Advances in Bamboo Science 7 (2024) 100070

Contents lists available at ScienceDirect

Advances in Bamboo Science

journal homepage: www.journals.elsevier.com/advances-in-bamboo-science

Investigation and application of different extraction techniques for the production of finer bamboo fibres☆

Fisseha Wubneh Asmare[a,c,*], Xiaodong Liu[a], Guanfang Qiao[d], Ruixia Li[a,b], Murugesh Babu K[c], Dacheng Wu[a,b]

[a] *Research & Development Centre of Fibre Materials, Chengdu Textile College, Chengdu 611731, China*
[b] *Textile Institute, Sichuan University, Chengdu 610065, China*
[c] *Ethiopian Institute of Textile and Fashion Technology, Bahir Dar University, Bahir Dar, Ethiopia*
[d] *Sichuan Zhuqianqian Biotechnology Co., Ltd, Guangyuan 628000, China*

ARTICLE INFO

Keywords:
Bamboo fibres
Fibre extraction
Properties of bamboo fibres
Textile application

ABSTRACT

Bamboos are an important source of fibres. Natural bamboo fibres possess have characteristics that make them of potential use in textiles. However, they have not received the attention they deserve due to the difficulty of extracting finer fibres. Full utilization of the potential of bamboo requires the extraction of the fibres using advanced techniques. In this study, three different extraction methods were developed, utilizing a newly created composite enzyme and alkalis in combination to extract finer natural bamboo fibres. The new enzyme was applied in both a solid form and a liquid state. Mechanical processes were also employed in preparing the bamboo culms and extracting the fibres. Three commonly grown bamboo species, Bambusa emeiensis (Neosinocalamus affinis), Phyllostachys edulis (Phyllostachys heterocycla), and Phyllostachys reticulata (Phyllostachys bambusoides), were used in the study to extract natural bamboo fibres. The bamboo samples were treated with 3–6% alkali and 24–36% composite enzyme, based on their weight. The composite enzyme was a recently developed enzyme that was used in both a liquid form and a solid form without the need for water as a solvent (non-aqueous treatment). The physical properties such as moisture content, length and fineness, and mechanical (tensile) properties such as breaking tenacity, breaking load and breaking extension of the resulting fibres were assessed with their minimum, maximum and average values. Structural analyses were performed using infrared spectroscopy (FTIR), X-ray diffraction (XRD), thermal analyzer (TGA) and scanning electron microscopy (SEM). The yield percentages of bamboo fibres were also determined. The bamboo fibres had a moisture content of 7.32–7.71%, an average length of 5.48–6.01 cm, a linear density of 9.71–11.43 tex, a breaking load of 138.96–147.67 cN, a breaking tenacity of 12.16–15.21 cN/tex, and a breaking elongation of 2.60–2.75%. SEM, TGA and FTIR tests indicated that the fibres were not single cellulosic fibres but rather fibre bundles in which single fibres were bonded by lignin and hemicellulose. The TGA results showed that the fibres were sufficiently thermally stable to withstand high temperature textile processes. The XRD results indicated the improvement of the crystallinity of the natural bamboo fibres owing to the partial removal of the non-crystalline lignin and other components. The measured properties of the fibres showed standard deviation values of 0.36–2.52, indicating a high level of uniformity within each sample. The experimental results demonstrated that the fibres obtained in this study have the potential to be used in textiles. The fibre yield percentages (approximately 52.7–55.2%) confirmed that all three bamboo species have the potential to provide usable fibres.

Introduction

Synthetic fibres are utilized extensively in the textile and composite industries (Tahri et al. (2016). The manufacture of synthetic fibres relies on petroleum feedstock, a diminishing non-renewable resource (Fu et al. (2012). The reliance on synthetic materials as a fibre source is limited due to environmental concerns associated with the production, utilization, and disposal of artificial fibres (May-Pat et al. (2013). Fibres can be

---

☆ This article is part of a special issue entitled: “Special issue on Future uses of bamboo” published at the journal Advances in Bamboo Science.

* Corresponding author at: Research & Development Centre of Fibre Materials, Chengdu Textile College, Chengdu 611731, China.
E-mail address: fisha.wubneh@gmail.com (F.W. Asmare).

https://doi.org/10.1016/j.bamboo.2024.100070
Received 12 September 2023; Received in revised form 4 March 2024; Accepted 4 March 2024

acquired from organic sources, including both plants and animals (Ticoalu et al. (2010). Bamboo is one of the sources of plant fibres. It is the fastest growing plant in the world, primarily distributed in tropical and subtropical regions (Lipp-Symonowicz et al. (2011). More than 1400 bamboo species from 115 genera are found in diverse climates and regions (Kelchner, 2013). *Phyllostachys* Siebold & Zucc. is one of the bamboo genera that has been identified as a potential source for fibre extraction owing to the anatomical characteristics of the species within this genus. *Phyllostachys* spp. are commonly grown in warm-temperate climates. They can also grow in the colder climates common in Europe (Ohrnberger, 1999). *Bambusa emeiensis* L.C.Chia & H.L.Fung (*Neosinocalamus affinis* (Rendle) Keng.f.) is a bamboo species native to southwest China (Yu et al. (2014) and available in enormous quantities, especially in Sichuan Province (Zhiyong et al. 2005; Li et al. 2013; Zhang et al., 2013). It is one of the largest bamboo species (Zhiyong et al. 2005; Li et al., 2013). It has been utilized for pulping in Sichuan because of its long fibres (Sun et al., 2011; Yu et al., 2014; Xie et al., 2016). It has also been an important material for bamboo fibre-based materials such as composites (Sun et al., 2011; Yu et al., 2014).

Because of its rapid growth, substantial quantities of biomass can be made available for fibre processing (Afrin et al., 2009; Afrin et al., 2012; Mishra et al., 2012). Bamboo plants that are six months to three years old can be harvested for the extraction of fibres (Afrin et al., 2009). Bamboo fibre is a newly emerging natural fibre (Jin et al., 2018). It is a promising fibre with the potential to be employed in many textiles (Shunliu et al., 2008).

Bamboo fibres are derived from the bamboo culm. The characteristics of the extracted fibres need to be related to their intended use. A variety of fibre extraction methods have been developed and applied in the production of bamboo fibres for use in textiles and the reinforcement of composites. The methods of manufacturing of bamboo fibres can be categorized into two broad groups, natural fibres and regenerated (viscose) fibres (Qingchun, 2003). Regenerated fibre is produced through a chemical method called wet spinning in a process similar to the production of rayon fibre (Munja and Kashyap, 2015). Since the cellulosic and non-cellulosic components of the bamboo culm are solubilized by different chemicals such as acids and alkalis with variable degree of solubility or degradation, regenerated bamboo fibres can be obtained after a series of chemical treatments including soaking, boiling, washing and softening. These procedures are repeated several times under a certain pressure so as to extract fibres (Xu et al., 2007; Erdumlu and Ozipek, 2008; Kumar et al., 2010; Yueping et al., 2010; Bensah and Moses, 2013). In the process of regenerated bamboo fibre production, bamboo culms are crushed into strips and the strips are soaked in a solution of 18% sodium hydroxide at 20–25 °C for 1–3 hours. The bamboo cellulose and sodium hydroxide (NaOH) mixture is pressed to remove excess NaOH, crushed by a grinder and left to dry for 24 hours. Carbon disulfide (CS_2) is added to the mixture and then the mixture is decompressed to remove CS_2 resulting in cellulose sodium xanthate. Addition of a diluted solution of NaOH to the cellulose sodium xanthate dissolves it into a viscose solution. After subsequent ripening, filtering and degassing, the viscose solution is finally discharged through spinneret nozzles into a large bowl of diluted sulphuric acid solution which hardens the viscose bamboo cellulose sodium xanthate and reconverts it to bamboo filaments (regenerated bamboo fibres) which can be spun into yarns to be woven or knit into textile products (Munja and Kashyap, 2015).

Regenerated bamboo fibre is composed of α cellulose (80%), hemicelluloses (15%) pentosans (3.5%) and traces of other components such as resin, soap, sulphur, ash, and lignin-like substances. It is utilized in paper and textile applications (Luo et al., 2014); Munja and Kashyap, 2015; Sugesty et al. (2015); Xie et al. (2015); Jing-Huan et al., 2016; Junior et al., 2018; Ermias Girma, 2020). However, this process is environmentally hazardous (Munja and Kashyap, 2015; Nayak and Mishra, 2016). Moreover, the natural properties of bamboo fibres such as UV protection, antimicrobial and anti-odour are not retained in regenerated bamboo fibres (Nayak and Mishra, 2016). Furthermore, a significant amount of water and energy are consumed in the viscose process (Steffen et al., 2013; Parisi et al., 2015). Therefore, recent research efforts have been concentrated on the manufacture of natural bamboo fibres for use in textiles, composites, and other products (Deshpande et al., 2000; Erdumlu and Ozipek, 2008; Zupin and Dimitrovski, 2010; Tanaka et al., 2014).

Natural bamboo fibres are extracted directly from the bamboo culm by a degumming or retting process which can involve chemical, mechanical, biological or combined methods (Deshpande et al., 2000; Kumar et al., 2010; Majumdar et al., 2011; Nguyen et al., 2012; Hyojin et al., 2013). Each extraction method has been done based on the application or end use of bamboo fibres. A lower amount of cellulose and a higher amount of non-cellulosic components are found in natural bamboo fibre than in regenerated bamboo fibre (Latif et al., 1993). The crystalline structure properties of the original bamboo fibre do not change during the extraction process, meaning that the natural bamboo fibres maintain the natural properties of the original bamboo (Cai et al., 2013). However, natural bamboo fibres are not commonly used due to the challenging extraction process (Afrin et al., 2009; Rocky and Thompson, 2018). The primary (technical) bamboo fibres are usually too short, typically less than 2 mm, to be suitable for textiles. They are held together by non-cellulosic substances such as lignin, hemicellulose and pectin. Although these non-cellulosic substances are crucial for binding the very short primary fibres, they contribute to the roughness and rigidity of the fibres. The main objective in producing natural bamboo fibres for textile applications is to partially eliminate non-cellulosic substances without causing damage to the resulting fibres (Sulaiman et al., 2005; Xu et al., 2006; Kostic et al., 2008; Zou et al. (2009); Liu et al. (2010); Yueping et al., 2010).

Mechanical, steam explosion, chemical, biological and combined methods have been utilized in the extraction of natural bamboo fibres. Mechanical procedures are typically incorporated in other methods for the preparation of the bamboo culms and the extraction of bamboo fibre bundles (Kazuya et al. 2004; Rao and Mohana Rao, 2007) Shunliu et al. (2008); Hebel et al., 2014; Zhang et al., 2014; Zhuo et al., 2020). The entire mechanical process was commonly used to produce coarser bamboo fibres and strips whose end uses were bamboo-based composites. However, it failed to produce sufficiently fine fibres for use in textiles unless further modified by other methods (Gupta et al., 2011; Thakur et al., 2016; Dessalegn et al., 2022). Similarly, the steam explosion method barely produces bamboo fibres suitable for textile application [20]. Chemical treatments are the most frequently used (Liu et al., 2011). They are usually assisted by mechanical procedures for the pretreatment and post treatment of the bamboo culms and fibres, respectively. Various types of acids, peroxides, alkalis and other additive chemicals have been involved in the extraction of bamboo fibres (Tang et al., 2007; Chen et al., 2018; Rocky and Thompson,2020; Tan et al., 2020).

Alkali-based manufacturing processes of bamboo fibres have been widely tested (Liu et al. (2011); Das and Chakraborty, 2006). Among several alkalis, NaOH (caustic soda) is mostly preferred for the extraction of bamboo fibres because it is cheaper than other alkalis and commercially available (Beltran et al. (2002); Weyenberg et al. (2006); Chen et al. (2017); Chen et al. (2018); Chin et al., 2020.However, the use of significant amounts of alkali made the process non-ecofriendly (Nguyen et al., 2012; Yang et al., 2023). The higher pH of waste water and effluent requires treatment before it is drained off (Nguyen et al., 2012). Most of the research done using chemical methods has produced coarser bamboo fibres that could only be applied as a reinforcement in bamboo-based composites (Liu et al., 2011). Biological methods involving enzymes are also practised (Han et al., 2008). Despite their environmental friendliness, they have some drawbacks. They require a slow process that mostly involves the use of multiple enzymes (Fu et al. (2012); Rocky and Thompson, 2018). Additionally, they are not an effective method for industrial textile fibre production (Fu et al. (2012).

