Journal of Wood Science

ORIGINAL ARTICLE

Bamboo slivers with high strength and toughness prepared by alkali treatment at a proper temperature

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Abstract

Despite bamboo slivers having long been used to manufacture bamboo weaving products, the flexibility is still well below satisfactory, especially for those split from inner layer of bamboo culm. Here, a facile approach was reported to obtain strong and flexible bamboo slivers, in which the slivers from the outer and inner layer of bamboo culm were processed with 5 wt% alkali treatment at various temperatures (23, 40, 60, and 80 °C), respectively. Compared with untreated bamboo slivers, the treated ones were investigated in terms of the microstructure, chemical composition, morphology, tensile and bending performances. The results showed that tensile and bending properties of all treated bamboo slivers were significantly improved, especially for those from inner layer of bamboo culm. The tensile strength of outer bamboo sliver treated at 60 °C and the inner ones treated at 40 °C increased up to the maximum, respectively, increasing by 86.6% and 132.0% compared with the untreated ones. The highest flexibility of the outer- and inner bamboo sliver can be achieved at 80 °C and 60 °C alkali treatment, respectively. The slivers can be completely wound around a nylon rod with a diameter of 10 mm without fracture. The excellent tensile and bending performance of bamboo slivers alkali-treated at proper temperature was largely attributed to tightly cellulose molecule aggregating induced by substantially increasing hydrogen bonding after the partial removal of lignin and hemicellulose. A denser and interlocking cellular structure due to the collapse of parenchyma cells after alkali treatment at proper temperature also partly contributed to the increased tensile and bending strength. The results suggest that strong and flexible bamboo slivers can be prepared by one-spot alkali treatment at a proper temperature, which may widen the application scope of bamboo slivers.

Keywords Bamboo slivers, Alkali treatment, Temperature, Tensile properties, Bending properties

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Introduction

As one of the fast-growing green bio-resources, bamboo has been attracting growing attention from academics and industry, the use of bamboo for a wide range of products has also been substantially increasing [1]. Bamboo has long been split into slivers to manufacture bamboo weaving products without any adhesion, such as furniture, handicraft, etc., that are very environmentally friendly. Not all the bamboo slivers were flexible enough to be used for weaving products, especially the slivers from the inner layer of bamboo culm that contains more parenchyma cells and fewer fibers compared with those from the outer layer [2, 3]. The inner bamboo slivers were often abandoned as waste by bamboo weaving product manufacturers in China because of their poor flexibility and low tensile strength. In our previous work [4], it was found that alkali treatment with different concentrations at room temperature can effectively improve both tensile and bending performance of bamboo slivers simultaneously, bamboo slivers can be bent into a small circle without fracture when treated with 15 wt% NaOH solution. However, alkali treatment with a high concentration brought many problems, such as environmental pollution, high cost and so on. It raised a question that is it possible to obtain strong and flexible bamboo slivers through alkali treatment with low concentration?

In much previous research, it was found that the treatment temperature was an important factor affecting the chemical, physical and mechanical properties of bamboo, such as heat, hot saturated steam, oil treatments, and so on. When bamboo was treated with saturated steam at different temperatures, the bending properties were improved at 140 °C, but decreased at 160 °C and 180 °C, respectively [5]. Besides, when the treatment time of hot saturated steam increased, both modulus of rupture (MOR) and modulus of elasticity (MOE) of bamboo increased gradually at 140 °C while decreasing significantly at 160 °C and 180 °C [6]. The bending strength and the MOE of bamboo treated with hot oil at 140–210 °C changed differently and the highest values were obtained when treated at 180 °C [7]. The treatment at a proper temperature (e.g., steam treatment, oil treatment) can improve the performance of bamboo.

To date, most of research mainly focused on the effect of the temperature of alkali treatment on natural plant fibers. When kenaf fibers were treated with alkali solutions at various immersion temperatures (27, 60 and 100 °C), the density and the weight loss increased with the increase of temperature [8]. Furthermore, the tensile strength of kenaf fiber with alkali treatment at 95 °C increased much more compared with that treated at room temperature [9]. There were much research on the effect of alkali treatment with various concentrations and immersion times on bamboo fibers or bamboo fiber composites [10–17], whereas few studies on the effect of alkali treatment temperature on bamboo were reported. Manalo et al. [18] investigated that the increasing alkali treatment temperatures had a positive influence on the flexural and tensile strength of bamboo fiber composite as the slight softening of the matrix allowed the fibers to be stretched in the loading direction rearranging themselves for transmitting stress better.

In this study, bamboo slivers split from the outer and inner layer of bamboo culm were treated with 5 wt% NaOH solution at various temperatures. The microstructure, chemical composition, tensile and bending properties were characterized by scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FT-IR), X-ray diffraction (XRD) and mechanical testing machine.

Materials and methods

Sample preparation

There-year-old Moso bamboo (*Phyllostachys pubescens*) was obtained in October from Zhejiang province, China. The bamboo culm at a height of 1.5–3.5 m from the base was cut and air-dried until moisture content was between 8 and 12%. Two types of tangential bamboo slivers with the same cross section of 1 mm in thickness × 0.4 cm in width but with different lengths (120 mm and 200 mm) were cut from both the outer layer and inner layer of bamboo culm, respectively. Bamboo slivers with a length of 120 mm include slivers with nodes and without nodes, and bamboo slivers with a length of 200 mm are all slivers without nodes. Then, bamboo slivers were immersed in 5 wt% NaOH solutions at various temperatures (23 °C, 40 °C, 60 °C, 80 °C) with a water bath for 4 h. The treated bamboo slivers were thoroughly washed with water to remove the alkali until to neutral. All the treated bamboo slivers were dried in an oven at 50 °C for 8 h.

