in the amorphous region undergo condensation reactions, causing a rearrangement of cellulose molecular chains and crystallization in the quasi-crystalline region, thereby increasing the relative crystallinity of the bamboo strips [23].

3.3. Infrared Spectroscopy

In the infrared spectroscopy region of wavenumbers between 4000 cm^{-1} and 2000 cm^{-1}, the spectra mainly reflect stretching vibrations of hydrogen-containing groups and the presence of triple bonds and cumulative double bonds. Strong absorption peaks at 3450 cm^{-1} and 2945 cm^{-1} represented the stretching vibrations of –CH and –OH groups, respectively. This region underwent some shifts during water boiling, but the shift effects were relatively minor in 15% NaOH and 25% NH3 treatments (Figure 8). Under water boiling, the hydroxyl group became active, and the water in the bamboo provided space for the hydroxyl group to move [24].

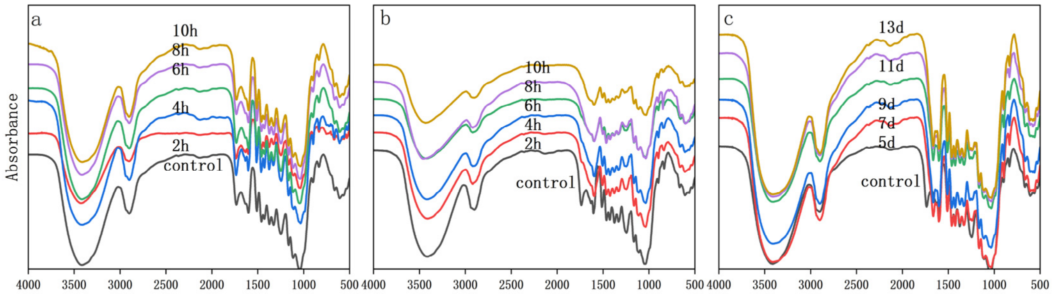

Figure 8. Infrared spectra diffraction of bamboo strips for different treatment methods: (**a**) water boiling, (**b**) 15% NaOH, and (**c**) 25% NH_3 treatment.

In the infrared spectroscopy region of wavenumbers between 2000 cm^{-1} and 800 cm^{-1}, more information about the changes in chemical composition was provided. In the water boiling and 15% NaOH treatments, the intensity of the absorption peaks gradually weakened with increasing treatment time, while there was almost no change in the 25% NH_3 treatment.

Therefore, we primarily discussed the first two treatment methods. The highest peak at wavenumber 1750 cm^{-1} was caused by ester bonds of acetyl, ester, or carboxyl groups [25]. The peak at 1632 cm^{-1} represented the stretching vibration of the conjugated carbonyl group, and its weakening indicated the damage to hydroxyl and conjugated carbonyl groups [26]. The absorption peaks at 1600^{-1} and 1500 cm^{-1} showed no significant changes, suggesting the relative stability of the benzene ring framework without apparent alterations. The weakening of the absorption peak at wavenumber 1244 cm^{-1} was due to the stretching vibration between the benzene ring and oxygen bonds. Changes in the intensity of the absorption peak at wavenumber 1376 cm^{-1} was caused by C–H stretching vibrations on phenolic hydroxyl groups. The weakening of the absorption peak at wavenumber 1043 cm^{-1} indicated a reduction in the quantity of C–O bonds.

3.4. Chemical Composition

All three treatment methods affect the chemical constituent content. The relative content of cellulose and hemicellulose all decreased. Compared with the control group, after the three treatments, the relative contents of cellulose and hemicellulose decreased significantly, while lignin increased slightly. In water boiling, the relative content of cellulose and hemicellulose gradually increased, while lignin increased lightly as treatment time increased. In the 15% NaOH treatment, the relative content of cellulose and hemicellulose initially decreased and then increased, with a gradual increase in lignin's relative content as treatment time increased. In the 25% NH_3 treatment, the relative content of cellulose and hemicellulose changed slightly in a pattern; initially, it decreased and then increased, with a slight decrease in lignin's relative content as the duration of the treatment increased (Figure 9).

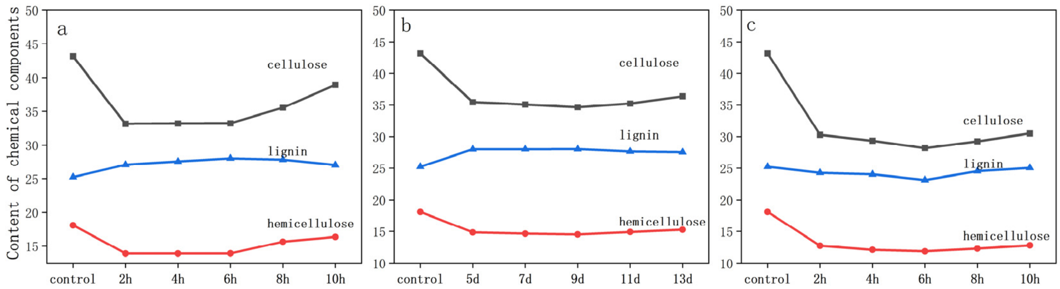

Figure 9. Infrared spectra diffraction of bamboo strips for different treatment methods: (**a**) water boiling, (**b**) 15% NaOH, and (**c**) 25% NH_3 treatment.

