Classification and Properties of *Bambusa blumeana* Fiber

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This study extracted *Bambusa blumeana* fiber using alkaline boiling and then applied double-roll pressing in order to develop it, explore the applications of its various parts, and improve its utilization potential. The results showed that the outer bamboo fibers are finer and straighter than the inner and middle fibers, and the fracture mode of the bamboo fibers is brittle. From the inside to the outside, the tensile strength of the fiber bundle gradually increases from the top to the bottom. Moreover, the tensile strength of the outside bamboo fiber is twice that of the inside, reaching a maximum of 982 MPa. The surface of the interior bamboo fiber is relatively smooth and can be used in textile and decorative fields. Compared with internal and central bamboo fiber, the outer fiber has higher thermal stability and higher crystallinity, which makes it more advantageous in the process of strengthening composite materials. Studying the structures of fibers from different parts of *Bambusa blumeana* can provide substantial scientific support for the differential applications of bamboo fibers.

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Keywords: Bambusa blumeana; Fiber structure; Bamboo fiber; Tensile strength; Crystallinity; Thermal stability

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INTRODUCTION

With the global scarcity of non-renewable resources and the increasing awareness of the need for environmental protection, research and development into natural plant fibers has become vital. These natural fibers are derived from plants containing lignocellulose and are seen as environmentally friendly alternatives due to their high strength, sustainability, renewability, and biodegradation qualities (Saw *et al.* 2014). Typical natural plant fibers, including cotton (Singh *et al.* 2022), jute (Tanguy *et al.* 2018), sisal (Dun *et al.* 2019), and hemp (Väisänen *et al.* 2018), have played considerable roles in the creation of composite materials.

At present, bamboo fiber has great potential in terms of promoting sustainability and environmental protection; the development of sustainable high-performance bamboo fiber can greatly reduce plastic pollution (Chen *et al.* 2023), and bamboo fiber applications in the field of renewable resources have been extensively researched (Mousavi *et al.* 2022).

The fibers of different bamboo species have been studied by various scholars. Sethu *et al.* (2023) studied the thermal and chemical properties of a particular bamboo species in India and found that its bamboo fiber can be used as an effective reinforcement unit for the development of polymer-based composites in the automotive and construction industries.

Sikam *et al.* (2021) studied the physicochemical and mechanical properties of *Bambusa vulgaris* (BV) fiber, which is common in Cameroon, and pointed out that BV fiber can be used as a reinforcement material in the textile or construction fields.

Many studies have been conducted on the various parts of plant fibers. Cui *et al.* (2018) found that the mechanical properties, surface structure, and crystal structure of the head, middle, and root of ramie fiber showed significant differences when alkali boiling and degluing were applied. Shahinur *et al.* (2015) studied the upper, middle, and lower parts of jute fibers and found that the middle part of the fiber had better mechanical, thermal, chemical, and crystalline properties. At present, the influential studies on bamboo fiber structure and properties are mainly as follows: Han *et al.* (2023) conducted radial analysis on bamboo, and quantitatively analyzed the influence of fiber bundles and interface uniform distribution structures in the radial direction on the chemical composition and physical and mechanical properties of bamboo wall layers. Wang and Shao (2020) found that the tensile strength of bamboo fibers showed a slight increase from inside to outside the bamboo stem, which was closely related to the structural changes in the radial direction of the bamboo stem. The internal fibers showed signs of brittle fracture, while the outer fibers showed signs of ductile fracture, which was consistent with the changes in their radial tensile properties.

The cell structures of different parts of bamboo also changed in differing ways. Bamboo fiber cells were densely distributed in the outer area of the bamboo stem, and they gradually became sparser the further inward the area was analyzed, roughly following the law of exponential distribution. The diameter, thickness, and microfiber angles of bamboo fiber walls also followed certain rules (Bin *et al.* 2003). Hu *et al.* (2020) isolated internal and outer fibers from bamboo and explored the differences in their properties, leading to their wider applications in various fields. Amada *et al.* (1997) studied the mechanical properties of fibers in cross-sections of bamboo, and the results showed that the fibers on the outer surface were more densely distributed and had higher strength than the fibers on the inner surface. Ray *et al.* (2005) studied the relationship between the microstructure and tensile strength of bamboo fibers. They found that there were more fibers near the outside of bamboo than the inside, and the bamboo fibers near the outside were more dense, with a strength four times that of the inner bamboo fiber. These results clearly show the different properties of bamboo fibers from different parts of the plant.