Microstructure and chemical composition analysis

The cross section of the bamboo slivers was observed with a field emission scanning electron microscope (FE-SEM, Quanta 200, USA). The FT-IR spectra of the bamboo sliver were carried out with a spectrometer (VERTEX 80 V, Bruker, German) within the range of 4000–500 cm^{-1} at a resolution of 4 cm^{-1} and 64 scans. The crystal structure and crystallinity index (CrI) of cellulose in all bamboo slivers were measured by an X-ray diffractometer (XRD, Ultima IV, Rigaku, Japan) with a CuKα (λ = 1.5406 Å) radiation source at an angle of 5°-45° and a speed of 10°/min. The relative crystallinity index was calculated according to Segal's [19] formula (1):

$$CrI = \frac{I_{200} - I_{\mathrm{am}}}{I_{200}} \times 100\% \quad (1)$$

where I_{200} is the maximum intensity of the (200) diffraction peak, and I_{am} is the amorphous diffraction intensity.

Mechanical properties

The tensile test of bamboo slivers with nodes was according to GB/T 15780–1995 and performed by a universal mechanical testing machine (AGS-X20KN, Japan) with a strain rate of 3.0 mm/min. The bamboo slivers with a length of 120 mm and the reinforcing sheets were attached to both ends to reduce the stress concentration and avoid the samples from being pinched. Six replicates were tested for each sample. The tensile testing was

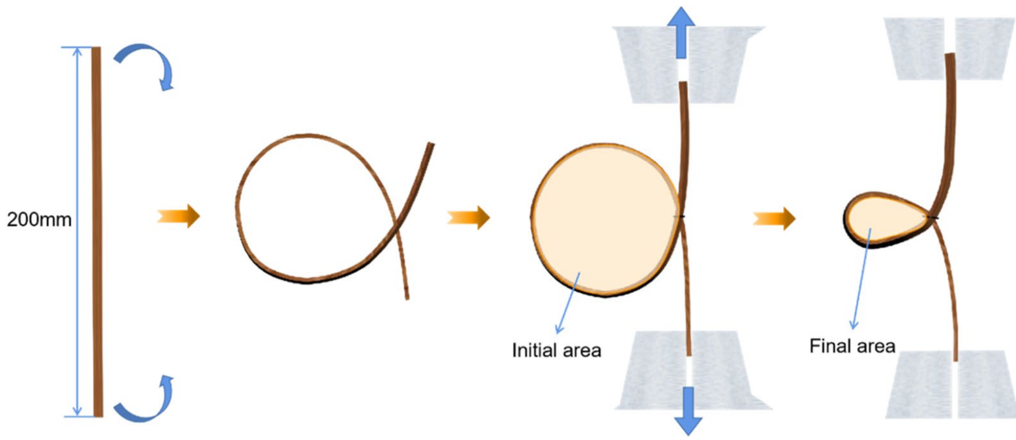

Fig. 1 Schematic diagram of bending test

carried out in a room environment with a temperature of 21.2 °C and relative humidity of 33%. The moisture content of untreated and treated bamboo slivers was 8% - 9%.

Two testing methods were used to characterize the bending performance of bamboo slivers.

Method 1: The bamboo slivers with a length of 120 mm and without nodes were wound on a nylon rod with a diameter of 10 mm tangentially. Six replicates were tested for each sample. The test was carried out at ambient environment with a temperature of 18 °C and a relative humidity of 10%. The moisture content of untreated and treated bamboo slivers was 8% - 9%.

Method 2: The "Water Drop" test method was used for evaluating the bending properties of bamboo slivers as described in the reference [20]. The test process is shown in Fig. 1. The bamboo slivers with a length of 200 mm were bent into a circle and clamped at both ends in the chuck of the mechanical testing machine. The bamboo slivers were pulled at a speed of 20 mm/min The area change of the circle was recorded and calculated according to formula (2). Six replicates were tested for each sample. The bending test was carried out at 20 °C and relative humidity of 32%, and the moisture content of untreated and treated bamboo slivers was 7% - 8%:

$$S_c = \frac{S_a - S_b}{S_a} \times 100\% \quad (2)$$

where S_c is the bending area change, S_a and S_b are the initial bending area and the final bending area, respectively. The final bending area was the bending area at the point when the bamboo slivers were broken. The results of bending area change were analyzed by ANOVA with IBM SPSS Statistics software and marked by the letter marking method, as well as the results of tensile strength, MOE, density and CrI, etc. The same letters indicated that the difference between the two columns of data was not significant, two groups marked with different letters indicated the difference was significant.

Results and discussion

Microstructure and chemical composition

The microstructure of treated and untreated bamboo slivers is shown in Fig. 2 and Additional file 1: Fig. S1. The cells in bamboo slivers, especially parenchyma cells, collapsed obviously when treated with alkali at different temperatures leading to a much denser microstructure compared with that of untreated bamboo slivers. The parenchyma cells in untreated bamboo slivers had a large cell cavity, where there were many starch particles but collapsed after alkali treatment forming an interlocking structure regardless of in the outer- or inner bamboo slivers. The parenchyma cells collapsed increasingly severely as the alkali treatment temperature increased. When the temperature was below 60 °C, there were still cavities in parenchyma cells and some cell corners between adjacent parenchyma cells (yellow arrow). However, the cavity and cell corners in bamboo slivers disappeared when treated above 60 °C, resulting in a much denser structure. The fibers in treated bamboo slivers slightly changed with increasing alkali treatment temperature, which was different from the changes of parenchyma cells. It was because parenchyma cells and bamboo fibers' microstructure, chemical composition and mechanical properties were different. Bamboo parenchyma cells with a thin cell wall and large cavity had a higher content of lignin and hemicellulose and lower cellulose content compared with those of bamboo fibers with a thick cell wall and small cavity [21–23]. The density and mechanical properties of parenchyma cells were much lower in comparison with bamboo fiber [24]. The modulus of parenchyma cell walls was lower than that of middle lamellae between parenchyma cells, but the modulus of fibers cell wall