Bamboo fibre extraction methods are not usually carried out individually in real fibre production process. The extraction of the fibre often requires a combination of methods to meet the application requirements (Liu et al., 2012; Fu et al., 2012; Rocky and Thompson, 2018; Hanana et al., 2015; Chen et al., 2011).

The majority of the investigations conducted on bamboo have led to the utilization of bamboo fibres in order to improve composites. In terms of extracting natural bamboo fibres for textile applications, there is a limited amount of research available (Deshpande et al., 2000; Kazuya et al. 2004; Rao and Mohana Rao, 2007; Shunliu et al. (2008); Kumar et al., 2010; Liu et al., 2011; Zhang et al., 2014; Yang et al., 2017; Zhuo et al., 2020). Additionally, the methods employed to create finer or easily spun bamboo fibres have been extremely demanding in terms of labour, energy and chemicals (Rao and Mohana Rao, 2007; Liu et al., 2011).

In this research, three different methods of extraction were examined and applied to three species of bamboo in order to produce finer bamboo fibres. These techniques were developed using enzymatic, chemical, and mechanical processes with the goal of reducing the environmental impact, treatment time, and water and energy usage, while still maintaining the quality of the resulting fibres. Sodium bicarbonate, caustic soda, and a composite enzyme were utilized.

This study offers several advantages and innovations. Specifically, a composite enzyme known as biological enzyme solution A (Patent No 19503677), developed by the research team at Chengdu Textile College Research & Development Centre of Fibre Materials in Chengdu, Sichuan, China, was used for the first time in this research for the extraction of bamboo fibres. The newly developed enzyme has numerous benefits. It is known that enzymes are specific in their actions; each type of enzyme reacts with only one type of substance. As a result, since there are several non-cellulosic substances such as lignin, hemicellulose, and pectin in the bamboo culm that need to be degraded, multiple enzymes are necessary. However, the newly developed composite enzyme is multifunctional, which avoids the need for multiple enzymes. It contains cellulase, pectinase, and hemicellulose, and is capable of dissolving these components of the bamboo culm. Being a neutral enzyme, it does not require an alkaline or acidic environment for its degumming activity. Additionally, it does not necessitate the use of other auxiliary chemicals such as boosters, stabilizers, wetting agents, or activators. Another advantage of this enzyme is that it can be applied at the lower temperature of 32°C. It can also be applied without the use of an aqueous medium as a solvent.

In comparison to previous research, this study used less sodium bicarbonate and caustic soda at lower temperatures, ranging from ambient to 50 °C, owing to the effectiveness of the composite enzyme at a relatively higher concentration (26–36%). Treatment of bamboo strips with alkalis and enzymes at lower temperatures results in lower energy consumption. Moreover, no additional substances or agents were used in any of the three extraction techniques to enhance the effects of the alkalis. The use of minimal alkalis without auxiliary chemicals reduces the cost of chemicals, the environmental impact, and the effluent load. Some of the enzymatic and alkaline treatments were carried out with no involvement of water as a solvent (non-aqua or anhydrous treatment), with the objectives of enhancement of the decomposition of non-cellulosic components, minimization of the amount of the enzyme and sodium bicarbonate and lowering water consumption. To the best of our knowledge, no one has utilized a non-aqua treatment (stacking) on bamboo strips using chemicals or enzymes.

In addition to the extraction methods, the species type, growth location, harvesting conditions, and age of the bamboo plant can impact the extraction process and the quality of the resulting fibres (Rao and Mohana Rao, 2007; Khalil et al. (2012). While there are more than 1200 bamboo species belonging to 70–91 genera (Waite, 2010; Rai et al. (2011); Correia et al. (2014); Nayak and Mishra, 2016), only a limited number of bamboo species have been investigated for the extraction of natural bamboo fibres (Rocky and Thompson, 2020). This study therefore focused on some bamboo species that are readily available and reproducible for the purpose of producing natural bamboo fibres.

Sodium hydroxide (NaOH) and sodium bicarbonate ($NaHCO_3$) were selected based on a review of existing literature and were found to be effective in breaking down the non-cellulosic components of bamboo strips. The appropriate concentration of alkalis and enzymes, as well as the material-to-liquid ratio, processing temperature, and time, were determined through multiple experiments and trials.

The objective of the study was the development and application of three different methods of fibre extraction in order to produce finer bamboo fibres that could potentially be used in textile applications.

Experimental design

Materials

The bamboo culms utilized in the current study were provided by the research team of the Development of Fibre and Material Research Centre of Chengdu Textile College, Chengdu, Sichuan, China. They were acquired from three bamboo species, namely 1–1.5 years old *Phyllostachys edulis* (Carrière) J.Houz. (*P. heterocylca* (Carrière) Matsum.), 1–1.5 years old *Phyllostachys reticulata* (Rupr.) K.Koch (*P. bambusoides* Siebold & Zucc.) (Variegated bamboo) and 2–3 years old *Bambusa emeiensis*. All the samples were collected from bamboo plants cultivated in Sichuan Province, China.

Chemicals

Chemicals utilized in the treatments included sodium bicarbonate (98% $NaHCO_3$) and sodium hydroxide (98% NaOH). Food-grade glacial acetic acid (95% CH_3COOH) was utilized for alkaline neutralization. All of the chemicals were of analytical grade and manufactured by Tianjin Yitongmaoyuan Chemicals Co., Ltd., Wuqing District, Tianjin, China. A newly developed enzyme known as biological compound solution A (patent No 19503677) was also employed in the treatment of bamboo strips. It was developed and generously provided by the research group of Chengdu Textile College Research & Development Center of Fibre Materials, Chengdu, Sichuan, China. This study utilized the new enzyme for the first time. Collodion and glycerin solutions were used in the process of measuring the diameter of the fibres using an electron microscope.

Methods and apparatus

Apparatus

Cutter, automated cutter (produced by Zhejiang Anji, China), roller press (rolling mill) with four sets of rollers (manufactured by the research team of Chengdu Textile College Research & Development Center of Fiber Materials, Chengdu, Sichuan, China), vibrating sieve machine, radiofrequency dryer (produced in Wuxi, Jiangsu province China), electronic balance (Manufactured in Tianjin, China with maximum weighing range of 1000 g), drying oven (Manufactured in Tianjin, China with a temperature range from room temperature to 150 ℃), vibrating fiber separator (splitter) (produced by the research team of Chengdu Textile College Research & Development Center of Fiber Materials, Chengdu, Sichuan, China), conditioning cabinet, electron microscope, scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), thermo gravimetric analyzer (TGA), Single fiber tensile tester (LLY-06 Tensile Tester, Laizhou Electronic Instrument Co. Ltd, Shandong

Province, China), scale, reaction kettle (reactor), weighing bottle, thick plastic sheet, plastic tank beakers and spoons were used for the preparation of bamboo culms, extraction and characterization of bamboo fibers. Vibrating fiber separator and roller press were produced by the aforementioned research team.

Pretreatment

The initial step was the preparation of bamboo culms for extraction. In this investigation, mechanical methods were used in both the preparation of bamboo culms and as a subsequent treatment after the enzymatic and chemical treatments. All the bamboo culms underwent the same pretreatment procedures. The bamboo culms were harvested from the bamboo plantation 20 cm above the base and also 20 cm below the tip. Fresh culms were utilized for fibre extraction as they are simpler to crush and split (comb). The culms were brushed to eliminate surface materials. The moisture content of the bamboo culms was determined using the loss on drying technique. They were then placed in the sun on a plastic sheet for 16 hours. The plastic sheet was used to prevent the culms from coming into direct contact with the soil, which could have contaminated the culms and also affected the drying process. The bamboo culms were rotated in a longitudinal direction every hour to ensure even drying. The culms were then passed through a roller press once (crushed) at a speed of 120 m/min with a pressure of 0.3 MPa to produce bamboo strips. After passing through the roller machine once, they were rolled four more times as they went through the four pairs of rollers. Immediately after the rolling process, the bamboo strips were cut at their nodes by an automated cutter running at a speed of 35 cycles/min. Mechanically pretreated bamboo strips were then prepared for fibre extraction treatments.

Extraction of bamboo fibres

Different extraction methods were used for each species. Mechanical, alkaline, and enzymatic approaches were combined in various ways to extract more delicate bamboo fibres. The extraction process for bamboo fibres using combined techniques also included dry (non-aqueous) procedures. A novel enzyme known as biological compound solution A (patent No. 19503677) was employed in this investigation.

(1) Combined enzymatic (stacking)-chemical (stacking)-mechanical-enzymatic (stacking)

This combined extraction technique was utilized in the extraction of fibres from *B. emeiensis* (sample S-1). The technique can also be referred to as the anhydrous extraction method as there was no involvement of aqueous solution except during washing. The mechanically processed bamboo slices were placed in the reactor. 16% enzyme (based on weight of the slices) was added in the reactor and the slices were exposed to a controlled temperature of 32 ℃ for 72 hours. 3% $NaHCO_3$ powder was sprayed on the slices which were retted with the enzyme, agitated and then kept for another 72 hours at 50 ℃. The addition of alkali aided in the further decomposition of the degraded non-cellulosic constituents. The alkaline treated slices were rolled by a roller press, rinsed with water for half an hour at 80 °C in a reaction kettle and placed on a vibratory sieve machine to remove the water. They were then opened by the fibre splitter and dried at 85 °C by a radio frequency dryer for 3 hours. The coarse bamboo fibres were once again stacked with 8% enzyme in the reactor at 32 °C temperature for 48 hours for further purification. The treated fibres were rinsed with water for half an hour at 70 °C, drained off and finally dried at 85 °C for 2 hours.

(2) Combined chemical (at room temperature)-enzymatic (stacking)-mechanical-enzymatic (solution)

Slices of *Phyllostachys edulis* (sample S-2), were extracted by this technique. The bamboo pieces were soaked in a 6% NaOH solution with a pH of 11 in a plastic tank at room temperature for 72 hours with a ratio of 1:5. The slices treated with alkali were washed and neutralized using a 2% acetic acid solution at a temperature of 35 ℃ with a ratio of 1:5 for 1 hour and then rinsed with water for 30 minutes at 80 ℃. The alkali-treated slices were drained off. They were then placed in a reactor with20% enzyme at a controlled temperature of 32 ℃ for 48 hours. After the enzymatic treatment the fibres were rinsed, drained off, rolled, opened and dried sequentially. The coarse bamboo fibres were again subjected to a 16% enzyme solution treatment with a liquor ratio of 1:5 at a temperature of 32 ℃ for 48 hours to further refine them into finer fibres. The treated fibres were then rinsed with water for 30 minutes at 70 ℃, drained, and finally dried at 85 ℃ for 2 hours.

(3) Combined chemical (at room temperature)-enzymatic (solution)-mechanical- enzymatic (solution)

In the combined treatment of bamboo slices from the species *Phyllostachys reticulata* (sample S-3), the enzyme was applied in a liquid form. The bamboo slices were immersed in a plastic container in a 6% NaOH solution at room temperature for 72 hours with a ratio of 1:5. The pH of the alkaline solution was 11. The alkaline treatment was followed by cleansing, neutralization, rinsing and draining off before being treated in a 20% enzyme solution at a temperature of 32 ℃ for 48 hours with a ratio of 1:5. The treated slices were once again rinsed with water and drained. After being rolled by the roller press, the coarse fibres were opened by the fibre splitter followed by drying. The coarse bamboo fibres were further treated in a 16% enzyme solution with a ratio of 1:5 for 48 hours with the objective of further purification into finer fibres. The final enzymatic treatment of the fibres was followed by rinsing, draining off and final drying. The extraction of natural bamboo fibre from three bamboo species using three different integrated processes is depicted in Fig. 1.