Although bamboo fiber has been widely used in the field of fiber-reinforced composite materials, the research on bamboo species of different regions needs to be supplemented. The purpose of this study was by means of alkaline boiling and double-roll pressing to investigate the differences in the mechanical strength and thermal properties of various *Bambusa blumeana* fibers, which are divided into inner, middle, and outer fibers along the radial direction and divided into bottom, middle, and top fibers along the longitudinal direction.

The properties of the *B. blumeana* fibers analyzed were diameter distribution, tensile strength, elongation, infrared spectroscopy, thermo-gravimetric analysis, crystallinity, and microscopic characteristics. This study can broaden the range of bamboo species applications, improve the processing technology of *Bambusa* fiber, reduce resource waste, and improve cost competitiveness.

EXPERIMENTAL

Materials

A three-year-old *B. blumeana* plant was harvested from Cangyuan Wa Autonomous County, Lincang City, Yunnan Province (99° 27'e, 23° 21'n). It had a diameter of 36.3 to 63.7 mm at breast height, a height of 33.3 to 41.5 cm at internode height, and a wall thickness of 4.8 to 9.9 mm. Sodium hydroxide (NaOH) was purchased from Shantou Xilong Science Co., LTD., Guangdong, China; sulfuric acid: AR grade, 98%, Xilong Chemical Co., LTD., was diluted to 0.05% for use.

Alkali Pretreatment and Separation of *Bambusa* Fiber

The *Bambusa blumeana* was divided into three parts of 1 to 3, 3 to 5, and 5 to 7 meters. Each part was sawn along the radial direction into bamboo tubes with a length of 150mm, and then the bamboo tubes were evenly divided into four bamboo strips (excluding the nodes). Next, 80 g of *B. blumeana* in each part was selected according to the solid–liquid ratio of 1:15 (mass ratio, bamboo strips–lye), impregnated in a 5% sodium hydroxide solution and heated in a 90 °C water bath for 4 h. The bamboo strips were drained and then rinsed with diluted sulfuric acid and 40 °C warm water until the rinse solution was neutral. After alkali treatment, each part of the bamboo strip was vertically cut into 3 parts: the one near the yellow section was the inside, the one near the green section was the outside, and the rest was the middle. The cut bamboo strips were placed in a double-roller press (model: SY-6215-A), the spacing was adjusted to 18 mm, and the crushing was repeated several times (to ensure the maximum integrity of the fiber). Finally, the bamboo fibers were loosened, and the bamboo fibers were left at room temperature for 24 h and stored for use. The process of unpacking *Bambusa* samples and fibers is shown in Fig. 1.

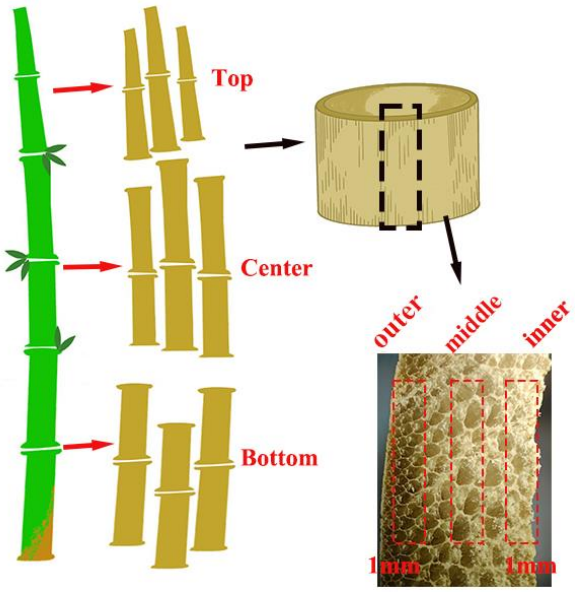

Fig. 1. Schematic diagram of sample preparation of different parts of *Bambusa blumeana*

Different parts of *Bambusa blumeana* showed obvious differences in Fig. 2, and the internal bamboo fibers were messier and more curved, which may be related to their strength. The overall feel of the isolated *Bambusa* fiber was softer than that of the

commonly used bamboo fiber. In order to explore the properties of different parts of bamboo fiber, the lateral directions of the bottoms of the inner, middle, and outer sections were analyzed. In the longitudinal direction, the outer low, middle, and top sections were selected for comparison, and the bamboo fibers were grouped from inside to outside and from bottom to top in the transverse direction as follows: bottom inner bamboo fiber (BIB), bottom middle bamboo fiber (BMB), bottom outer bamboo fiber (BOB), center outer bamboo fiber (COB), and top outer bamboo fiber (TOB).