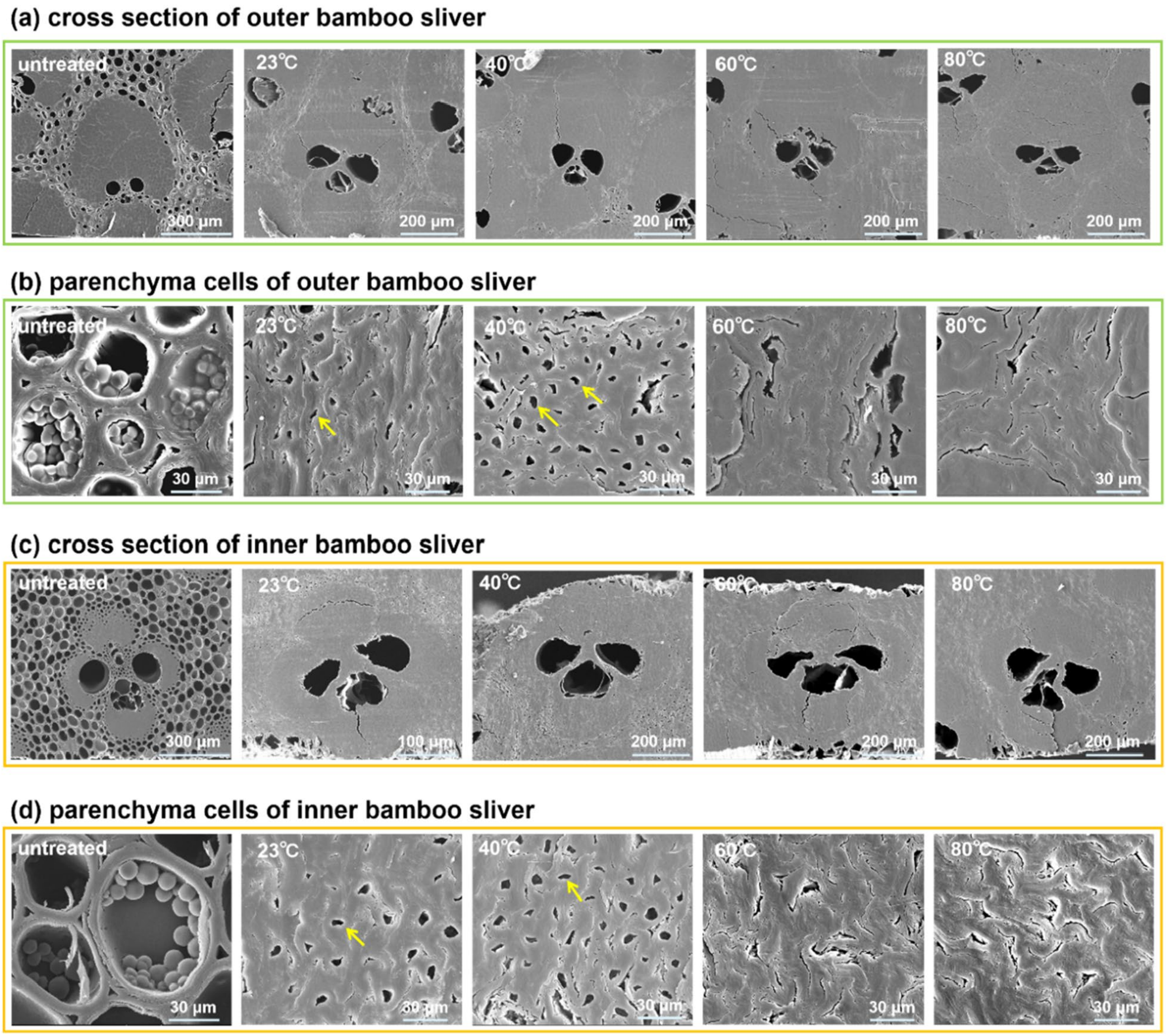

Fig. 2 SEM images of the microstructure of bamboo slivers treated with alkali at different temperatures. **a** Cross section of outer bamboo slivers; **b** cross section of inner bamboo slivers; **c** parenchyma cells in outer bamboo sliver; **d** parenchyma cells in inner bamboo sliver

was higher than that of middle lamellae between fibers [6]. Therefore, bamboo fibers were more resistant to the influences generated by external environment changes compared with parenchyma cells [25].

The FT-IR spectra of untreated and treated bamboo slivers are shown in Fig. 3. The band at 1730 cm^{-1} of untreated bamboo slivers was detected due to C=O stretching vibration in acetyl and carboxyl groups [26], which was the characteristic peak of hemicellulose and lignin [27]. Regardless of the alkali treatment temperature used, the band at 1730 cm^{-1} of treated bamboo slivers from both outer and inner layer of bamboo disappeared, which indicated that part of hemicellulose and lignin was effectively removed. The decrease in the intensity of bands was observed at 1593 cm^{-1}, 1509 cm^{-1}, and 1460 cm^{-1} that was mainly assigned to the benzene ring carbon skeleton and C–H bending in lignin, indicating partial removal of lignin in treated bamboo slivers [28, 29]. The intensity of the band at 1238 cm^{-1} of treated bamboo slivers decreased considerably with the increase of alkali treatment temperature which was attributed to C–C, C–O, C=O stretching vibration and G-ring stretching in hemicellulose and lignin [27, 30]. It showed that alkali treatment with