Tests and assessments

The mass and moisture levels of the bamboo strips were examined prior to undergoing the subsequent treatments. Once the bamboo fibres were obtained, they were stored in an airtight plastic bag in a desiccator until they could be utilized. Their physical and mechanical characteristics were assessed. To prepare the fibre samples for testing, they were conditioned in a standard atmosphere (20±2 °C temperature and 65 ±5%) for 48 hours using a conditioning cabinet, following the instructions outlined in ASTM D1776 (ASTM D1776/D1776M-20 2020). All the fibres within each sample were thoroughly mixed. Three small clusters of fibreers were extracted from three different areas (top, bottom and middle) of the samples for measurement. The essential physical and mechanical properties of the fibres, such as moisture content, fibre length, diameter, fineness, and tensile properties, were evaluated. The percentages of fibre yield and weight loss were also determined. The data collected were analyzed, and the minimum, maximum, and average values were determined. Up to 250 test specimens (individual fibres) were randomly selected from each sample in order to maximize the representativeness of the specimens for the sample.

Scanning electron microscope (SEM) analysis

The morphology of the fibres obtained in the study was analyzed using scanning electron microscopy (Zeiss Sigma VP, Germany) with a 10 kV acceleration voltage.

Fourier transform infrared spectroscopy (FTIR) analysis

FTIR spectra of the bamboo fibres were recorded with a Fourier transform infrared spectrometer (Nicolet IS5, Thermo Fisher Corp., USA/ Nicolet Nexus 670) using the KBr disc technique (1 mg powder of sample/300 mg KBr). Scans were taken with a resolution of 2 cm^{-1}. Data was collected in the wave number range of 4000–400 cm^{-1}.

X-ray diffraction (XRD) analysis

Crystallinity is a critical parameter for evaluating the effect of fibre extraction techniques (Chen et al., 2011). Several methods that can be applied in the determination of crystallinity of polymers such as differential scanning calorimetry (DSC), XRD, solid-state nuclear magnetic resonance (NMR), infrared (IR) spectroscopy, Raman spectroscopy, density measurement, and heat fusion (Rocky and Thompson, 2018,

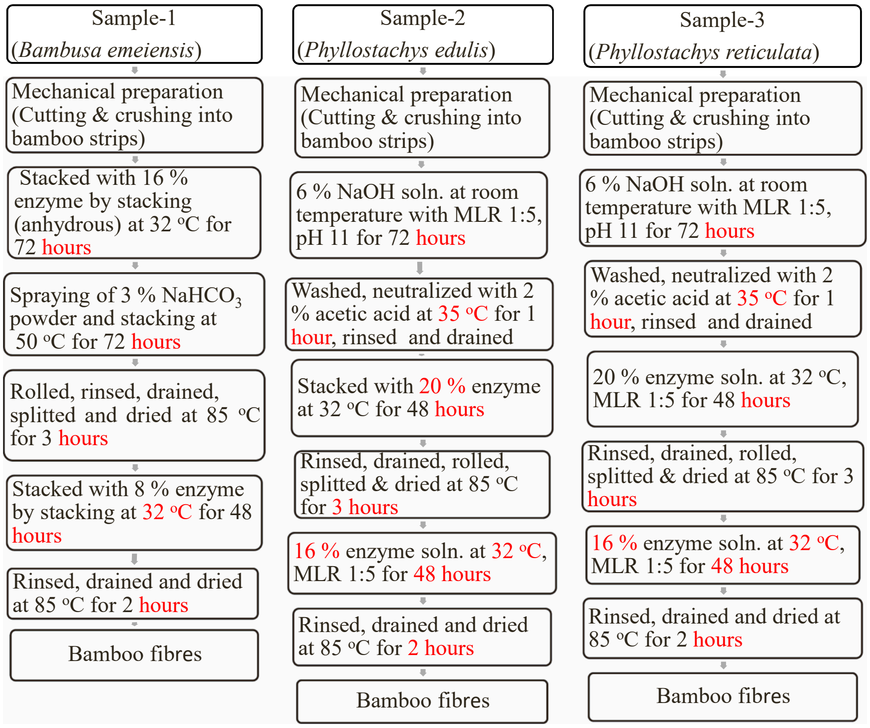


Fig. 1. Flowchart of natural bamboo fibre extraction from three bamboo species using three different combined processes.

2020). Though DSC is most common, XRD, a nondestructive method, has recently been found to be the most direct, widely used, and easier method to determine CI of polymers (Rocky and Thompson, 2020). XRD measurements of the bamboo fibres were carried out on a diffractometer (Ultima IV, Rigaku, Japan) using Cu-kα as the X-ray source (λ = 0.15418 nm), 25 mA current, 1 kw and a 40 kV accelerating voltage. The Segal empirical method was adopted to evaluate the crystallinity index of the bamboo fibs. The crystal index (CrI) was calculated from Eq. (1).

$$\mathrm{CrI}(\%) = \frac{I_{002} - I_{am}}{I_{002}} \mathrm{X}100 \tag{1}$$

where I_{002} is the maximum intensity of the peak on 002 plane (at 2θ = 22.6°) and I_{am} is the minimum height of the amorphous phases of the diffracted beam between 002 and 001 planes (Segal et al., 1959; Ju et al., 2015). The X-ray from the copper source (Ni-filtered Cu-K_α) with wavelengths of 1.5418 Å was run at a beam voltage of 40 kV and a filament current of 25 mA using a wide-angle X-ray diffraction (WAXD) method. Angular scanning was conducted from 10° to 80° (2θ) with an effective data collection time of 30 min with 360° rotation around Z-axis.

Thermo-gravimetric (TG) analysis

The thermal stability of the bamboo fibres was evaluated by a thermo gravimetric instrument (TG209-F1, Netzsch, Germany). About 5 mg specimens were heated to 800 °C under nitrogen atmosphere at a heating rate of 10 °C/min.

Measurement of the moisture content (%) of raw bamboo strips and fibres

The moisture content of the bamboo fibres was determined by the method outlined in ASTM D629–15 using a conditioning cabinet (ASTM, D629, 2015). By measuring the weight of the fibres after conditioning (W_w) and the weight of the fibres after drying in an oven (W_d), the moisture content percentage (Mc) was calculated using Eq. (2). This process was repeated twice to ensure consistent results. The moisture content of bamboo strips was also determined using the same equation by measuring the conditioned weight (W_w) and oven-dry weight (W_d) of the strips.

$$\mathrm{Mc} = \frac{\text{Weight of moisture}}{\text{Weght of material before oven drying}} \times 100\% \tag{2}$$

$$= \frac{W_w - W_d}{W_w} \times 100\%$$

Measurement of fibre yield (%)

Fibre yield is defined as the quantity of cellulose-rich fibrous materials that are extracted from raw bamboo samples. It is typically expressed as a percentage. It was determined using the direct gravimetric method (Kostic et al. 2008). The yield percentage (F_y) was calculated using Eq. (3) by measuring the weight of the raw bamboo strips (W_b) and the weight of the extracted fibres after the process (W_f), both of which were dried in an oven. Percentage weight loss was also determined based on the fibre yield percentage. This represents the amount of non-cellulosic components that were removed from the fibres.

$$F_y = \frac{W_b - W_f}{W_b} \times 100\% \tag{3}$$

Measurement of fibre length

A textile fibre should have a specific length to fulfill the textile processing requirement. A fibre length of 15–50 mm is required for yarn manufacturing (Li and Dai, 2006). Fibre length is one of the most important characteristics for spinning (Lin et al., 2012; Kuang and Yu, 2015; Parsi et al., 2016). Staple length is defined as the average length of spinnable fibre. Fibre length affects yarn strength (Barella and Manich, 2002; Ibrahim, 2018), yarn unevenness (Barella and Manich, 2002), yarn hairiness (Matsuo, 2019), the spinning limit, process performance and spinning efficiency (Khan et al., 2021). The length of the aligned bamboo fibres was assessed using a scale with millimeter markings by arranging them at the bottom of the scale. 250 samples were randomly selected from the clusters of specimens and used for the assessment. The distribution of lengths for each sample was also examined and illustrated using a distribution chart. The lowest, highest, and mean length values of the samples were calculated.

Measurement of fibre fineness

Fineness is another significant quality of fibres for use in textile applications. It can be characterized by its linear mass density. Linear mass density was assessed using manual techniques employing an electronic balance. The balance was utilized to measure the weight of fibres in grams. Linear mass density in tex was calculated by dividing the weight of fibres by their known length (Kostic et al. (2008). As the balance was not highly sensitive to small weights, multiple fibres were

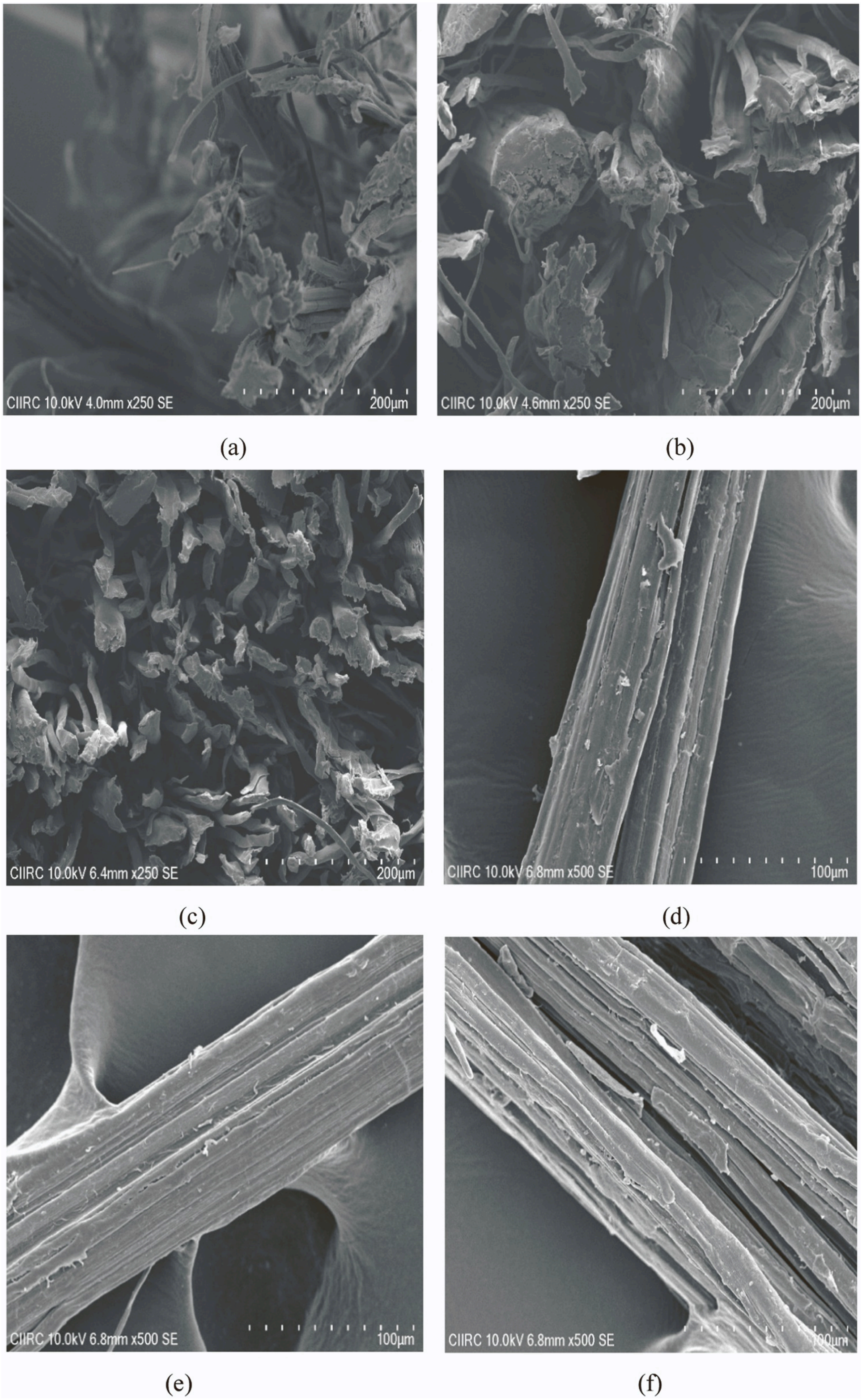


Fig. 2. SEM images of longitudinal and cross-sectional surfaces of bamboo fibres ((a) – (c) cross-sectional images & (e) – (f) longitudinal images. *Bambusa emeiensis* ((a) & (d), *Phyllostachys edulis* ((b) & (e) and *P. reticulata* (c) & (f)).

weighed together at once, and the combined length of the fibres was used as the length for that specific weight. Three clusters of fibres (samples) were taken from each specimen. The minimum, maximum, and average linear mass density values were determined.