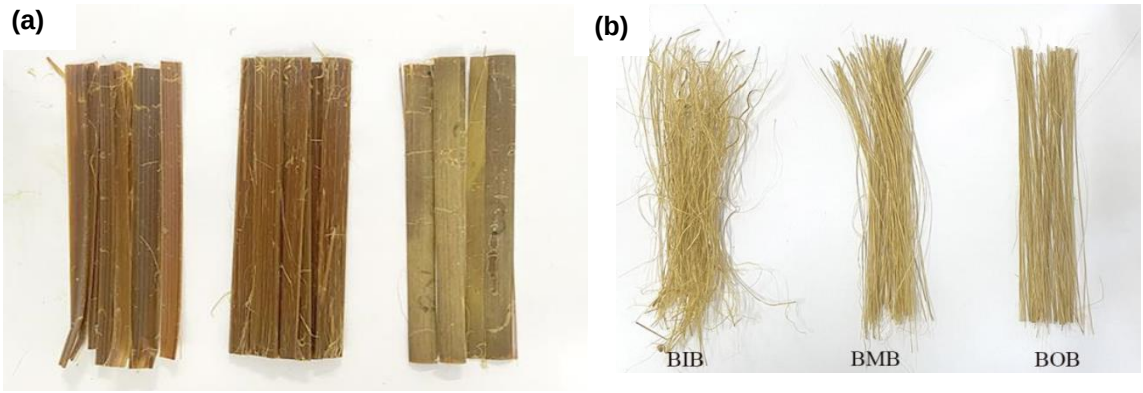

Fig. 2. Morphology of separation of *Bambusa blumeana* fibers from different parts (a) before separation and (b) after separation. Key to code names: First letter "B" means "bottom"; second letter "I" means "inner", second letter "M" means "middle", section letter "O" means "outer", and third letter "B" means "bamboo" fiber.

Performance Tests of *Bambusa* Fiber

Scanning electron microscopy (SEM)

SEM was used to observe the morphology of the surface and fracture surface of *Bambusa* fiber in order to determine the connection mode and the arrangement of the fibers. A sputtering coater (Quorum SC7620) was used to spray gold onto the samples for 45 s with a gold-spraying current of 10 mA. Subsequently, the morphology of *Bambusa* fibers was photographed using a Czech TESCAN MIRA LMS scanning electron microscope with an acceleration voltage of 3 kV and magnifications of 500 and 5000.

Diameter distribution of Bambusa fiber

By analyzing the diameter distribution frequency of different sections of bamboo fiber, their differing characteristics were determined. Thirty bamboo fibers were randomly selected from each group, the diameter of each bamboo fiber was measured using an optical microscope (model: Olympus BX51), and the diameter distribution curve was fitted by the Gaussian distribution function.

Tensile strength of Bambusa fiber

The tensile tests of the *Bambusa* fiber were carried out in accordance with ASTM D3822-07 (2007). In order to reduce the variations in fiber performance data caused by the clamping degree of the universal testing machine (model: CMT5501), the fixture used was a pneumatic fixture. The universal testing machine fixture was controlled so that the card hole slot end was flush with the inner end of the fixture and clamped. The bamboo fiber was prepared with reference to the test sample in the study (Osorio *et al.* 2011). Experimental parameters of tensile test: tensile speed 1 mm/min, clamping length 80 mm,

marking distance 40 mm, 40 samples/group. Test environment: room temperature 23 ± 2 °C relative humidity 62 to 68%.

Fourier transform infrared spectrum

Bamboo fiber samples from different parts of the plant were washed with distilled water, dried, and ground into 100-mesh powder. An instrument (model: Thermo Scientific iN10 of the United States) was used to test the chemical structure of the *Bambusa* fiber powder, with a scanning range of 4000 to 500 cm^{-1}, a resolution of 4 cm^{-1}, and 128 scanning times.

X-ray diffraction

Crystallinity (CrI) was measured using an X-ray diffractometer (model: DB Discover with Gados XRD in Japan) at a scanning speed of 2.5°/min over a scanning range of 5° to 40° at 40 kV energy and a current of 30 mA. The crystal index (CrI) can be calculated by formula 1 (French *et al.* 2013),

$$CrI = \frac{I_{002} - I_{am}}{I_{002}} \times 100\% \quad (1)$$

where I_{002} is the maximum diffraction intensity, and I_{am} is the diffraction intensity of the amorphous region.

Thermogravimetric analysis

Thermogravimetric analysis was used to evaluate the thermal stability of *Bambusa* fiber from different parts of the plant. The thermal properties of the fiber samples were tested using a thermogravimetric analyzer (model: Netzsch STA 449 F3, Germany). Each fiber sample, weighing 20 mg, was placed in an alumina crucible, and then heated from 30 to 550 °C at a heating rate of 10 °C/min. All experiments were carried out in a nitrogen atmosphere, and the weight loss rate was calculated by Eq. 2,

$$W = \frac{W_1 - W_2}{W_1} \times 100\% \quad (2)$$

where W_1 is the weight of a fixed number of dried and cleaned fibers and W_2 is the number of treated fibers.