The chemical composition concentration changes of bamboo strip after water boiling were the main reason for alterations in bamboo color, mechanical properties, and density [27]. The result of the cellulose and hemicellulose relative content that increased with treatment time was consistent with the findings of Meng et al., who suggested that the chemical constituent content increase was due to the difficulty of macromolecules to degrade and other small molecule substances were lost because of thermal reactions or dissolution in the alkaline solution [28]. Due to the relatively good thermal stability of lignin, its content was less affected but increased compared to the control. This increase was not a substantial increase in lignin content, but rather a result of the degradation of cellulose and hemicellulose, leading to an increase in lignin's relative percentage content in the bamboo matrix [29]. Additionally, the degradation of cellulose and hemicellulose, being similar to lignin, would be mistakenly calculated as acid-insoluble lignin in the current detection method, further increasing the relative content of lignin [30].

In 15% NaOH and 25% NH_3 treatments, both were alkaline, and they had a certain decomposition effect on cellulose and hemicellulose. Therefore, the relative content of cellulose and hemicellulose initially decreased, reaching the lowest point at 6 h (15% NaOH) and 5 d (25% NH_3). With increasing treatment time, the alkaline solution disrupted the cell wall structure of bamboo, causing more small molecule substances to dissolve [31], and the relative content of cellulose and hemicellulose to increase again [32]. Regarding lignin, the 15% NaOH had a stronger decomposition ability compared to the 25% NH_3, resulting in much lower lignin content than the control and the other two treatment methods. Bamboo strips treated with 15% NaOH also exhibited noticeable discoloration and structural damage (Figure 2).

3.5. Correlation and Comprehensive Analysis

Based on the above data, a correlation was shown in Figure 10. The density of the bamboo strips has a strong positive correlation with MOR, which was 0.92 and 0.93, respectively. It has a weak positive correlation with the elastic displacement of 0.27, and a weak negative correlation with the plastic displacement with a correlation of −0.35. There was a moderate positive correlation between cellulose, hemicellulose, and MOR, with a correlation of 0.59 and 0.52, respectively. Cellulose and hemicellulose both had a weak positive correlation with plastic displacement, with a correlation of 0.36 and 0.40, respectively. Lignin had a moderate positive correlation of 0.57 with plastic displacement, but a weak positive correlation of 0.27 with elastic displacement. Lignin had more of an effect on plastic displacement than on elasticity displacement. The correlation between elastic displacement and all other parameters was low. Density, cellulose, and hemicellulose of bamboo strips had a great impact on MOR, but had a relatively small impact on plastic displacement. The modulus and elastic displacement were affected by multiple factors.

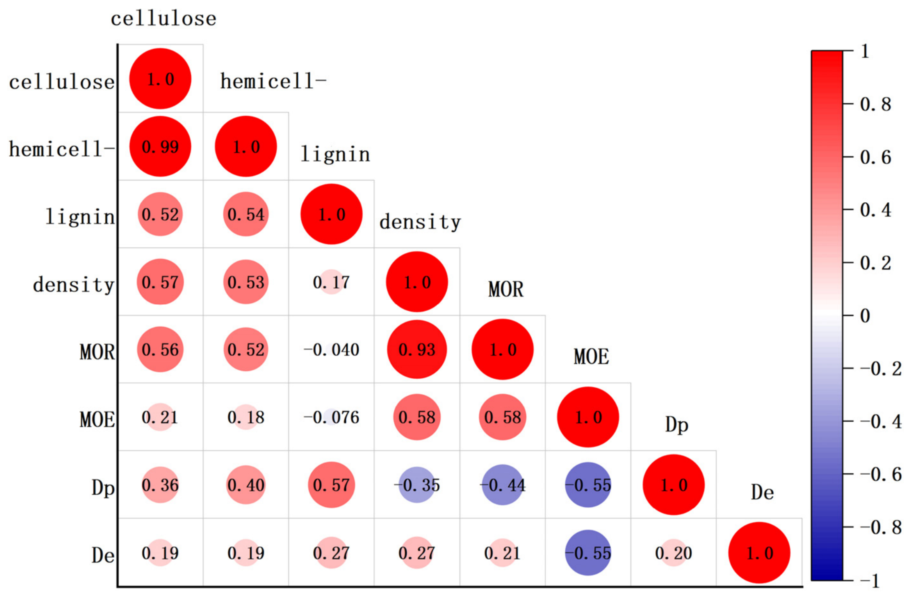

Figure 10. Correlation diagram of mechanical and physical properties.