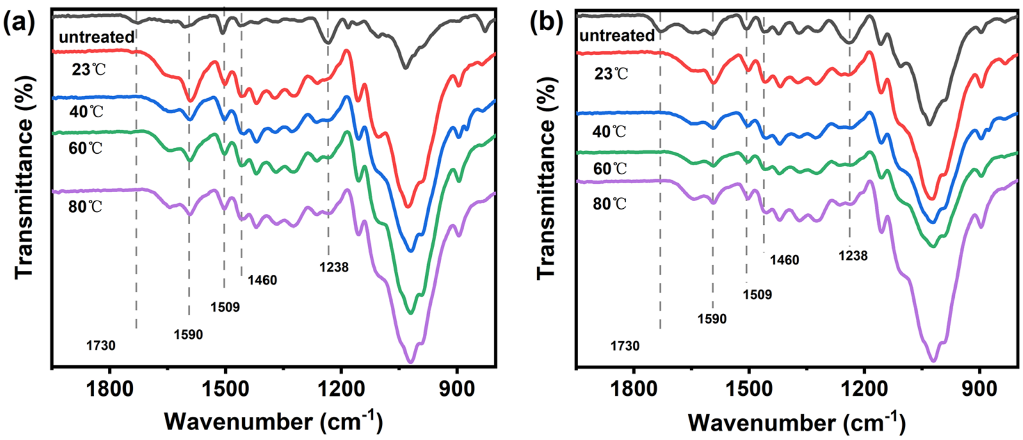

Fig. 3 FTIR spectra of alkali-treated bamboo slivers with different temperatures. **a** Outer bamboo slivers; **b** inner bamboo slivers

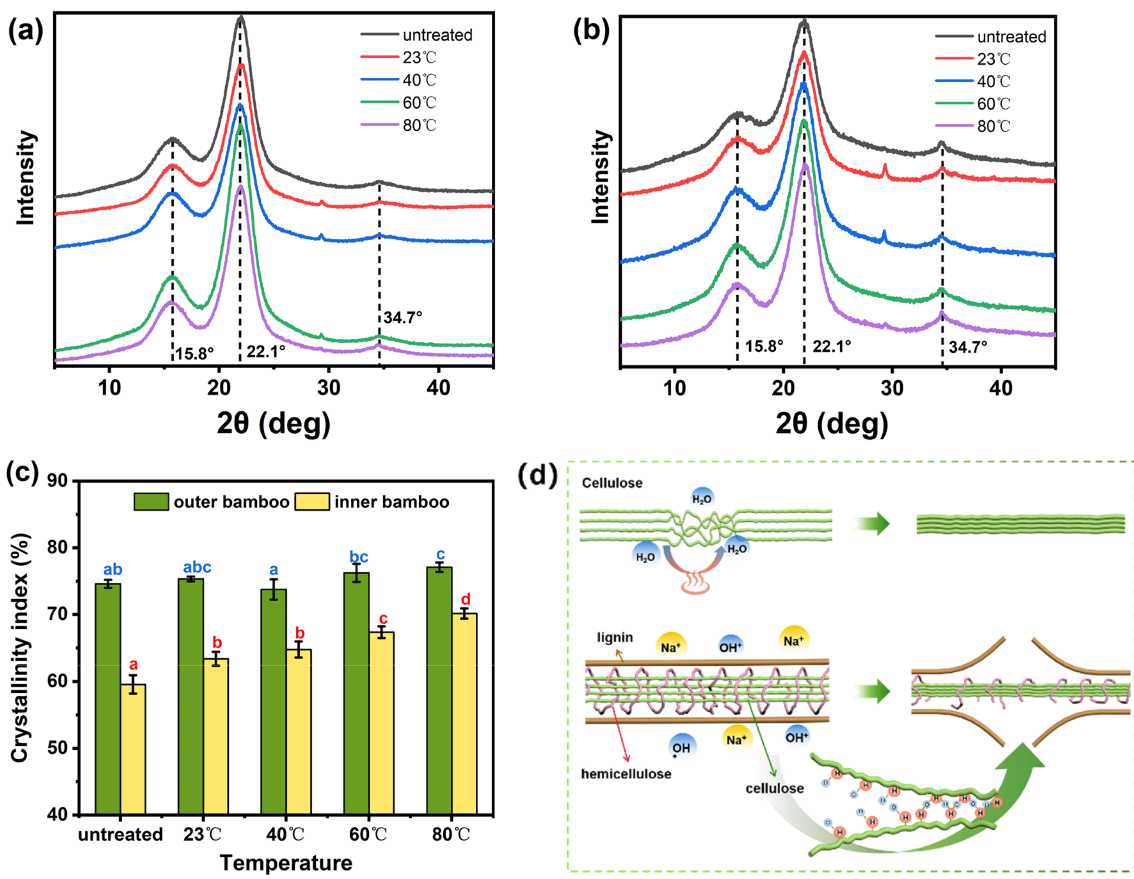

Fig. 4 XRD patterns and crystalline index of cellulose in alkali-treated bamboo slivers with different temperatures. **a** Outer bamboo silver; **b** inner bamboo sliver; **c** crystallinity index of bamboo slivers; **d** schematic diagram of crystallinity improvement

higher temperatures could effectively remove more hemicellulose and lignin from bamboo slivers.

The XRD patterns and the CrI values of bamboo slivers treated with alkali at different temperatures are shown in Fig. 4. The diffraction peaks of treated and untreated bamboo slivers were around 15.8°, 22.1° and 34.7° due to (1−10)/(110), (200) and (004) crystal planes [31], which indicated the crystal form of cellulose in untreated bamboo slivers was typical cellulose I. Therefore, the alkali treatment at different temperatures