RESULTS AND DISCUSSION

SEM Analysis of *Bambusa* Fiber

The microstructure assessment of the different parts of bamboo fiber is shown in Fig. 3. The microstructure of the parts was observed using an electron microscope, and the different fracture modes and degumming degrees were determined. After partial removal of lignin and hemicellulose, bamboo fiber still retained its fibrocytes and parenchyma cells. At the same time, after treatment with an alkali solution, a typical aggregation of fiber on the surface of the wrinkled features was observed (Chen *et al.* 2017).

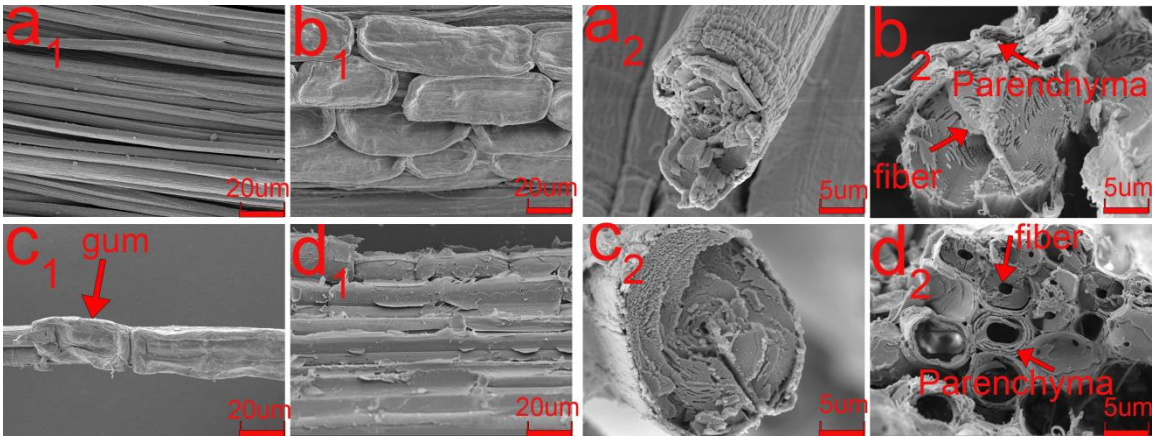

Fig. 3. Surface and cross-sectional views of bamboo fibers from different parts of *Bambusa blumeana.* a_1, b_1, c_1, and d_1 refer to the surface condition of the inner, middle, outer, and untreated bamboo fiber under 500x magnification. a_2, b_2, c_2, and d_2 represent the internal, middle, outer, and untreated sections of bamboo fiber enlarged 5000x.

The bamboo fibrillar structure shown in Fig. 3a_1 contains the largest number of single fibers, and the surface is wrinkled. Due to the removal of impurities, there are deep slot gaps between the single fibers, and the section shown in Fig. 3a_2 is relatively neat, which can be regarded as a brittle fracture surface. The surface of the fiber bundle in the middle of b_1 is covered with a large number of colloids existing in sheets. The section shown in b_2 is rougher than the inside of the bamboo fiber, and there are more non-cellulose substances attached at the ports. These results indicate that lye could not penetrate fully into the middle of the bamboo during the treatment, and bamboo fibers were still enveloped by a large number of parenchyma cells, which was not conducive to the combination of bamboo fibers and polymers, demonstrating a brittle fracture mode. The outer bamboo fibril shown in Fig. 3c_1 contained the least number of single fibers, and there was a small amount of gum in the form of a sheet on the surface. In Fig. 3c_2, the fracture surface appears relatively smooth, with almost no gum, and the fracture mode is brittle. In the untreated bamboo (d_1), it can be observed that the fibers are coated with colloids and only show the outline shape, with more impurities such as surface extracts present. In the cross-section shown in Fig. 3d_2, it can be observed that many fibers were tightly wrapped by parenchyma cells. It can be seen that the surface gelation of bamboo fiber in the transverse direction is outer < internal < middle. With the removal of the semi-fibers, lignin, and other surface pollutants, the morphological roughness of the fiber surface was enhanced. Because they provide good interfacial bonding between polymer bodies, these rough surfaces have a greater advantage in the manufacture of composites (Shravanabelagola Nagaraja Setty *et al.* 2022). Therefore, observing the outer bamboo fiber through the microstructure has greater advantages in the preparation of composite materials than the middle and the interior.