Measurement of tensile properties of fibres

The tensile properties of the bamboo fibres were measured by an electronic single fibre strength tester (LLY-06 Tensile Tester, Laizhou Electronic Instrument Co. Ltd) in accordance with the ASTM D2256M standard (ASTM D2256/D2256M-10 2015) with some modifications in the parameters. Testing was conducted at room temperature with a cross head speed of 10 mm/min, a gauge length of 50 mm and a load cell of 500 lb. Due to the challenge of measuring shorter fibres, longer fibres over 5 cm length were chosen to measure their tensile properties. The average thickness of the samples was used for tenacity analysis. Each fibre specimen was adhered to a rigid paper frame with the specified gauge length. To align the fibres as straightly as possible between the clamps and to prevent slipping, the ends of the fibres were fixed with adhesive to the paper frame. Once the ends of the supporting frame were clamped by the jaws of the testing machine, the frame edges were carefully severed in the middle (Zhang et al. (2015); Wang et al. (2018). The breaking force, tenacity and elongation of the fibres were measured. The minimum, maximum and average values of 250 test specimens were determined.

Results and discussion

As the samples came from three species with varying ages and were subject to different extraction procedures, direct comparisons between the samples cannot be made.

SEM analysis

Lengthwise sections and the cross-section of the fibres observed by SEM are shown in Fig. 2(a) – (c) and (c) – (f), respectively. The fibres were long cylinders with tapered ends and uniform in size, without any natural twist on the surface typical of cotton fibres. There were lumen structures in the cross section (He et al. (2007). From the cross-sectional view of SEM images, several single fibres were observed in bundle form. Each fibre bundle was also composed of clusters of individual fibres. The greatest number of clusters were found in the fibre bundle of *Phyllostachys reticulata* (S-3). There was no apparent difference in the number of clusters between *Bambusa emeiensis* (S-1) and *Phyllostachys edulis* (S-2). A greater number of individual fibres of *P. edulis* were bound more tightly in clusters than fibres of *B. emeiensis*. Though individual fibres were held tightly in each cluster of fibre bundle of *P. reticulata*, there were fewer number of fibres in each cluster than in the other two species (Fig. 2(a) – (c)). The longitudinal images showed that single fibres were longitudinally aligned in the flat-wise direction. They were held together by hemicelluloses and lignin. Clusters of fibres were bonded

by these non-cellulosic components (matrices) with different levels. Only a little residual hemicellulose and lignin was found on the surface of fibre bundle of *B. emeiensis* whereas there was relatively more on the surface of fibre bundle of *P. reticulata*. However, the longitudinal surface of fibre bundle of *P. edulis* was clean (Fig. 2(e) – f)).

FTIR analysis

The FTIR spectra of bamboo fibres are shown as characteristic spectra of cellulose I in Fig. 3 (He et al., 2007). All the bamboo fibre samples displayed similar curves implying that they had similar chemical components. The broad adsorption bands in the range of 3650–3000 cm^{-1} are ascribed to the stretching vibrations of -OH (Khawas and Deka, 2016). Bands observed in 1640 cm^{-1} in all the fibres are attributed to the OH bending mode of water. However, *P. edulis* and

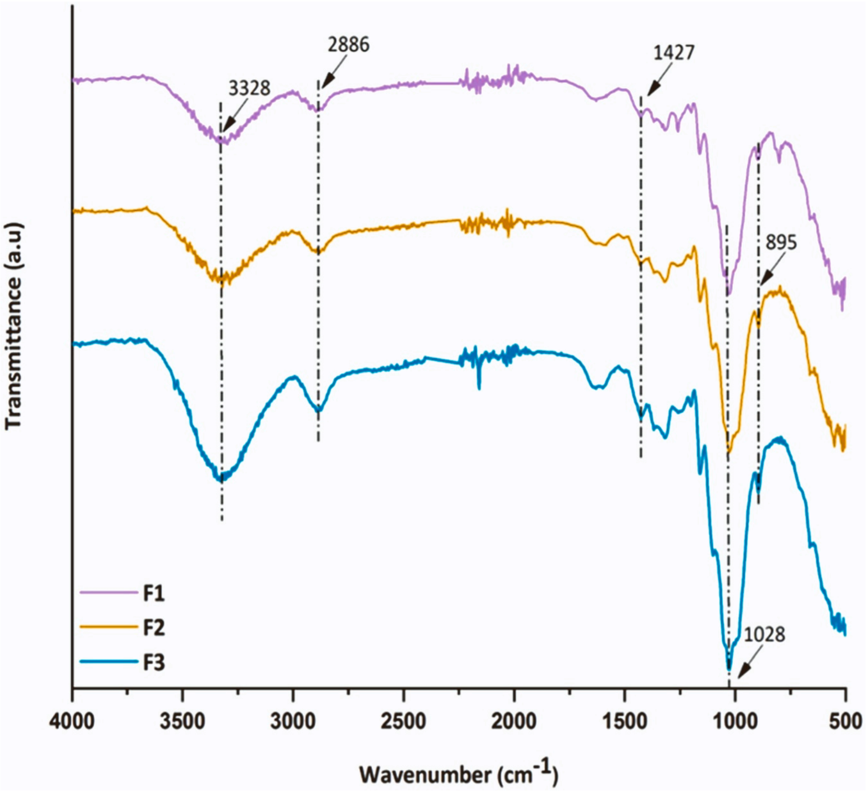


Fig. 3. FTIR spectra of bamboo samples before and after steam explosion.

P. reticulata showed double peaks at 1640 cm^{-1} and 1652 cm^{-1}. A small band at 2886 cm^{-1} is related to the stretching vibration of C-H in cellulose (Khawas and Deka, 2016; Phinichka and Kaenthong, 2018). The adsorption band at 1738 cm^{-1} is associated with acetyl and uronic ester groups in hemicellulose or the ester linkage of carboxylic groups of ferulic and p-coumaric acid in lignin or hemicellulose (Tanpichai et al., 2019). The peaks at 895 cm^{-1} & 905 cm^{-1} is a characteristic of β-glycosidic linkage contributed by both cellulose and hemicellulose in the fibres (stretching vibration of C-H) (Mortazavi and Moghaddam, 2010). The adsorption bands located at 1427, 1378 and 1256 cm-1 are assigned to the aromatic skeletal

vibration of lignin (Phinichka and Kaenthong, 2018).The peaks at 1317 cm^{-1} and 1367 cm^{-1} are caused by the C-H and C-O chemical bonds of the polysaccharides ring in cellulose and hemicellulose (Wrόbel-Kwiatkowska et al. (2007). The strong absorption peak at 1028 cm^{-1} and the other two characteristic peaks of cellulose at 1100 cm^{-1} and 1159 cm^{-1} are all ascribed to the stretching vibration of three C-O bonds in a cellulose glucose ring (Zhang et al. (2015). The intensity of the adsorption band at 3328 cm^{-1} indicates the higher content of cellulose (Sui and Chen, 2016). The FTIR results indicate that all the bamboo fibres obtained in the study were composed of cellulose, hemi-celluloses, lignin, pectin and other substances. Lignin and hemicellulose components in the fibres glued single cellulosic bamboo fibres. Thus, it implied that all the fibres obtained in this study were fibre bundles.

Crystallinity analysis

Fig. 4 shows the results of XRD profiles of the fibre samples. Three crystalline peaks were detected in all fibres at $2\theta = 16.15°$ (broad), 34.6° (broad) and 21.95°(sharp) crystallographic planes which correspond to (101), (040) and (002) crystallographic plane reflections respectively (Oudiani El et al., (2011). The peak which is observed as one broad peak around 16–17° was related to the presence of amorphous compounds such as hemicelluloses and lignin in the fibres while the sharp and intense peak at about 22° was due to the increasing crystallinity with the efficient removal of non-cellulosic polysaccharides and the solvation of amorphous zones and related to cellulose I_β (Reis et al. (2020); Li et al. (2023). The Segal method can be applied to the raw data and the data after subtracting the background. Using the Segal empirical method, the crystallinity indices of *B. emeiensis* (S-1), *P. edulis* (S-2) and P. reticulata (S-3) were 71.4%, 69.1% and 68.4%, respectively. These results are similar to the crystallinity of ramie fibres (*Boehmeria nivea* (L.) Gaudich.) and greater than that of flax and cotton (He et al., 2007).

The crystallinity indices of natural bamboo fibres extracted by combined mechanical and chemical treatments were found to be 69–73%, respectively, (Rocky and Thompson, 2020) which are in good agreement with the current study. The same researchers also studied the crystallinity indices of abundantly available bamboo plant species, recording values of 61–67%. The results indicated the improvement of the crystallinity of the natural bamboo fibres due to the partial removal of the non-crystalline lignin and other components (Chen et al. (2011a); Rocky and Thompson, 2020).

Thermal stability

The thermal properties of fibres are an important characteristic. The TG and DTG curves of the fibres are shown in Fig. 5. The pyrolysis reaction could be divided into four regions including region I: 25–180 °C, region II: 180–340 °C, region III: 340–470 °C and region IV: 470–600 °C. In the first region, a small weight loss in all the samples was observed in the temperature range 25–140 °C, ascribed to a mass loss of absorbed moisture and possibly also the residues from the extraction processes. The decomposition regions for hemicellulose, cellulose and lignin were 200–280 °C, 280–380 °C, and 380–600 °C, respectively (Chen et al. (2013). From the DTG curves, the maximum thermal degradation temperatures of cellulose of *B. emeiensis*, *P. edulis* and *P. reticulata* were observed at 330 °C, 330 °C and 340 °C, respectively. The highest temperature of *P. reticulata* might be due to the presence of a little more hemicellulose which inhibited the depolymerization of cellulose. The increased crystallinity of cellulose of the same fibre sample might improve the thermal stability (Ray and Sarkar, 2001). Peaks in the DTG curves at 430, 420 and 430 °C of *B. emeiensis*, *P. edulis* and *P. reticulata*, respectively, indicated the commencement of decomposition of lignin in the fibre samples. There was no significant difference in thermal stability among the samples. These results indicate that all the fibre samples were sufficiently thermally stable to undergo high temperature textile processes.