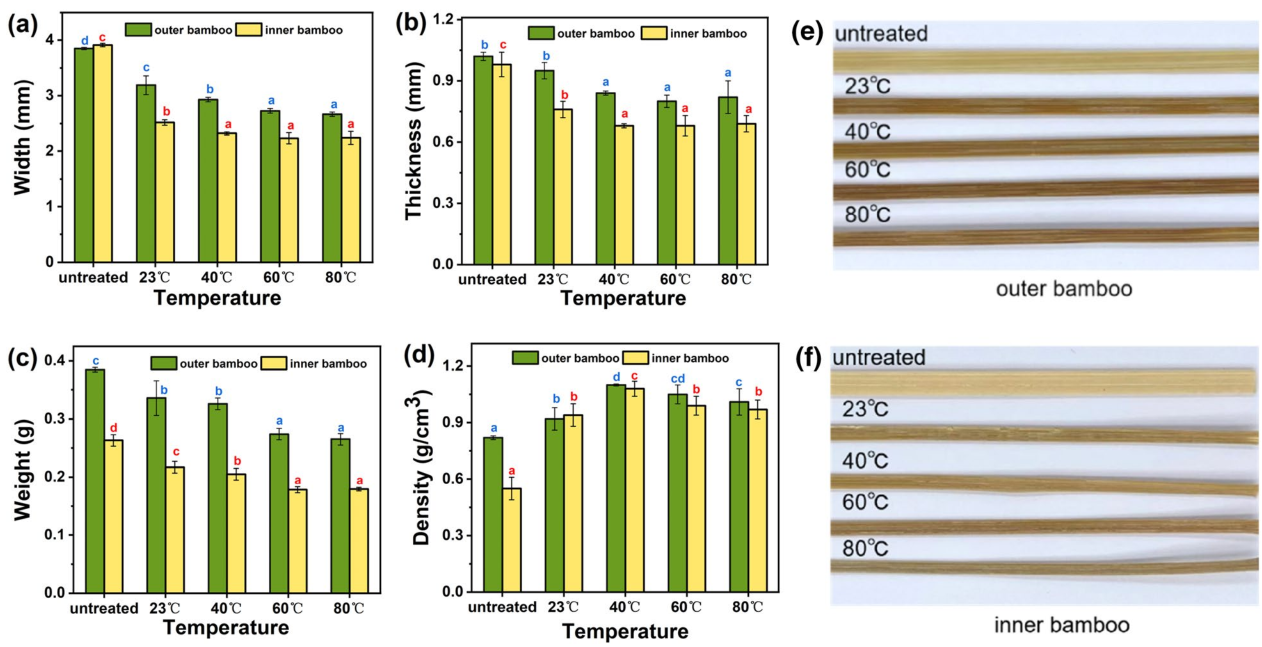

Fig. 5 Changes in dimension and morphology of bamboo slivers after alkali treatment at different temperatures. **a** Width; **b** thickness; **c** weight; **d** density; **e** morphology of outer bamboo slivers; **f** morphology of inner bamboo slivers

had little effect on the cellulose crystal forms of bamboo slivers. The CrI of bamboo slivers from the inner layer of bamboo was much lower than that from the outer layer (Fig. 4c), because there were more parenchyma cells and fewer fibers in the inner bamboo, and parenchyma cells had a much lower CrI compared with fibers [14, 21]. With the alkali treatment at different temperatures, the CrI of the outer and inner bamboo slivers changed differently. The CrI of treated inner bamboo slivers was considerably improved compared with the untreated ones and increased significantly with the increase in temperature. The CrI of cellulose in inner bamboo slivers treated at 80 °C was 70.2%, which increased by 17.8% compared with the untreated ones. In this study, the increase in crystallinity might be partly due to the hydrolysis of amorphous region of cellulose by alkali solution, thus increasing the proportion of crystallization area. As shown in Fig. 4d, water molecules were more likely to enter the amorphous region when the temperature of NaOH solution increased, causing hydrolysis of the cellulose amorphous region [32]. Moreover, the removals of matrix materials might also partly contribute to the increase in the crystallinity. More cellulose molecules were exposed with the removal of hemicellulose and lignin, and a large number of hydroxyl groups on the surface made adjacent cellulose molecules easy to aggregate [4]. However, the CrI of outer bamboo slivers only increased slightly when treated at 80 °C. It might be due to that the cellulose in fibers and parenchyma cells had different molecular structure and changed differently with the same alkali treatment [23, 33, 34].

Morphology

The changes in dimension and morphology of untreated and treated bamboo slivers at different temperatures are shown in Fig. 5 and the length of the bamboo slivers is shown in Additional file 1: Fig. S2. The width, thickness and weight of bamboo slivers decreased significantly with the increase in temperature. The width of the outer and inner bamboo slivers decreased by 30.7% and 43.4% when treated with NaOH solution at 80 °C, respectively. The thickness of outer and inner bamboo slivers decreased the most at 40 °C and 60 °C, by 20.0% and 32.5%, respectively. The length of bamboo slivers was almost unchanged. The shrinkage of bamboo slivers was mainly due to the collapse of parenchyma cells. The treatment at 80 °C for the outer bamboo silvers cause the most reduction in weight, 30.2% weight was lost compared to the untreated one, while the most reduction in weight (32.1% weight loss) was found at 60 °C for the inner bamboo slivers. The shrinkage of treated bamboo slivers led to a much denser structure and the density of both outer and inner bamboo slivers treated at 40 °C were highest, which increased by 45.6% and 88.3% comparing with the untreated ones, respectively. The color of treated bamboo slivers was deepened after alkali treatment at different temperatures, and the inner bamboo