Diameter Distribution of *Bambusa* Fiber

Using Gaussian function, the diameter distributions of different parts of *Bambusa blumeana* fiber were fitted, which more intuitively showed the diameter distribution of each group of fibers and explored the relationship between diameter and fiber properties. Wang *et al.* (2015) found that the tensile strength of fibers decreases with an increase in their diameter, and changes in diameter between fibers have a significant impact on tensile

strength. Monteiro *et al.* (2017) also found an inverse correlation when obtaining the highest tensile strength in the finest fibers. Figure 4 shows that the Gaussian function fits the normal distribution. The diameter distribution of bamboo fiber is mostly concentrated between 0.15 and 0.25 mm, which was found in the finer fibers. In the transverse direction, the diameter of bamboo fibers showed a change from internal to outer BIB> BMB>BOB, and the longitudinal position increased with the bamboo height BOB > COB>TOB.

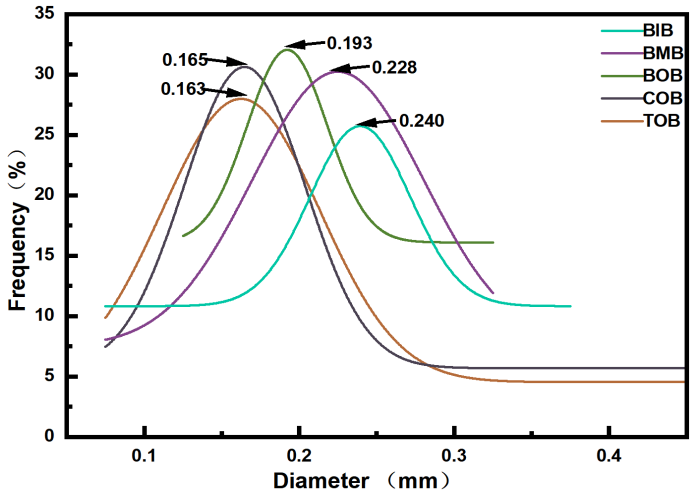

Fig. 4. Diameter distribution of fiber from different parts of *Bambusa*

Mechanical Properties of *Bambusa* Fiber

As shown in Fig. 5a, the tensile strength and modulus of the different parts of *Bambusa* fiber were as follows: BIB<BMB<BOB in the transverse position, and, more obviously, TOB<LEB<BOB in the outer longitudinal position. Figure 5b shows that BMB > COB > BIB > BOB > TOB.

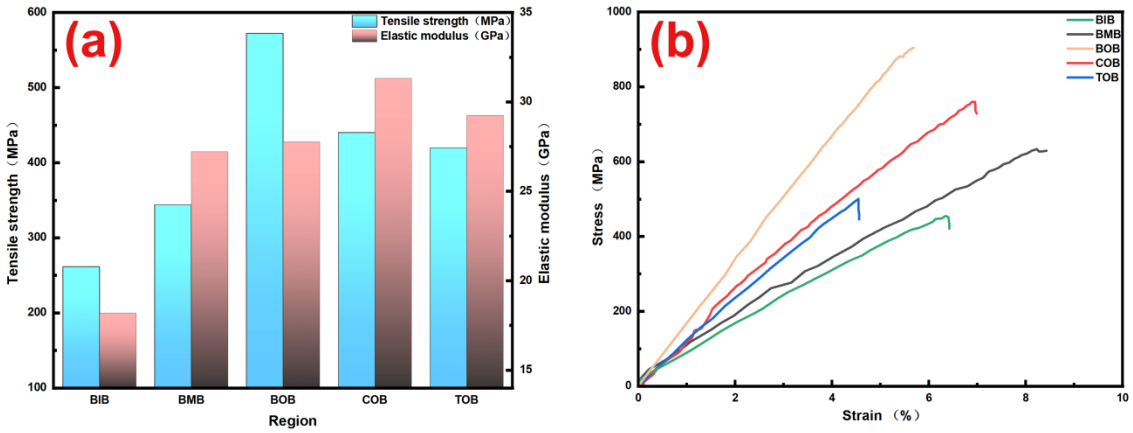

Fig. 5. Mechanical properties of *Bambusa* fiber from different parts of plant
a: tensile strength and modulus, b: elongation at break

The elongation at the break of a single treated bamboo fiber was approximately the same as that of a bamboo fiber bundle that can be used to make yarn (Chen *et al.* 2015). The results indicate that *Bambusa blumeana* fiber has the potential to be used for spinning

soft, fine, and high-quality textile yarn. The maximum strength of the outer bamboo fiber can reach 982 MPa, the modulus can reach 62.2 GPa. The elongation at break was between 0.95% and 2.99%. Under the same treatment, the main distribution range of tensile strength was 100 to 700 MPa, the main range of tensile modulus was 10 to 60 MPa, and the average elongation at break was 1.22 to 1.95%. From the significant difference analysis in Table 1, it can be seen that there were very significant differences ($P < 0.001$) in the fibers of different parts of *Bambusa*, indicating that the change in elongation at the break has an obvious relationship to the different parts of *Bambusa*.