After water boiling treatment, the MOE (the ability of the bamboo strips to resist bending stress) showed a clear downward trend from untreated to 10 h. The plastic displacement at 2 h was the highest, which had an obvious downward trend and reached a minimum value after 8 h and remained unchanged (the higher the total displacements, the better the deformation performance). This change was consistent with the decreasing trend of crystallinity [33], and the relevant groups decreasing in the infrared spectrum. It showed that water boiling changed the content and arrangement of cellulose and hemicellulose in bamboo strips, while the crystallinity and the related groups decreased. The increase in cellulose and lignin was the main reason for the increase in the deformation effect. The significant reduction in MOE after 8 h also greatly enhanced flexibility and plasticity of bamboo strips. Water boiling has a significant impact on the crystallinity, cellulose content and arrangement [34,35], and lignin content of bamboo strips. A 10-h treatment was most beneficial to its flexibility and plasticity.

MOR and plastic displacement of the bamboo strips treated with 15% NaOH all showed a downward trend from untreated to 10 h. Compared with the control, MOR showed a cliff-like decrease. This change was consistent with XRD. All the crystallinity, cellulose, and lignin contents had a downward trend, indicating that 15% NaOH treatment greatly changed the content and arrangement of cellulose and hemicellulose in bamboo strips and reduced the crystallinity [36,37]. The MOR and MOE first decreased and then increased in a small range at 6 h. The change dropped cliff-like at 10 h compared with control. The overall change was consistent with the significant change in the XRD diffraction intensity, indicating the damage caused by long-term alkali treatment. The effect of short-term treatment on crystallinity, cellulose, and lignin was obvious [38] (Table 2, Figure 7b). While the long treatment effect was mainly concentrated on crystallinity, it would have a certain impact on cellulose and lignin in the short term [39]. If the treatment duration exceeds 8 h, it would cause irreversible damage to the bamboo strips.

The mechanical properties of the bamboo strips treated with 25% NH_3 first decreased and then increased. Compared with the control group, MOR decreased precipitously. This change was related to decreasing cellulose and lignin content [40]. As the treatment time exceeded more than five days, the cellulose content changed significantly and was related to mechanical properties. Meanwhile, hemicellulose and lignin had no obvious changes in the more than five day samples. The 25% NH_3 treatment affected the content of chemical components in bamboo [41]. It had a certain impact on hemicellulose and lignin in a short time. After five days, it mainly affected cellulose, and the best effect was nine days.

Comparing these three treatment methods against MOE, 25% NH_3 and water boiling had similar effects, both were better than 15% NaOH treatment, while the change in elastic displacement after water boiling was the smallest, and the strength properties of bamboo strips after water boiling was the optimal. In MOE, the changes in 15% NaOH and water boiling were similar, and the plastic displacement increased by water boiling was three times that of 15% NaOH, and toughness and bending properties were significantly better than the 15% NaOH treatment. The density change after these three treatment methods decreased by 40%–50%, and the difference was small. As to the surface status changes, the fiber breakage after water boiling and 25% NH_3 treatment was significantly less than that of the 15% NaOH treatment, and the color and texture retention was in a better condition than 15% NaOH. Based on various data analysis and appearance changes, the treated bamboo strips had excellent performance by water boiling in terms of toughness, bending performance, strength and color and texture. The ranking for these three treatments was, in order, water boiling > 25% NH_3 > 15% NaOH in processing.

4. Conclusions

In terms of toughness, bending performance, strength, color, and texture, the ranking of treatment methods was water boiling > 25% NH_3 > 15% NaOH. Water boiling has a significant impact on bamboo crystallinity, cellulose content and arrangement, and lignin content, with a treatment duration of 10 h being the most favorable for flexibility and plasticity, greatly enhancing its bending performance.

The 15% NaOH treatment effected bamboo destructively. Although MOE and plastic displacement increased by 73% and 122.7%, respectively, compared to the control, 15% NaOH treatment directly damaged the fiber structure, resulting in a significant decrease in bamboo strength. A short treatment time had a certain impact on cellulose and lignin, with the impact mainly concentrated on crystallinity. A prolonged treatment time exceeding 8 h brought irreversible damage to bamboo.

The improvement of bamboo bending performance by 25% NH_3 was lower than water boiling, with the impact on various mechanical properties being approximately 50% of water boiling. Its impact mainly changed the content of chemical components, with a short treatment time having a certain impact on hemicellulose and lignin. The optimal effect occurred after nine days.

This study provides a reference for improving the toughness and bending performance of bamboo. In general, water boiling and 25% NH_3 treatments were better than the 15% NaOH treatment for enhancing bamboo bending properties. Water boiling with a treatment duration of 10 h was useful in optimal flexibility and plasticity in bamboo bending applications. In order to maintain the natural color of bamboo, balancing original strength and bending performance, 25% NH_3 for nine days is recommended. Using 15% NaOH was not recommended as it damaged the bamboo structure obviously. Based on these results, further study could focus on refining process parameters of water boiling and 25% NH_3 treatments, and also using multiple thicknesses of bamboo strips, to explore the optimal treatment process to decrease production cost, improve applicability to bamboo material, thus facilitating industrial production of bamboo strips with different specifications.

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