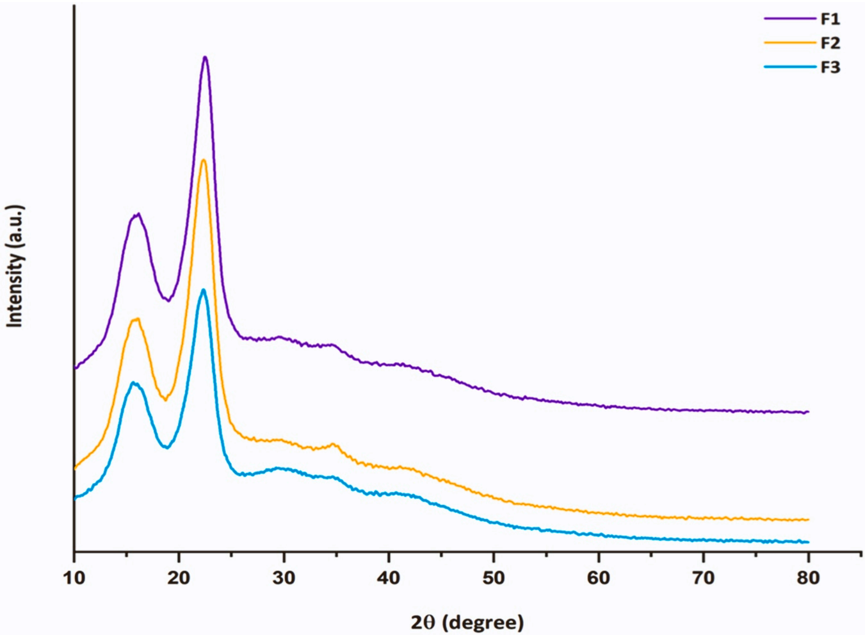
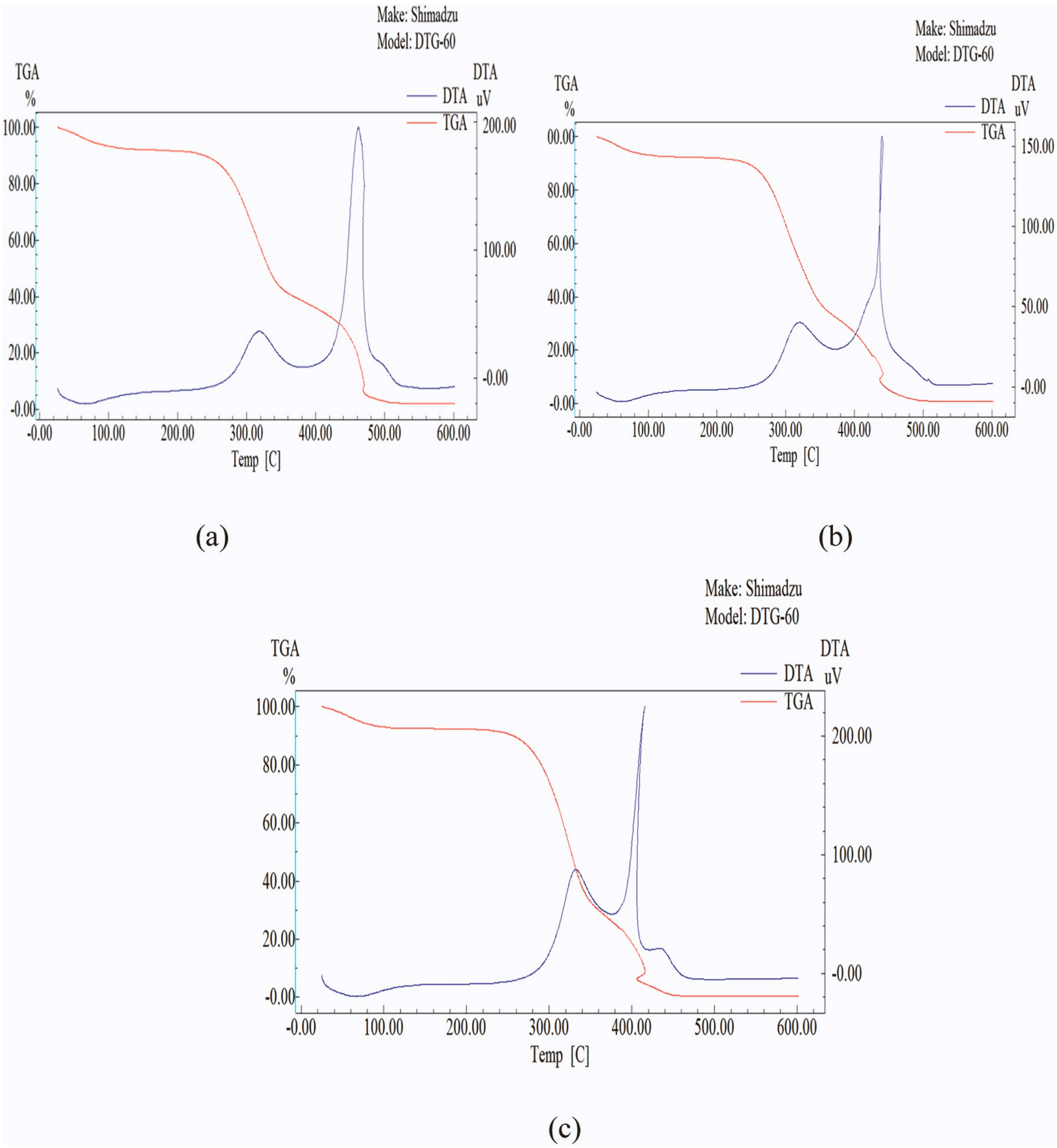


Fig. 4. XRD patterns of bamboo fibre samples.



(a) (b) (c)

Fig. 5. TG/DTG curves of the fibre samples (Bambusa emeiensis (a), Phyllostachys edulis (b) and P. reticulata (c)).

Table 1
Fibre yield (%) and moisture content (%) of culms and fibres.

Samples	Moisture content of culms (%)	Moisture content of fibres (%)	Fibre yield (%)	Weight loss (%)
B. emeiensis	44.52	7.44	54.02	45.98
P. edulis	45.11	7.32	52.66	47.34
P. reticulata	44.75	7.71	55.19	44.81

Moisture content (%) of raw bamboo strips and fibres

Table 1 presents the test results of moisture content (% Mc) of the culms and fibres of the three bamboo species. Strips of *B. emeiensis* (S-1), *P. edulis* (S-2) and *P. reticulata* (S-3) had 44.5%, 45.1% and 44.8% moisture content, respectively, while the moisture content of fibres extracted from the strips were 7.44, 7.32 and 7.71%, respectively. The variations in moisture content amongst the strips as well as the fibres were insignificant. However, greater differences of moisture content were exhibited between the bamboo strips and fibres. Like other lignocellulosic fibres, bamboo is a multicellular composite fibre. It is composed of cellulose microfibrils surrounded and bonded together with lignin and hemicellulose (Ray and Sarkar, 2001). These cells extend longitudinally overlapping each other. Because of this overlapping nature, a mesh-like structure arises. There are many voids (empty spaces) in-between where the fibres are held together. Both the structure (voids) and components (cellulosic & non-cellulosic) are responsible for the considerable amount of moisture retention.

The alkaline and enzymatic treatments reacted with lignin and hemicellulose resulting in the disruption of the cellular structure and removal of these components, As a consequence there was degradation in the hydrophilic nature of the fibre (Cao et al. (2006). As a consequence, the moisture contents of the fibres were much lower than their corresponding untreated bamboo strips. The variation of moisture content between the fibre samples is directly related to the proportions of lignin and hemicellulose present. The higher the amount of these components in the fibres, the higher is the moisture content. *P. edulis*, *B. emeiensis* and *P. reticulata* had progressively increasing moisture contents, respectively. This was also indicated by their weight loss values or fibre yield percentages (Table 1). Another study has found that the moisture content of the bamboo culms has a direct relationship with extraction processes; fresh culms with higher moisture regain were easier to crush and split (Rocky and Thompson, 2020). In this respect, the *P. reticulata* (S-3) was slightly superior among the three species in preprocessing.

Fibre yield (%)

Fibre yield or weight loss can be utilized to assess the efficacy of the extraction methods. Our investigation produced approximately 53–55% usable finer fibres. Fibre outputs of 54.0%, 52.7%, and 55.2% were observed in *B. emeiensis* (S-1), *P. edulis* (S-2), and *P. reticulata* (S-3), respectively, with the proportion of non-cellulosic material eliminated from the samples (% mass loss) varying from 44.8% to 47.3% (Table 1). Treatments involving sodium bicarbonate, sodium hydroxide and enzymes were capable of breaking down the strong bonds between non-cellulosic materials (primarily hemicellulose and lignin) and cellulose fibrils at low temperatures (room temperature to 50 °C) and low concentrations, effectively removing them to yield usable fibres. Lower yield percentages or higher weight loss percentages indicate a greater removal of non-cellulosic components. Weight loss is linked to the strength of the extraction method. The extraction method applied to *P. edulis* was the most powerful of the three methods. The weight loss of the strips exceeded 47%, which is significantly higher than that of other bast fibres such as flax (~20–30%) and hemp (~22–33%) [120], indicating the difficulty of separating bamboo fibres for fibre end-use. Similar findings regarding fibre yield for finer fibres suitable for textiles have been found in other studies. Additionally, weight loss results significantly surpassing these values may suggest cellulose degradation (Liu et al. (2011); (Rocky and Thompson, 2020). The bamboo fibres extracted from different techniques are shown in Fig. 6.

Fibre length

The study extracted bamboo fibres ranging from 2.1–11 cm in length (Table 2). The average length of fibres from *B. emeiensis*, *P. edulis* and *P. reticulata* were 5.76 cm, 6.01 cm, and 5.48 cm, respectively (Table 2 & Fig. 7(a)). Only 6.0–8.8% of the specimens were shorter than 3 cm, and 20.4–38.8% were shorter than 5 cm. More than half of the fibres in each sample were longer than their average length. Approximately 80% of the fibres in *P. edulis* were longer than 5 cm and this species produced longer fibres than the other two species. However, most of the fibres in each sample were close to their average length, as indicated by the low standard deviation values (1.60–1.78) of the samples (Table 2). The data and standard deviation values suggested that the fibres obtained in each sample were uniform.

Table 2
Length of bamboo fibre samples.

Samples		Length (cm)			
	No.of tests	Minimum	Maximum	Average	STD
B.emeiensis	250	2.1	11	5.76	1.78
P. edulis	250	2.5	10	6.01	1.60
P.reticulata	250	2.5	9.1	5.48	1.65

There was variation in the length of fibres within each sample and between samples. It is natural for fibres from plant sources to vary in length. This variation can occur between fibres within the same bamboo internode, between different internodes in the same culm, and between different culms of the same or different species (Liese and Grosser, 1972; Yulong and Liese (1997); Kamthai and Puthson, 2005). Although the length of the fibres in this study was not directly related to the extraction method or strength, stronger treatments could potentially damage the fibres or result in very short and non-uniform fibres. Since different lengths of fibres can be chosen for different purposes based on spinning type, yarn type (coarse or fine), and composite applications, these fibres have great potential for use in textile products based on the measured characteristics (Liu et al., 2011; Morton and Hearle, 2008).

Fibre fineness

A summary of the fibre linear density of the samples is provided in Table 3. Fibres had linear density values ranging from 7.72 to 13.58 tex. The average linear density values for S-1, S-2, and S-3 were 10.14 tex, 9.71 tex, and 11.43 tex, respectively (Table 3 & Fig. 7(b)). Most of the fibres were sufficiently fine for use in textiles. The fibres of *P. edulis* were finer than those of the other two species, with the fibres of *P. reticulata* being the coarsest.

Fibre fineness is directly influenced by the removal of non-cellulosic substances from the bamboo fibres during the treatments. The use of alkalis and enzymes degraded the lignin, hemicellulose and pectin materials in the strips, making it easier to wash these away and resulting in fibres with reduced linear density values or, in other words, finer fibre bundles. These results were supported by the significant weight losses observed (Table 1). The intensity of the treatments applied to the strips played a major role in determining the fineness of the resulting fibres. A more rigorous treatment might produce finer fibres compared to a milder one (Liu et al. (2011). The extraction treatment applied to *P. edulis* was stronger than the others, although there was little difference in fineness between the samples. The preceding caustic treatment softened the non-cellulosic substances, making it easier for the subsequent enzymatic treatments to degrade them, as shown in Fig. 1. These processes resulted in finer and stronger fibres compared to those in the

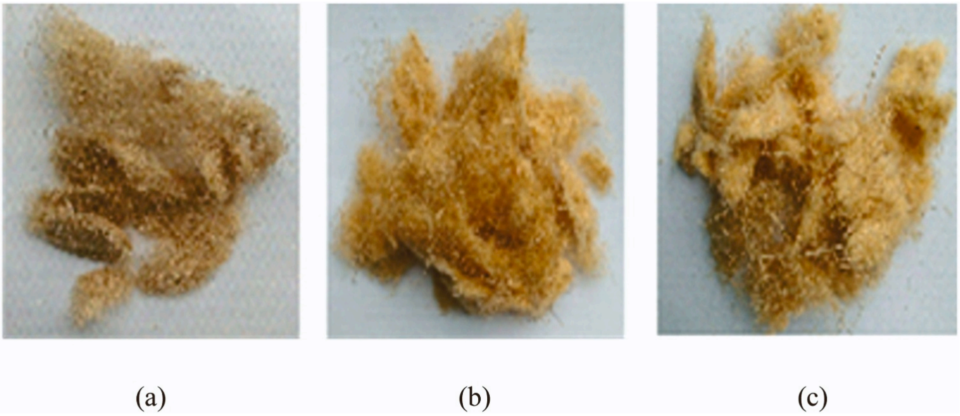
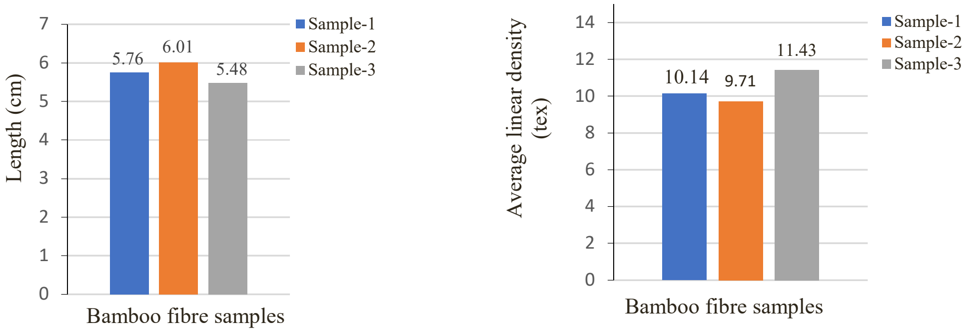


Fig. 6. Bamboo fibres extracted by different techniques, (a) Bambusa emeiensis, Phyllostachys edulis (b) and P.reticulata (c).