Table 1. Elongation at Break of Different Parts of *Bambusa* Fiber

Region	Average	Range (%)
BIB	1.52b	1.09 to 2.47
BMB	1.40a	0.95 to 1.77
BOB	2.03b	1.01 to 2.99
COB	1.51b	1.03 to 2.03
TOB	1.55b	1.04 to 2.12

The same trend was observed in the tensile modulus. The bamboo fiber in the outer position had a higher tensile modulus, while the bamboo fiber in the middle and inner positions had a lower tensile modulus. This indicates that bamboo fibers in the outer position are more rigid when stressed and can better maintain shape and structural stability. This may be due to the sparse distribution of vascular bundles near the outside of the bamboo, and the greater number of single fibers in bamboo fiber (Kabir *et al.* 2012). The outer bamboo fiber at the bottom has the greatest tensile strength compared to other locations and is ideal for applications as a polymer composite reinforcement, while the inner middle has great potential for textile and decorative purposes.

Fourier Transform Infrared Spectrum Analysis of *Bambusa* Fiber

The chemical structure of the different parts of *Bambusa* fiber is shown in Fig. 6. The absorbance peak near 836 cm^{-1} disappeared, indicating the characteristic peak of substituents in the S and H rings of lignin which may be caused by the degradation of alkali-soluble lignin, indicating that lignin partially dissolved during the fiber extraction process. The absorbance peak near 900 cm^{-1} was enhanced, which represented the β-D glucoside bond of cellulose. The enhanced absorbance peak there indicated that the cellulose content in bamboo fiber was higher than that in bamboo. On the one hand, bamboo fiber is a thick-walled cell, and its cellulose content may be higher than that of other tissues and therefore higher than that of untreated bamboo. On the other hand, some hemicellulose and lignin were dissolved during bamboo fiber bundle extraction, which increased the relative content of cellulose. The strong absorbance peak at 1054 cm^{-1} and the other two characteristic peaks of cellulose at 1109 cm^{-1} and 1159 cm^{-1} are attributed to the stretching vibrations of the three C-O bonds in the cellulose glucose ring. The absorbance peak near 1645 cm^{-1} was the characteristic peak of lignin, indicating that the lignin content in bamboo fiber was lower than that in bamboo. The strength of the absorbance peak near 3421 cm^{-1} was greatly weakened, corresponding with the hydroxy-OH stretching vibration. The decrease in adsorption peaks at two places in bamboo fiber bundles was caused by the decreases in hemicellulose and lignin content, and the partial substitution of cellulose. According to the peak results of IR spectrum, the chemical structure of the fibers from the different parts of blumeana are basically the same, which

are all composed of cellulose, hemicellulose, lignin, pectin, and other substances. The absorption peak strength of bamboo fiber in different parts varies, which is due to the different chemical content of different parts of bamboo fiber.