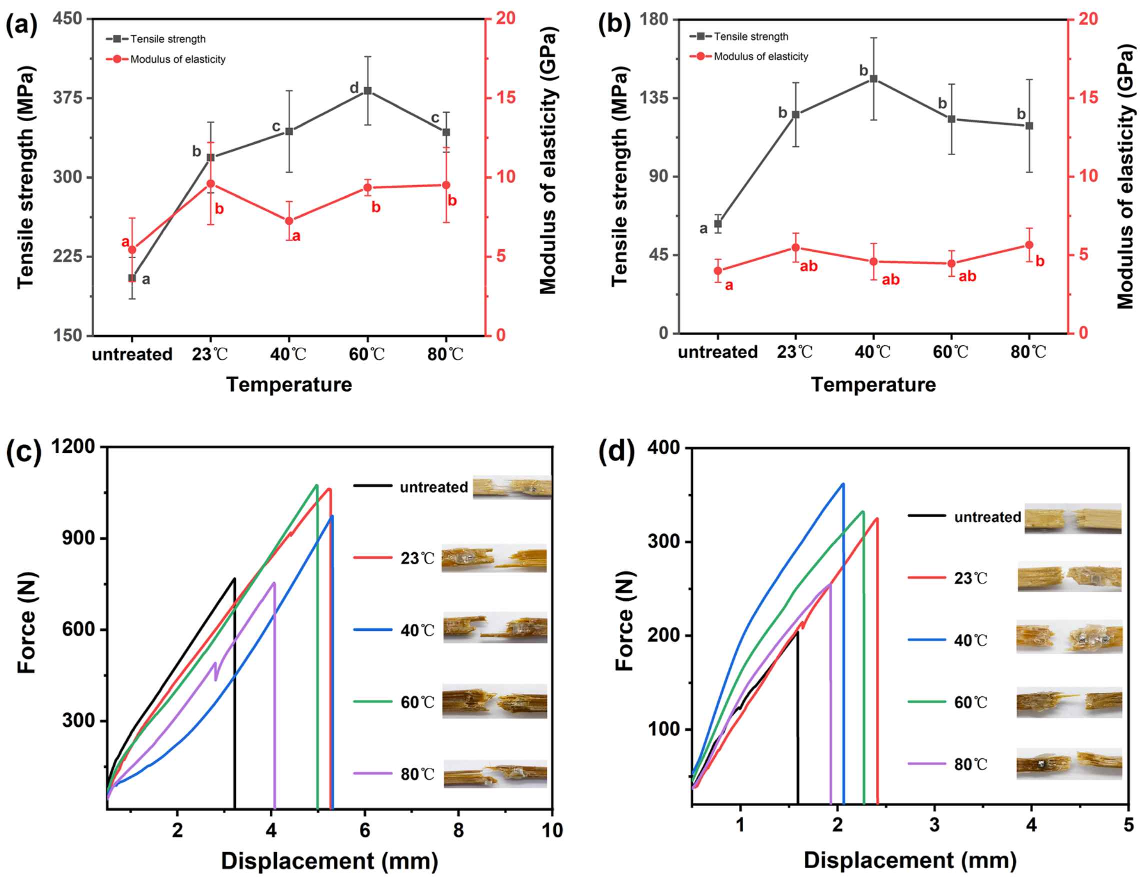

Fig. 6 Tensile properties of bamboo slivers treated with NaOH at different temperatures. **a** Tensile strength and MOE of outer bamboo slivers; **b** tensile strength and MOE of inner bamboo slivers; **c** displacement–load curve and fracture form of outer bamboo slivers; **d** displacement load curve and fracture form of inner bamboo slivers

slivers distorted when treated above 60 °C. The color change of bamboo slivers was mainly due to the reaction of lignin and alkali solution, which produced a large number of color-forming and color-assisting groups, resulting in a brownish-yellow color of bamboo slivers [35, 36]. This might be due to a large amount of shrinkage and collapse of parenchyma cells in inner bamboo slivers occurred when treated at high temperature, thus resulting in deformation.

Mechanical properties

The tensile properties of treated and untread bamboo slivers are shown in Fig. 6. The tensile strength of bamboo slivers increased substantially after alkali treatment at different temperatures. The tensile strength of the outer bamboo sliver treated at 60 °C and the inner ones treated at 40 °C increased up to the maximum, respectively, increasing by 86.6% and 132.0% compared with the untreated ones. While the changes of the MOE of the treated outer- and inner bamboo slivers were different from tensile strength. The MOE of both outer and inner bamboo slivers significantly increased, reaching the highest value at 80 °C and increasing by 75.1% and 41.1% in comparison with the untreated ones, respectively. The specific tensile strength of outer and inner bamboo sliver is shown in Table 1. After alkali treatment, the density of the bamboo sliver increased slightly, the specific tensile strength of alkali-treated bamboo slivers was much higher than that of untreated ones due to the significant increase of tensile strength. With the removal of a large number of pores in slivers after alkali treatment, the density of bamboo slivers increased and the interior of bamboo slivers became denser, the increased density and more compact structure might partly account for significant improvement in the tensile strength of bamboo slivers. The density of outer and inner bamboo sliver reached the maximum when treated at 40 °C. However, the tensile strength of outer bamboo slivers reached the maximum at 60 °C, while that of inner bamboo slivers reached the maximum at 40 °C. It was indicated that the increase in the tensile strength of the alkali-treated bamboo slivers might be also ascribed to other factors

Table 1 Density, tensile strength, and specific tensile strength of outer and inner bamboo slivers

		Untreated	23 °C	40 °C	60 °C	80 °C
Outer bamboo sliver	Density (g/cm^3)	0.82	0.92	1.10	1.05	1.01
	Tensile strength (MPa)	204.76	318.80	343.48	382.01	342.82
	Specific tensile strength ((N·mm)/g)	249.707	346.522	312.255	363.819	339.426
Inner bamboo sliver	Density (g/cm^3)	0.55	0.94	1.08	0.99	0.97
	Tensile strength (MPa)	62.96	125.54	146.07	122.93	119.11
	Specific tensile strength ((N·mm)/g)	114.473	133.553	135.250	124.172	122.794

in addition to the increased density. The longitudinal tensile load of bamboo slivers was mainly undertaken by fibers, and the parenchyma cells played the role of load transfer [37]. The parenchyma cells in treated bamboo slivers collapsed after alkali treatment to form an interlocking cellular structure (Fig. 2), which enabled the parenchyma cells to resist part of the load [29, 38]. In addition, due to the partial removal of hemicellulose and lignin, a large number of hydroxyl groups in cellulose was released and formed new hydrogen bonds, thus leading to a strong material. The tensile strength of the outer bamboo slivers treated at 60 °C and the inner ones treated 40 °C reached the maximum, respectively, which was mainly due to the combination of the interlocking structure formed by parenchyma cells and new hydrogen bonds resulting from the partial removal of lignin and hemicellulose. Therefore, besides density, the formation of interlocking structure and hydrogen bonding were another contributor to improve tensile properties. However, excessive removal of hemicellulose and lignin would weaken the interfacial interaction between cells [14]. When outer bamboo slivers were treated below 60 °C, the parenchyma cells were not completely collapsed and there were still some cell corners between the cells, making the intercellular contact not dense enough. As the temperature increased to 80 °C, the interlocking mechanism could not compensate for the effect of excessive removal of hemicellulose and lignin, thus resulting in the tensile strength of outer bamboo slivers lower than at 60 °C. For inner bamboo slivers, the temperature (40 °C) of maximum tensile strength was lower than that of outer bamboo slivers, mainly because hemicellulose and lignin were not excessively removed, although the parenchyma cells were not completely collapsed at this temperature and some voids (cell corners) still existed. Therefore, the degree of the removal of hemicellulose and lignin is crucial for enhanced tensile performance of bamboo slivers. In addition, the significant increase in CrI of inner bamboo slivers also contributed to the improvement of the tensile properties.