(a) (b)

Fig. 7. Physical properties of bamboo fibre samples (a) Average length (b) Average linear density.

Table 3
Fineness of bamboo fibres.

Samples	Fibre fineness (tex)			
	Minimum	Maximum	Average	STD
B.emeiensis	8.11	12.14	10.14	2.02
P. edulis	7.72	11.86	9.71	2.07
P.reticulata	9.03	13.58	11.43	2.29

other two species. Although *P. reticulata* underwent the same concentrations of caustic soda and enzyme as *P. edulis*, the enzymatic treatments applied to *P. edulis* were non-aqua treatments, indicating a higher concentration of enzyme that intensified the degradation of non-cellulosic substances. As the sodium bicarbonate and enzymatic treatments applied to *B. emeiensis* were also non-aqua, and the sodium bicarbonate treatment was carried out at a relatively higher temperature for a longer duration, finer fibres were produced from this species compared to *P. reticulata*. The low standard deviation values (2.02–2.29) of linear density indicated that the fibres obtained in each sample were uniform (Table 3).

As the fibres become finer, the difference between them within a sample declines. That explains why fibres in *P. edulis* showed the least variability and *P. reticulata* the most (Table 3). There is inherent variability within a sample and between samples. Thickness values of fibres in all the samples were within the acceptable range to be used for textile applications (Morton and Hearle, 2008). These values were also consistent with the results of other researchers (Zhang et al. (2014); Rocky and Thompson, 2018, 2020).

Tensile properties of fibres

The tensile tests yielded values ranging from 9.43 to 19.32 cN/tex breaking tenacity and 100.9–187.6 cN breaking load (Table 4). *P. edulis* had the highest average tenacity value (15.21 cN/tex), whereas *P. reticulata* had the lowest (12.16 cN/tex). The average value of *B. emeiensis* (13.88 cN/tex) was intermediate (Fig. 8(b)). The average tenacity values might be related to their average breaking load and fineness values (linear density). *P. edulis*, *B. emeiensis* and *P. reticulata* had decreasing average linear density values, respectively, whereas their average breaking force values occurred in reverse order (Table 4). The average breaking tenacity values were supported by information yielded from the SEM images (Fig. 2), where greater numbers of single fibres were more tightly held together in clusters of fibre bundle in *P. edulis* than in *B. emeiensis*. The greatest number of clusters, each composed of fewest number of single fibres, occurred in *P. reticulata*. The clusters themselves were located separately (Fig. 2(a) – (c)). The level of bonding between single fibres was greatest in *P. edulis*. Greater bonding was observed between single fibres in *B. emeiensis* than in *P. reticulata* (Fig. 2(e)–f)).

Regardless of sample type or age, these characteristics were related to the intensity (strength) of the extraction techniques. An indicator of treatment strength is the concentration of chemicals and enzymes. A stronger treatment could result in finer fibres with reduced strength. However, for limited concentration treatments, the removal of hemicelluloses, lignin and other impurities makes the fibrils in the finer fibres more capable of rearranging themselves along the direction of tensile deformation, resulting in better packing of cellulose chains and improved fibre breaking strength and tenacity (Sinha and Rout, 2009).

The enzymatic treatment of *P. edulis* fibres was preceded by a caustic treatment that weakened the non-cellulosic components of the fibres. The softened materials were further weakened by a higher concentration (20%) enzymatic treatment. They were then destroyed and eliminated in solution by the final stage enzymatic treatment, as shown in Fig. 1. These techniques produced finer and stronger fibres than the techniques used for the other two species. Although *P. reticulata* was treated with the same amounts of caustic soda and enzyme as *P. edulis*, the enzymatic treatments on *P. edulis* were performed by stacking (non-aqua treatment) without the use of water as a solvent. Non-aqua treatment resulted in a greater enzyme concentration, which accelerated the breakdown of non-cellulosic compounds.

All of the treatments used on *B. emeiensis*, including sodium

Table 4
Tensile properties of bamboo fibre samples.

Samples	No. of Samples	Values	Breaking load (cN)	Breaking tenacity (cN/tex)	Breaking elongation (%)
B. emeiensis	250	Range	103.7–185.0	10.23–18.25	1.80 – 3.40
		Mean	140.72	13.88	2.64
		STD	20.11	1.98	0.47
P. edulis	250	Range	100.9–187.6	10.39–19.32	1.80–3.60
		Mean	147.67	15.21	2.60
		STD	24.48	2.52	0.44
P. reticulata	250	Range	107.8–186.0	9.43–16.27	2.00–3.80
		Mean	138.96	12.16	2.75
		STD	22.11	1.93	0.36

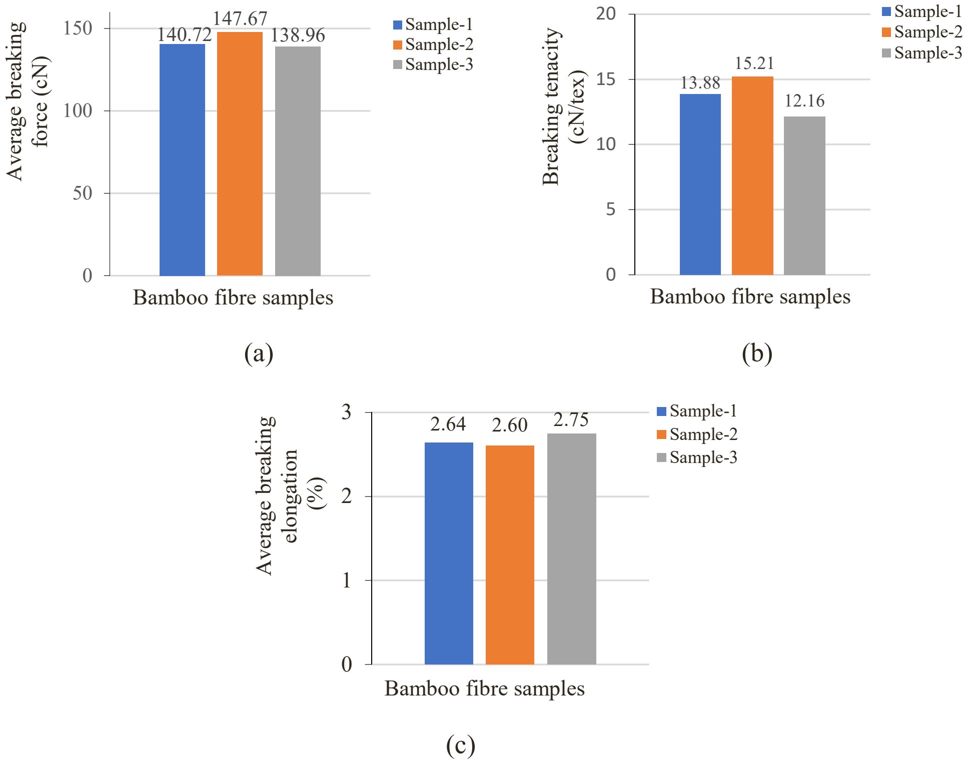


Fig. 8. Tensile properties of bamboo fibre samples (a) Average breaking force (b) Average breaking tenacity (c) Average breaking elongation.

bicarbonate and enzymatic, were carried out without the use of water. In addition, fibres were treated with sodium bicarbonate for an extended period of time at a considerably higher temperature. *B. emeiensis* produced finer and stronger fibres than *P. reticulata*. Cellulosic fibrils can be destroyed, resulting in weaker fibres, unless the quantity of enzyme or chemicals is restricted. Breaking load and tenacity standard deviation values were determined to be around 20–25 and 1.93–2.52, respectively (Table 4). The standard deviation of the tenacity was much reduced because it was determined based on the breaking force of individual fibres and average fineness.

Although the strength of fibres within a sample varies, the standard deviation values in this investigation were not significantly higher, and there was little change in the standard deviation values of the samples. The standard deviation values indicated that the concentration of the majority of fibres in each sample was closer to the average value, implying more consistent fibres in the samples. The variation in fibre strength is mostly due to the position of the fibres in different culms of the same or other species, different internodes of the same culm, and varied locations across the culm's cross section. The fibres obtained in all of the samples met the strength requirements for textile applications (Morton and Hearle, 2008).

Breaking elongation values ranging from 1.8% to 3.8% were obtained. The average values were 2.75%, 2.64% and 2.60% for *B. emeiensis*, *P. edulis* and *P. reticulata*, respectively. The difference between their average elongation values was insignificant (Table 4 and Fig. 4(c)). The breaking elongation values were very close to the average value, as confirmed by the standard deviations (Table 4). The breaking elongation range of the fibres extracted in this study was comparable to those exhibited in other studies (Liu et al. (2011); Prasad and Rao, 2011; Sanjay et al. (2018); Rocky and Thompson, 2020). The values indicate the potential spin ability of the fibres.

Conclusions

This research focused on the development and application of a combination of mechanical, enzymatic and chemical fibre extraction methods. The combined extraction methods, which involved alkali and a newly developed composite enzyme in concentrated and solution states, generated finer bamboo fibres from three different species of bamboo by breaking down and eliminating non-cellulosic components of the bamboo strips. Non-aqueous enzymatic treatments applied to *P. edulis* and *B. emeiensis* resulted in bamboo fibres with improved physical and tensile properties. This can be attributed to the higher concentration of the composite enzyme when applied through stacking, without the use of water as a solvent. The higher the concentration of an enzyme or chemical is, the more effective it is in breaking down the target components.

The bamboo fibres obtained in this study were generally coarser but still within the limit for spinning. They could be used for coarser yarns or further modified for finer counts. Although there were slight differences between the samples, they were not statistically significant. Additionally, the low standard deviation values for the measured properties of the fibres indicate a high level of uniformity within each sample. The physical and mechanical properties of the fibres demonstrated the effectiveness of the extraction techniques used in this research and were within the ranges used for textiles. The fibre extraction techniques developed and applied in this study were performed with reduced concentrations of chemicals, production times, energy and water consumption, environmental impacts and effluent loads. Based on these parameters as well as the quality of fibres, this study has produced results that are comparable to or better than may previous studies. The methods used are appropriate for commercialization, as they involve cheaper and easily available equipment and chemicals, adaptable procedures and the capability for the production of good quality fibres.

The structural analyses, moisture contens, fibre yields, length, fineness, and tensile properties of the natural bamboo fibres examined in this study provide a foundation for future research. Further studies could be conducted on different bamboo species, various age groups of the same or different species, and process optimization to achieve higher quality bamboo fibres. The development of specialized equipment and technologies for bamboo fibre extraction is also crucial for producing large quantities of usable bamboo fibres for various textile applications.

CRediT authorship contribution statement

Dacheng Wu: Supervision. **Ruixia Li:** Resources. **Guanfang Qiao:** Resources. **Xiaodong Liu:** Resources. **Murugesh Babu K.:** Writing – review & editing. **Fisseha Wubneh Asmare:** Writing – original draft, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors have no financial or proprietary interests in any material discussed in this article.