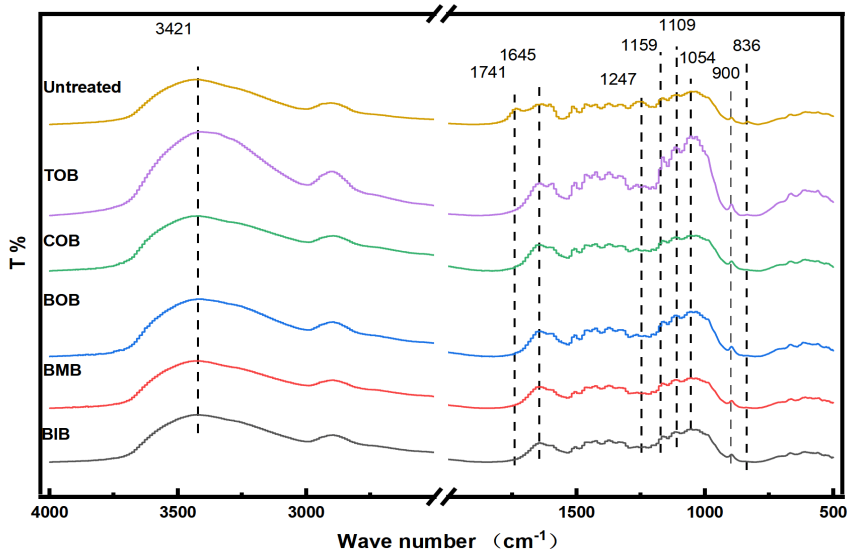

Fig. 6. FTIR spectra of different parts of *Bambusa* fiber

X-ray Diffraction Analysis of *Bambusa* Fiber

Figure 7 shows the X-ray diffraction results of different parts of *Bambusa* fiber. The diffraction peaks at 2θ = 22 to 23° and 2θ = 16 to 18° characterize cellulose (Seki *et al.* 2018). The transformation of the crystal structure of cellulose from cellulose I to cellulose II did not occur under the experimental conditions of alkali treatment. For the different parts of bamboo fiber, the peaks at the crystal plane with 2θ of 16.12°, 22.54°, and 34.60°, correspond to 110, 200, and 004, respectively, indicating that bamboo fiber crystals belong to typical cellulose I (Oudiani *et al.* 2011). The bamboo fibers seen in different parts and the wide peak observed near 16 to 17° are mainly due to the large content of amorphous compounds such as hemicellulose and lignin in the fibers. The BIB peak disappeared near 16.12 °C, which may be due to the absence of bamboo fiber crystals after alkali treatment.

The crystallinity index of different parts of *Bambusa blumeana* fiber was evaluated using Segal's empirical method, and the results are shown in Table 2. Untreated bamboo fiber was lower than BOB. In the longitudinal direction, BOB was greater than COB, which was in turn greater than TOB. Transverse BOB > BMB > BIB, which is consistent with the study of Keisuke Toba *et al.* (2015). They found that the crystallinity of bamboo gradually decreases from the outer layer to the inner layer in the radial direction, and the crystallinity of cellulose decreases with the increase in bamboo height. Natural fiber-reinforced polymer composites with high crystallinity have better characteristics (Bakar *et al.* 2020). It can be seen that the crystallinity of bamboo fiber in different parts was positively correlated with the tensile strength of bamboo fiber.

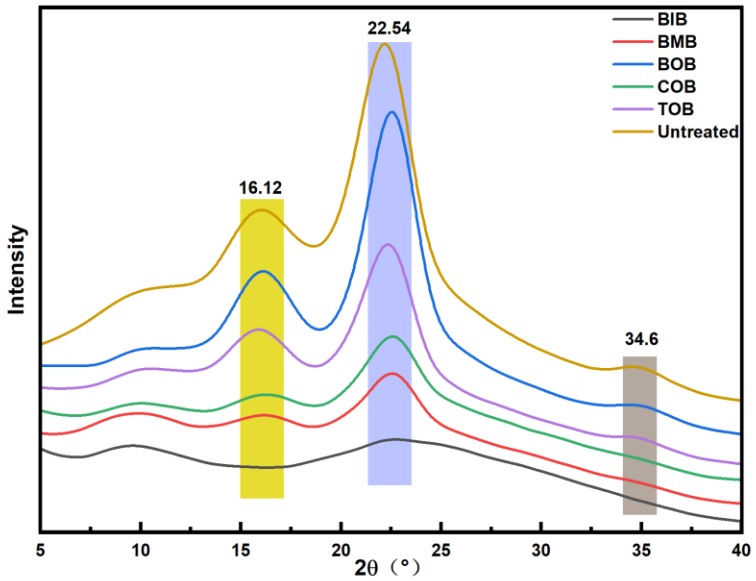

Fig. 7. Crystallinity of different parts of *Bambusa*

Table 2. Crystallinity Index of Different Parts of *Bambusa* Fiber Before and After Alkali Treatment

Number	BF	CrI (%)
1	Untreated	44.40
2	BIB	19.70
3	BMB	27.57
4	BOB	53.45
5	COB	41.11
6	TOB	32.80