The displacement–load curve and tensile fracture of bamboo slivers are shown in Fig. 6c, d. The untreated outer bamboo slivers had a ductile fracture form after being stretched to fracture, while the inner bamboo slivers were predominantly brittle fractured [39]. It was due to that the outer bamboo slivers contained more fibers than that of inner bamboo slivers. In addition, the modulus of the fiber cell wall is higher than that of the middle lamellae between the fibers [6, 38]. Therefore, the tensile fracture of the outer bamboo slivers shown that the fiber was pulled out. However, inner bamboo slivers with low fiber content had fewer fibers pulled out when they were fracture. After being treated in alkali solutions at different temperatures, the fracture forms in the outer bamboo slivers remained ductile fracture, while the inner bamboo slivers tended to be brittle fracture more severely, which was due to the excessive removal of hemicellulose and lignin resulting in the weakening of the fiber cell walls and intercellular layers. The large number of fibers in outer bamboo were less affected by the removal of matrix, and the fibers were still pulled out. However, this made it easier for inner bamboo to be separated from parenchyma cell walls when it fractured, and the small amounts of fibers were easier to be pulled off rather than pulled out.

The bending properties of bamboo slivers after alkali treatment at different temperatures are presented in Fig. 7 and Additional file 1: Fig. S3. The bending performance of both treated outer and inner bamboo slivers was significantly improved with the increase in alkali treatment temperature, especially for inner bamboo slivers. When the treatment temperature was lower than 60 °C, both treated outer and inner bamboo slivers could be bent around the nylon rod with a diameter of 10 mm. When the temperature increased to 60 °C, the treated outer bamboo slivers could be wound around the nylon rod, but some fibers would be pulled out. When bent further, more fibers were pulled out and tend to break. While the inner bamboo slivers treated at 60 °C could be completely wound around the nylon rod without fracture. When the temperature increased to 80 °C, both treated outer and inner bamboo slivers could be completely wound around the nylon rod without breaking, but there were still some fibers being