Data availability

No data was used for the research described in the article.

Acknowledgements

This work was supported partly by the Ethiopian Higher Education Project (No. 51235) of the German Development Bank. The support was gratefully acknowledged.

References

Afrin T., Tsuzuki T., Wang X., 2009. “Natural Fibers in Australasia: Proceedings of the Combined (NZ and AUS) Conference of the Textile Institute”. Dunedin, New Zealand, April 15–17, 77–82.

Afrin, T., Tsuzuki, T., Kanwar, R.K., Wang, X., 2012. The origin of the antibacterial property of bamboo. J. Text. Inst. 103 (8), 844–849. https://doi.org/10.1080/00405000.2011.614742.

ASTM D1776/D1776M-20, 2020. Standard practice for conditioning and testing textiles, ASTM International, West Conshohocken, PA.

ASTM D2256/D2256M-10, 2015. Standard test method for tensile properties of yarns by the single-strand method, ASTM International, West Conshohocken, PA.

ASTM D629-15, 2015. Standard test methods for quantitative analysis of textiles, ASTM International, West Conshohocken, PA.

Barella, A., Manich, A.M., 2002. Yarn hairiness: a further update. Text. Prog. 31 (4), 1–44. https://doi.org/10.1080/00405160208688953.

Beltran, R., Hurren, C.J., Kaynak, A., Wang, X., 2002. Correlating the fineness and residual gum content of degummed hemp fibres. Fibre. Polym 3, 129–133. https://doi.org/10.1007/BF02912656.

Bensah, E.C., Moses, Mensah, 2013. Chemical pretreatment methods for the production of cellulosic ethanol: technologies and innovations. Int. J. Chem. Eng. 2013, 1–21. https://doi.org/10.1155/2013/719607.

Cai, Y., Cui, X., Rodgers, J., Thibodeaux, D., Martin, V., Watson, M., Pang Su, S., 2013. A comparative study of the effects of cotton fiber length parameters on modeling yarn properties. Text. Res. J. 83 (9), 961–970. https://doi.org/10.1177/0040517512468821.

Cao, T., Shibata, S., Fukumoto, I., 2006. Mechanical properties of biodegradable composites reinforced with bagasse fibre before and after alkali treatments. Compos. Part A 37 (3), 423–429. https://doi.org/10.1016/j.compositesa.2005.05.045.

Chen, D., Yan, Z., Xifeng, Z., 2013. In-depth investigation on the pyrolysis kinetics of raw biomass. Part I: kinetic analysis for the drying and devolatilization stages. Bioresour. Technol. 131, 40–46.

Chen, H., Yu, Y., Zhong, T., Wu, Y., Li, Y., Wu, Z., Fei, B., 2017. Effect of alkali treatment on microstructure and mechanical properties of individual bamboo fibres. Cellulose 24 (1), 333–347.

Chen, H., Zhang, W., Wang, X., Wang, H., Wu, Y., Zhong, T., Fei, B., 2018. Effect of alkali treatment on wettability and thermal stability of individual bamboo fibers. J. Wood Sci. 64 (4), 398–405. https://doi.org/10.1007/s10086-018-1713-0.

Chen, X., Jie, Y., Zhibin, Z., Canhui, L., 2011. Study on structure and thermal stability properties of cellulose fibers from rice straw. Carbohydr. Polym. 85 (1), 245–250. https://doi.org/10.1016/j.carbpol.2011.02.022.

Chin, S.C., Tee, K.F., Tong, F.S., Ong, H.R., Gimbun, J., 2020. Thermal and mechanical properties of bamboo fiber reinforced composites. Mater. Today Commun. 23, 100876.

Correia, V.D.C., Santos, S.F., Mármol, G., Curvelo, A.A.D.S., Savastano, H., 2014. Potential of bamboo organosolv pulp as a reinforcing element in fibre–cement materials. Constr. Build. Mater. 72, 65–71.

Das, M., Chakraborty, D., 2006. Influence of alkali treatment on the fine structure and morphology of bamboo fibres. J. Appl. Polym. Sci. 102, 5050–5056.

Deshpande, A.P., Bhaskar Rao, M., Rao, C.L., 2000. Extraction of bamboo fibers and their use as reinforcement in polymeric composites. J. Appl. Poly. Sci. 76, 83–92.

Dessalegn, Y., Balkeshwar, S., Aart, W.V., Vuure, Irfan, A.B., Habtamu, B., Mohamed, H., Ahmed, Gulam M.S., Nazia, H., 2022. Investigation of bamboo fibrous tensile strength using modified Weibull distribution. Mater 15 (14), 5016. https://doi.org/10.3390/ma15145016.

Erdumlu, N., Ozipek, B., 2008. Investigation of regenerated bamboo fibre and yarn characteristics. Fibers Text. East Eur. 16, 43–47.

Ermias Girma, A., 2020. Optimization and modeling of ethanol–alkali pulping process of bamboo (Yushania alpina) by response surface methodology. Wood Sci. Technol. 54, 1319–1347. https://doi.org/10.1007/s00226-020-01188-z.

Jiajia Fu, Xiaoqiang Li, Weidong Gao, Hongbo Wang, Artur Cavaco-Paulo, Carla Silva,2012. A review, ‘Bio-processing of bamboo fibers for textile applications’. 30 (1), 141.

Gupta, A., Ajit, K., Amar, P., Sandhyarani, B., 2011. Effect of different parameters on mechanical and erosion wear behavior of bamboo fiber reinforced epoxy composites. Int. J. Polym. Sci., 592906 https://doi.org/10.1155/2011/592906.

Han, G., Lei, Y., Wu, Q., Kojima, Y., Suzuki, S., 2008. Bamboo–fibre filled high density polyethylene composites: effect of coupling treatment and nanoclay. J. Polym. Environ. 16, 123–130.

Hanana, S., Ahmed, E., Vincent, P., Hajer, T., Hafedh, B., Belghith, H., Chedly, B., 2015. An efficient enzymatic-based process for the extraction of high-mechanical properties alfa fibres. Ind. Crop. Prod. 70, 190–200.

He, J., Tang, Y., Wang, S.Y., 2007. Differences in morphological characteristics of bamboo fibres and other natural cellulose fibres: studies on X-ray diffraction, solid state 13C-CP/MAS NMR, and second derivative FTIR spectroscopy data. Iranian. Polym. J. 16 (12), 807–818.

Hebel, Dirk E., Alireza, J., Felix, H., Karsten, S., Dragan, G., Mateusz, W., 2014. Process-controlled optimization of the tensile strength of bamboo fiber composites for structural applications. Compos.: Part B 67, 125–131.

Hyojin, Kim, Okubo, K., Fujii, T., Takemura, K., 2013. Influence of fiber extraction and surface modification on mechanical properties of green composites with bamboo fibre. J. Adhes. Sci. Technol. 27 (12), 1–12. https://doi.org/10.1080/01694243.2012.697363.

Ibrahim, I.A.E., 2018. Effect of fibre length and short fibre percent in cotton on fibre and yarn quality. Alex. Sci. Exch. J. 39 (4), 663–668. https://doi.org/10.21608/asejaiqjsae.2018.20692.

Jin Q., Zhang W., Yao W., 2018. “Bamboo Conditions for Processing Bamboo Fiber with Combing Method. IOP Conf. Series”. Mater. Sci. Eng. 381.

Jing-Huan, C., Ji-Kun, X., Pan-Li, H., Run-Cang, S., 2016. Effect of alkaline pretreatment on the preparation of regenerated lignocellulose fibers from bamboo stem. Cellulose 23, 2727–2739. https://doi.org/10.1007/s10570-016-0983-1.

Ju, Xiaohui, Mark, B., Elvie, B., Xiao, Z., 2015. An improved X-ray diffraction method for cellulose crystallinity measurement, 476–48 Carbohydr. Polym. 123 (2). https://doi.org/10.1016/j.carbpol.2014.12.071.

Junior, M.G., Teixeira, F.G., Tonoli, G.H.D., 2018. Effect of the nano-fibrillation of bamboo pulp on the thermal, structural, mechanical and physical properties of nanocomposites based on starch/poly (vinyl alcohol) blend. Cellulose 25, 1823–1849. https://doi.org/10.1007/s10570-018-1691-9.

Kamthai, Suphat, Puthson, Pratuang, 2005. The physical properties, fiber morphology and chemical compositions of sweet bamboo (Dendrocalamus asper Backer). Kasetsart J. (Nat. Sci.) 39, 581–587.

Kazuya, Okubo, Fujii, T., Yamamoto, Yuzo, 2004. Development of bamboo-based polymer composites and their mechanical properties. Compos.: Part A. Appl. Sci. Manuf. 35, 377–383.

Kelchner, Scot A., 2013. Higher level phylogenetic relationships within the bamboos (Poaceae: Bambusoideae) based on five plastid markers. Mol. Phylogenet Evol. 67 (2), 404–413. https://doi.org/10.1016/j.ympev.2013.02.005.

Khalil, Abdul, Bhat, H., Jawaid, M., Zaidon, A., Hermawan, D., Hadi, S., 2012. Bamboo fibre reinforced bio composites: a review. Mater. Des. 42, 353–368. https://doi.org/10.1016/j.matdes.2012.06.015.

Khan, R., Rashid, M., Ahmed, Sh, Rashid, E., U. Haque, R., 2021. Investigation of fibre length change in different stages of ring spinning process. Eur. Sci. J. 17 (25), 66.

Khawas, P., Deka, S.C., 2016. Isolation and characterization of cellulose nanofibres from culinary banana peel using high-intensity ultrasonication combined with chemical treatment. Carbohydr. Polym. 137, 608–616.

Kostic, Mirjana M., Biljana, P., Petar, S., 2008. Quality of chemically modified hemp fibres. Bio Resour. Technol. 99 (1), 94–99. https://doi.org/10.1016/j.biortech.2006.11.050.

Kuang, X., Yu, C., 2015. Generating cotton fibre length probability density function from fiber length parameters by finite mixture model. J. Text. Inst. 106 (6), 655–662.

Kumar, S., Choudhary, V., Kumar, R., 2010. Study on the compatibility of unbleached and bleached bamboo-fiber with LLDPE matrix. J. Therm. Anal. Calor. 102, 751–761.

Latif, M.A., Ashaari, A., Jamaludin, K., Zin, J.M., 1993. Effects of age and height on physical and mechanical properties of bamboo. J. Trop. For. Sci. 6, 159–170.

Li, Nie, Jianhong, Zhou, Shaoxiong, Gan, 2013. Preliminary study on the Formula Experiment of "Zhuzhu" "3414". J. Mod. Agr. Sci. Technol. 1, 148–149.

Li, Y., Dai, X.Q., 2006. Biomechanical engineering of textiles and clothing, First ed. Wood head Publishing Limited and CRC Press LLC, New York.

Liese, W., Grosser, D., 1972. Variability of fibre length in bamboo. Holzforschung 26 (6), 202–211.

Lin, Q., Xing, M., Oxenham, W., Yu, C., 2012. Generation of cotton fibre length probability density function with length measures. J. Text. Inst. 103 (2), 225–230.

Lipp-Symonowicz, B., Sztajnowski, S., Wojciechowska, D., 2011. New commercial fibers called ‘Bamboo Fibers`- their structure and properties. Fibres Text. East. Eur. 19 (1), 18–23.

Liu, Lifang, Qianli, W., Longdi, C., Jingfang, Q., Jianyong, Y., 2011. Modification of natural bamboo fibers for textile applications. Fibre. Polym. 12 (1), 95–103.

Liu, Lifang, Longdi, C., Liqian, H., Jianyong, Y., 2012. Enzymatic treatment of mechano-chemical modified natural bamboo fibres. Fibre Polym. 13 (5), 600–605.

Majumdar, A., Makhopadhyay, S., Yadav, R., Mondal, A.K., 2011. Properties of ring-spun yarns made from cotton and regenerated bamboo fibres. Ind. J. Fib. Text. Res. 36, 18–23.

Matsuo T., (2019). Textile Progress. Textile Progress, May 2013, 37–41. https://doi.org/10.1201/9780429187766.