Thermogravimetric Analysis of *Bambusa* Fiber

The study of the pyrolytic properties of *Bambusa* fiber is very important for evaluating its applicability in the manufacture of biocomposites or flexible portable products (Ebissa *et al.* 2022). As shown in Fig. 8, three decomposition phases were identified. The weight loss of the first stage was observed at 60 to 110 °C, and the mass loss of BIB was 10%, which may be due to the high initial water content. Between 200 and 350 °C, a second stage of decomposition occurred, which corresponds to the degradation of cellulosic chemicals (mainly cellulose, lignin, and hemicellulose) (Wang *et al.* 2023). Lignin begins to break down at about 200 °C, separating its weaker parts and accelerating the hemicellulose and cellulose reactions (Yiga *et al.* 2021). Hemicellulose decomposition begins at around 250 °C and ends at around 300 °C. Untreated cellulose declines faster at 300°C and 350 °C, showed obvious mass loss, and there was little difference in mass loss among the five groups of delignification bamboo fibers. Driven by the thermal degradation of lignin at 350 to 500 °C, it decreased to about 500 °C (Fang *et al.* 2023). The peak corresponding to the highest decomposition temperature of alkali-treated fiber migrated significantly to the left, indicating that alkali treatment increased the thermal stability of bamboo fiber (Dong *et al.* 2014), ranked as follows: BMB (35.0%) > BOB (34.2%) > TOB (33.0%) > COB (32.6%) > BIB (28.0%) > untreated (24.1%). The residual content was related to the initial water content of the bamboo fiber. On the other hand, due to differences in thermal stability, the degradation of natural fibers is an important issue in the

manufacturing and use of composite materials (Kim *et al.* 2018; Sanjay *et al.* 2018). The above results indicate that the outer and middle *Bambusa* fibers have better thermal stability than the internal fibers.

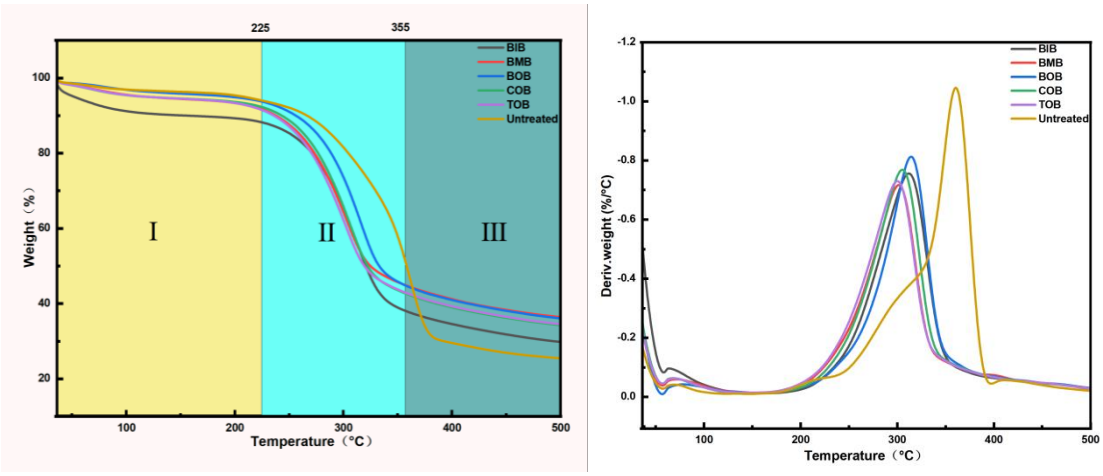

Fig. 8. TG/DTG curves of different parts of *Bambusa* fiber

CONCLUSIONS

1. After the same treatment was applied to different sections of *Bambusa blumeana*, the yield of the outer bamboo fiber was higher than that of the internal fiber. The microstructural observations showed that the outer bamboo fiber was smooth and smaller in diameter after treatment, and the outer diameter was about 25.6% thinner than the inner diameter. In the transverse direction, the diameter of bamboo fiber becomes smaller with decreasing distance to the outside. In the longitudinal position, the diameter gradually decreases as the diameter increases, and the overall fineness of the outside is lower than that of the inside.
2. The tensile strength, tensile modulus, and elongation at break of BOB were found to be 572 MPa, 27.8 GPa, and 2.3%, respectively. The tensile strength, tensile modulus, and elongation at break of BOB were 66.4%, 2.0%, and 79.8% and 118.9%, 52.7%, and 50.6% larger than that of BMB and BIB, respectively. The results showed that the tensile strength of bamboo fiber increased with the lateral direction with decreasing distance to the outside. The strength of the outer bamboo fiber was about twice that of the internal bamboo fiber. Compared with TOB, the tensile strength and elongation at break of BOB decreased by 30.0%, 55.7%, 36.2%, and 46.8%.
3. The tensile strength of bamboo fiber gradually decreased with increasing bamboo stalk height. Outer and central bamboo fibers exhibited higher thermal stability. The variations in crystallinity were consistent with that of tensile strength. The outer bamboo fiber showed more advantages in terms of mechanical strength and thermal stability, which can be attributed to the composite nature of the material. The inner and middle fibers were found to be relatively soft and weak and can be used in the fields of textiles and bamboo decorations. Therefore, the fractional extraction of bamboo fiber can further clarify the applications of *Bambusa blumeana* and improve its utilization rate.

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