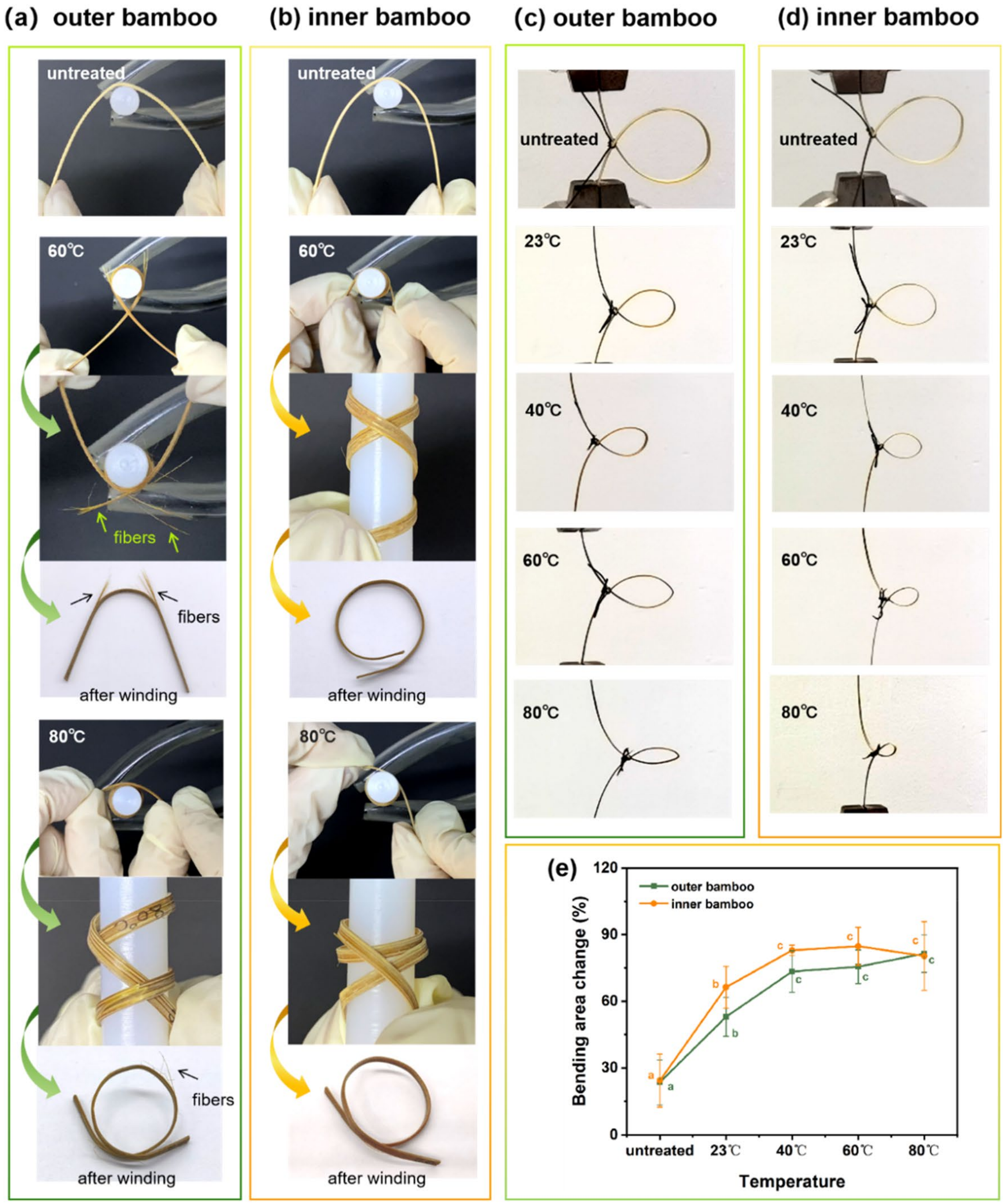

Fig. 7 Bending properties of bamboo slivers with different treated temperatures. **a** Maximum degree of outer bamboo slivers wound on nylon rod; **b** maximum winding degree of inner bamboo wound on the nylon rod; **c** bending area of outer bamboo slivers at fracture; **d** bending area of inner bamboo slivers at fracture; **e** bending area change of bamboo slivers

pulled out from the surface of the outer bamboo slivers (Fig. 7a).

As shown in Fig. 7c, d, the bending area at fracture of treated bamboo slivers decreased significantly with the increase of alkali treatment temperature, especially for the inner bamboo slivers, which indicated that the flexibility of treated bamboo slivers was remarkably improved. The bending area change of the treated bamboo slivers increased considerably with increasing temperatures (Fig. 7e). The change of bending area of treated inner bamboo slivers was more pronounced than that of treated outer bamboo slivers except for the one treated at 80 °C, suggesting that the flexibility of inner bamboo slivers was improved more pronouncedly in comparison with outer bamboo slivers after alkali treatment. The bending area change of outer bamboo slivers treated at 80 °C was the highest, while that of inner bamboo slivers treated at 60 °C increased up to the maximum, which was consistent with the result of winding around the nylon rod. The remarkable improvement in the bending performance of treated bamboo slivers was mainly due to the increase in temperature-induced denser cells in the bamboo slivers and a stronger mechanical interlocking mechanism between parenchyma cells, which could play an important role in inhibiting the generation of cracks, which was discussed in detail in our previous research [4]. In addition, compared with the outer bamboo slivers, the higher flexibility of treated inner bamboo slivers was because there were more parenchyma cells forming more interlocking structures, which resulted in a much denser internal structure after treatment. Although part of the intercellular layer material (lignin and hemicellulose) was removed after treatment, which made the connection between fibers weaker and easier to be pulled out, the interlocking structure formed by the collapse of a large number of parenchyma cells compensated for the defect appeared in the treated inner bamboo slivers.

Conclusions

In this study, the effects of different temperatures of alkali solution with a concentration at 5 wt% on the outer- and inner bamboo slivers were investigated in terms of the microstructure, chemical composition, morphology and mechanical properties. The conclusions are as follows:

(1) As the alkali treatment temperature increased, the parenchyma cells collapsed increasingly and the width and thickness decreased significantly, which led to a denser structure in the bamboo slivers, especially for the inner bamboo slivers. The highest density of both outer- and inner bamboo slivers was obtained when treated at 40 °C, which increased by 45.6% and 88.3% compared with the untreated ones, respectively.

(2) The chemical composition and crystallinity of both outer and inner bamboo slivers were significantly affected by the temperature of alkali treatment. With the higher temperature of the alkali solution, more hemicellulose and lignin were removed from the bamboo slivers. The CrI of cellulose in bamboo slivers increased as treatment temperature increased, especially for the inner bamboo slivers. The CrI increased by 10.6% when treated at 80 °C compared with of the untreated inner ones.

(3) The tensile and bending performance of both outer and inner bamboo slivers were considerably improved after being treated with NaOH solution at various temperatures. The highest tensile strength was achieved for outer bamboo sliver treated at 60 °C and for inner bamboo slivers treated at 40 °C, respectively, which were 86.6% and 132.0% higher than that of the untreated ones. The modulus of elasticity of outer and inner bamboo slivers treated at 80 °C increased by 75.1% and 41.1% compared with the untreated ones, respectively. The highest flexible outer bamboo slivers were obtained when treated at 80 °C and the highest flexibility of inner ones was achieved when treated at 60 °C, of which the bending area change increased up to 81.5% and 84.7%, respectively. Meanwhile, the treated bamboo slivers with the highest flexibility could be completely wound on a nylon rod with a diameter of 10 mm without breaking.

Abbreviations

MOR	Modulus of rupture
MOE	Modulus of elasticity
SEM	Scanning electron microscopy
FT-IR	Fourier-transform infrared spectroscopy
XRD	X-ray diffraction

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s10086-023-02084-3.

Additional file1: Fig. S1. SEM images of the microstructure of fibers in bamboo slivers treated with alkali at different temperatures. **Fig. S2.** Length Changes of bamboo slivers after alkali treatment at different temperatures. **Fig. S3.** Bending properties of bamboo slivers with different treated temperatures (a) maximum degree of outer bamboo slivers wound on nylon rod; (b) maximum degree of outer bamboo slivers wound on nylon rod.

Acknowledgements

The authors express their sincere thanks to Zhejiang Province and the International Center for Bamboo and Rattan for the financial support of the current work.

Author contributions

WJY and ZYX were the major contributor in data analysis and writing the manuscript, and they have contributed equally to the manuscript. ZTH and ZYX revised the manuscript. ZTH and ZWF financed the research. CH designed the experiment and participated in the writing. All authors read and approved the final manuscript.

Funding

The research was financed by the project funded by Zhejiang Province (Grant No. 2020SY09) and Basic Scientific Research Funds of the International Center for Bamboo and Rattan (Grant No.1632021025).

Availability of data and materials
All data generated or analyzed during this study are included in this published article and its Additional files.

Declarations

Competing interests
The authors have declared no competing interest.

Received: 3 November 2022 Accepted: 8 February 2023
Published online: 01 March 2023

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