May-Pat, Alejandro, Valadez-Gonźalez, A., Herrera-Franco, P.J., 2013. Effect of fiber surface treatments on the essential work of fracture of HDPE-continuous henequen fiber-reinforced composites. Polym. Test. 32 (6), 114–1122.

Mishra, R., Behera, B.K., Pal, B.P., 2012. Novelty of bamboo fabric. J. Text. Inst. 103 (3), 320–329. https://doi.org/10.1080/00405000.2011.576467.

Mortazavi, S., Moghaddam, M.K., 2010. An analysis of structure and properties of a natural cellulosic fiber (leafiran). Fibre Polym. 11, 877–882.

Morton, W.E., Hearle, J.W.S., 2008. Physical properties of textile fibres fourth ed. Woodhead Publishing Limited, Cambridge, England.

Munja, Kalpana, Kashyap, Radha, 2015. Bamboo fiber: an approach toward sustainable development. Int. J. Sci. Res. 4, 4.

Nayak, L., Mishra, S.P., 2016. Prospect of bamboo as a renewable textile fiber, historical overview, labeling, controversies and regulation. Fash. Text. 3, 2. https://doi.org/10.1186/s40691-015-0054-5.

Nguyen, Phong, Fujii, T., Chuong, B., Okubo, K., 2012. Study on how to effectively extract bamboo fibers from raw bamboo and wastewater treatment. J. Mater. Sci. Res. 1, 144–155.

Ohrnberger, D., 1999. The Bamboos of the World: Annotated Nomenclature and Literature of the Species and the Higher and Lower Taxa. Elsevier, Amsterdam, p. 596.

Oudiani El, A., Chaabouni, Y., Msahli, S., Sakli, F., 2011. Crystal transition from cellulose I to cellulose II in NaOH treated Agave americana L. fibre. Carbohydr. Polym. 86 (3), 1221–1229.

Parisi, M.L., Fatarella, E., Spinelli, D., Pogni, R., Basosi, R., 2015. Environmental impact assessment of an eco-efficient production for colored textiles. J. Clean. Prod., Part (A) 108, 514–524.

Parsi, Rajendra D., Madhuri, V.K., Kuldip, P., Police, P., 2016. Influence of fibre length on ring spun yarn quality. Int. J. Res. Sci. Innov. 3 (8), 2321–2705.

Phinichka, N., Kaenthong, S., 2018. Regenerated cellulose from high alpha cellulose pulp of steam-exploded sugarcane bagasse. J. Mater. Res. Technol. 7, 55–65. https://doi.org/10.1016/j.jmrt.2017.04.003.

Prasad, A.V.R., Rao, K.M., 2011. Mechanical properties of natural fibre reinforced polyester. Composites: Jowar, sisal and bamboo. Mater. Des. 32, 4658–4663.

Qingchun, Li, 2003. The properties of bamboo fiber and key technology in development. sichuan text. Sci. Technol. 5, 56–58.

Rai, V., Ghosh, J.S., Pal, A., Dey, N., 2011. Identification of genes involved in bamboo fibre development. Gene 478, 19–27. https://doi.org/10.1016/j.gene.2011.01.004.

Rao, Murali Mohan, Mohana Rao, K., 2007. Extraction and tensile properties of natural fibers: Vakka, date and bamboo. Compos. Struct. 77, 288–295. https://doi.org/10.1016/j.compstruct.2005.07.023.

Ray, Dipa, Sarkar, B.K., 2001. Characterization of alkali-treated jute fibers for physical and mechanical properties J. Appl. Polym. Sci. 80, 1013–1020. https://doi.org/10.1002/app.1184.

Reis, R.S., Tienne, L.G.P., Souza, D.H.S., Marques, M.F.V., Monteiro, S.N., 2020. Characterization of coffee parchment and innovative steam explosion treatment to obtain micro fibrillated cellulose as potential composite reinforcement. J. Mater. Res. Technol. 9 (4), 9412–9421.

Rocky, Bahrum P., Thompson, Amanda J., 2020. Production and modification of natural bamboo fibers from four bamboo species, and their prospects in textile manufacturing, Fibre. Polym, 21, pp. 2740–2752.

Rocky, Bahrum Prang, Thompson, Amanda J., 2018. Production of natural bamboo fibers-1: experimental approaches to different processes and analyses. J. Text. Inst. 109, 1381–1391. https://doi.org/10.1080/00405000.2018.1482639.

Sanjay, M.R., Madhu, P., Jawaid, M., Senthamaraikannan, P., Senthil, S., Pradeep, S., 2018. Characterization and properties of natural fibre polymer composites: a comprehensive review. J. Clean. Prod. 172, 566–58.

Segal, L., Creely, J.J., Martin, J., A.E, Conrad, C.M., 1959. An empirical method for estimating the degree of crystallinity of native cellulose using the X-ray diffractometer. Text. Res. J. 29, 786–794. https://doi.org/10.1177/004051755902901003.

Sinha, E., Rout, S.K., 2009. Influence of fibre-surface treatment on structural, thermal and mechanical properties of jute fibre and its composite. Bull. Mat. Sci. 32 (1), 65–76.

Steffen D., Marin A.W., Müggler I.R., 2013. “10th European Academy of Design Conference. Crafting the Future”. The University of Gothenburg., April 17-19, 1–14.

Sugesty, S., Kardiansyah, T., Hardiani, H., 2015. Bamboo as raw materials for dissolving pulp with environmentally friendly technology for rayon fiber. Procedia Chem. 17, 194–199. https://doi.org/10.1016/j.proche.2015.12.122.

Sui, W., Chen, H., 2016. Effects of water states on steam explosion of lignocellulosic biomass. Bioresour. Technol. 199, 155–163. https://doi.org/10.1016/j.biortech.2015.09.001.

Sulaiman, O., Murphy, R.J., Hashim, R., Gritsch, C.S., 2005. The inhibition of microbial growth by bamboo vinegar. J. Bamboo Ratt. 4 (1), 71–80.

Sun, B.L., Chai, Y.B., Huang, A.M., Liu, J.L., 2011. Application of NIR spectroscopy to estimate of MFA and fiber length of Neosinocalamus affinis. Spectrosc. Spect. Anal. 31 (12), 3251–3255.

Tahri, Ichrak, Isabelle, Z.D., Julien, R., Cesar, S., Nicolas, B., 2016. Extraction and characterization of fibers from palm tree. Bio Resour. 11 (3), 7016–7025.

Tan, Mingquan, Xuepeng, J., Huali, K., Wenwang, W., Re, X., 2020. Experimental investigations on the mechanical properties of bamboo fiber and fibril. J. Fibre Polym. 21 (6), 1382–1386. https://doi.org/10.1007/s12221-020-9554-z.

Tanaka, A., Zhu, Q., Tan, H., Horiba, H., Ohnuki, K., Mori, Y., Shimizu, K., 2014. Biological activities and phytochemical profiles of extracts from different parts of bamboo. (Phyllostachys Pubescens). Molecules 19, 8238–8260. https://doi.org/10.3390/molecules19068238.

Tang, Y., Wang, S., Jianxin, H., 2007. Differences in Morphological Characteristics of Bamboo Fibers and other Natural Cellulose Fibers: studies on X-ray Diffraction, Solid State 13C-CP/MAS NMR, and Second Derivative FTIR Spectroscopy Data. Iranian. Polym. J. 16, 807–818.

Tanpichai, Supachok, Anyaporn, B., Suteera, W., 2019. Use of steam explosion as a green alternative method to prepare pulp from pineapple leaves. J. Met. Mater. Miner. 29 (2), 110–114.

Thakur, Ashish, Telang, Amit, Purohit, Rajesh, 2016. Synthesis, testing & characterization of Epoxy-CNT-Bamboo polymer matrix hybrid composite. Int. Res. J. Eng. Tech. 3 (8).

Ticoalu A., Aravinthan T., Cardona F., 2010. “A review of current development in natural fiber composites for structural and infrastructure applications,” in Proceedings of the Southern Region Engineering Conference (SREC ’10). Toowoomba, Australia.113–117.

Waite, Marilyn, 2010. Sustainable textiles: the role of bamboo and a comparison of bamboo textile properties (Part II). J. Text. Appar. Technol. Manag. 6 (3).

Weyenberg, Van de, Truong, T.C., Vangrimde, B., Verpoest, I., 2006. Improving the properties of UD flax fibre reinforced composites by applying an alkaline fibre treatment. Compos. Part A. Appl. Sci. Manuf. 37 (9), 1368–1376.

Wróbel-Kwiatkowska, M., Starzycki, M., Zebrowski, J., Oszmiański, J., Szopa, J., 2007. Lignin deficiency in transgenic flax resulted in plants with improved mechanical properties. J. Biotech. 919–934.

Xie, Jiulong, Qi, J., Hu, T., Cornelis, F.D.H., Hse, C.Y., Shupe, T.F., 2016. Effect of fabricated density and bamboo species on physical–mechanical properties of bamboo fiber bundle reinforced composites. J. Mater. Sci. 51 (16), 7480–7490.

Xie, X., Zhou, Z., Jiang, M., Xu, X., Wang, Z., Hui, D., 2015. Cellulosic fibers from rice straw and bamboo used as reinforcement of cement-based composites for remarkably improving mechanical properties. Compos. Part B 78, 153–161. https://doi.org/10.1016/j.compositesb.2015.03.086.

Xu, Xiangyu, Yueping, W., Xiaodan, Z., Guangyin, J., Dapeng, Yu, Shouguo, W., 2006. Effects on surface properties of natural bamboo fibres treated with atmospheric pressure argon plasma. Surf. Interface Anal. 38, 1211–1217.

Xu, Y., Lu, Z., Tang, R., 2007. Structure and thermal properties of bamboo viscose, tencel and conventional viscose fibre. J. Therm. Anal. Calor. 89 (1), 197–201.

Yang, Xi, Lili, S., Xing’e, L., Shumin, Y., Genlin, T., 2017. Changes in bamboo fibre subjected to different chemical treatments and freeze-drying as measured by nano indentation. J. Wood Sci. 63, 24–30. https://doi.org/10.1007/s10086-016-1590-3.

Yang, Yinzhi, Fan, F., Xie, J., Fang, K., Zhang, Q., Chen, Y., Cao, X., Deng, Z., 2023. Isolation and characterization of cellulosic fibers from bamboo shoot shell. Polym. Bull. 80, 1817–1829. https://doi.org/10.1007/s00289-022-04158-6.

Yu, Y.L., Huang, X.A., Yu, W.J., 2014. High performance of bamboo-based fiber composites from long bamboo fiber bundles and phenolic resins. J. Appl. Polym. Sci. 131 (12), 1–8.

Yueping, Wang, Wang, G., Cheng, H., Tian, G., Liu, Z., Xiao, Q.F., Zhou, X., Han, X., Gao, X., 2010. Structures of bamboo fibre for textiles. Text. Res. J. 80, 334–343.

Zhang, T., Guo, M., Cheng, L., Li, X., 2015. Investigations on the structure and properties of palm leaf sheath fibre. Cellulose 22 (2), 1039–1051.

Zhang, Y., Wang, C.H., Peng, J.X., 2014. Preparation and technology of bamboo fiber and its products. China Text. Pub. House, Beijing.

Zhang, Y.M., Yu, Y.L., Yu, W.J., 2013. Effect of thermal treatment on the physical and mechanical properties of Phyllostachys pubescens bamboo. Eur. J. Wood Prod. 71, 61–67.

Li Zhiyong, Wang Dengju, Fan Baomin, 2005. J. Beijing Forestry University: Soc.Sci. Edit. 4 (4), 50–54.

Zhuo, G., Xiaolin, Z., Xiao, J., Mei, W., Xiongnan, Y., Shaoge, L., 2020. Effect of different enzymatic treatment on mechanical, water absorption and thermal properties of bamboo fibers reinforced poly (Hydroxybutyrate-co-Valerate) bio composites. J. Polym. Env 28, 2377–2385. https://doi.org/10.1007/s10924-020-01781-0.

Zupin, Z., Dimitrovski, K., 2010. Mechanical properties of fabrics made from cotton and biodegradable yarns bamboo. SPF PLA weft. Woven Fabr. Eng. 25–46. https://doi.org/10.5772/10479.