

Construction of high-strength paper based on multi-scale bamboo fiber network and its application in replacing plastic packaging boxes

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Construction of high-strength paper based on multi-scale bamboo fiber network and its application in replacing plastic packaging boxes

Abstract

The non-degradability of petroleum-derived materials presents potential hazards to both natural ecosystems and human health, thereby necessitating the development of sustainable, biodegradable, lightweight, and high-strength structural materials as a green strategy for packaging applications. In this study, a multi-scale engineering design was adopted, utilizing untreated bamboo fibers as the matrix and microfibrillated cellulose (MFC) as the reinforcing phase, to fabricate a high-strength, all-bamboo-based paper featuring a multi-scale fiber network structure via a wet-forming process. The MFC, prepared through purely mechanical methods, exhibited a high specific surface area of 135.1 m²/g and a high surface charge of −32.6 mV. Following gradient sieving, the MFC with a diameter of 300 nm formed a dense three-dimensional network with the host fibers through multi-scale interlocking, thereby enhancing intermolecular hydrogen bonding. This resulted in a bamboo paper with a strength of 58.6 MPa and a Young's modulus as high as 4.5 GPa. Furthermore, leveraging the multi-scale interactions and the processability of the fibers, molded pulp packaging boxes derived from this paper achieved a strength of 42.2 MPa and an elastic modulus of 1.25 GPa, withstanding impact forces from a three-meter drop, a performance comparable to that of petroleum-based plastic packaging. The integration of green, biodegradable bamboo fiber raw materials with multi-scale engineering strategies provides novel perspectives and theoretical guidance for the development of degradable, lightweight, and high-performance paper-based packaging materials.

Keywords: bamboo fiber; microfibrillated cellulose (MFC); multi-scale engineering; mechanical properties; degradable packaging materials.

Natural bamboo

Bamboo fiber (BF)

Micro-fibrillated bamboo fiber (MFC)

Morphological characterization of paper

Morphological characterization of bamboo fiber and MFC

Application of Paper-based Packaging Boxes

Mechanical strength of Paper-based Packaging Boxes

enhancement mechanisms

Mechanical strength

XRD, BET, Zeta potential Analysis of BF and MFC

Surface areas (m^2/g)

Sample	Surface areas (m^2/g)
BF@R100	46.0
BF@P100-R200	60.3
BF@P200-R300	88.8
BF@P300-R400	99.0
BF@P400-R500	112.3
BF@P500-R1000	145.9

Zeta potential (mV)

Sample	Zeta potential (mV)
BF@R100	21.6
BF@P100-R200	22.7
BF@P200-R300	23.3
BF@P300-R400	24.3
BF@P400-R500	25.9
BF@P500-R1000	36.3

Crystallinity (%)

Sample	Crystallinity (%)
BF@R100	77.3
BF@P100-R200	77.1
BF@P200-R300	76.1
BF@P300-R400	75.8
BF@P400-R500	75.1
BF@P500	74.3

Density (g/cm^3)

Sample	Density (g/cm^3)
BF@P-R100	0.64
BF@P100-R200	0.64
BF@P200-R300	0.64
BF@P300-R400	0.67
BF@P400-R500	0.69
BF@P500	0.77

Porosity (%)

Sample	Porosity (%)
BF@P-R100	55.5
BF@P100-R200	55.5
BF@P200-R300	55.5
BF@P300-R400	55.5
BF@P400-R500	55.5
BF@P500	55.5

Tensile stress (MPa)

Strain (%)

Young's modulus (GPa)

Transmittance (%)

Wavelength (nm)

Tensile strength (MPa)

Young's modulus (GPa)

Introduction

Currently, plastic pollution represents one of the most pressing interdisciplinary challenges in global environmental governance (Houssini et al., 2025, Zhang et al., 2026). Its ecological toxicity has infiltrated all levels of the biosphere and presents a potential risk of exposure to human health (Li et al., 2024, Ran et al., 2024). The Global Plastic Pollution Convention, adopted during the fifth session of the United Nations Environment Assembly in 2022, represents a significant milestone in international environmental law (Ralston et al., 2023). By the end of 2023, 148 sovereign states globally have enacted plastic restriction measures or economic regulatory instruments through legislative processes, thereby establishing a comprehensive control system that spans the entire life cycle from production to consumption (Tumu et al., 2023).

Among various alternative materials, plant fiber-based materials have distinguished themselves in the sustainable materials arena due to their biological safety, natural degradability, and cost-effectiveness (Samir et al., 2022, Rajak et al., 2019). The development of the plant fiber-based alternatives industry can facilitate the effective substitution of plastic products, mitigate environmental pollution, and contribute positively to global climate governance through carbon sequestration and the carbon sink mechanism (Alamerew et al., 2026, Peter, 2018).

The primary raw materials for paper-based alternatives to plastics include softwood, hardwood, bagasse, straw, and bamboo pulps (Ogunwusi, Ibrahim, 2022, Chaudhary et al., 2024). However, their selection is constrained by resource availability and growth cycles (El-Sayed et al., 2020). Softwood pulp faces shortages due to resource constraints, while hardwood fibers are relatively short and have extended growth cycles (Pennells et al., 2020). In contrast, bamboo, a perennial herbaceous plant, exhibits rapid growth and a high fiber length-to-width ratio, enabling the formation of a denser and stronger fiber

network in paper. Additionally, bamboo provides multiple co-benefits in ecological carbon sequestration, economic substitution, and strategic resource management, thereby positioning it as a critical biomass resource for the circular bioeconomy and sustainable development (Zheng, Pacala, 2024, Tripathi et al., 2024, Kotangale et al., 2025).

However, the development of bamboo-based plastic substitutes faces substantial limitations, primarily due to issues associated with the direct use of bamboo fibers (BF), including their strong hydrophilicity, weak interfacial adhesion, and low reactivity resulting from the thick cell walls and the parallel arrangement of multilayered microfibrils (Jakes et al., 2025, Wang et al., 2024, Prasetya et al., 2026). These drawbacks ultimately compromise material performance. The underlying cause lies in the complex and stable multi-component structure of bamboo fibers: cellulose, hemicellulose, and lignin are tightly interlinked through strong hydrogen and covalent bonds, forming a dense cross-linked network. Consequently, bamboo fiber-based materials are difficult to achieve both satisfactory mechanical properties and favorable processability (Dong et al., 2023, Banerjee et al., 2025).

In this study, through multi-scale engineering design, a high-strength all-bamboo-based paper with a multi-scale fiber network structure was constructed, and the mechanism by which bamboo fibers of different scales enhance its mechanical strength was revealed. The results show that bamboo fibers within a specific size range can promote the reconstruction of the hydrogen bond network and optimize the interfacial stress transmission, thereby significantly improving the mechanical properties of the paper. By further applying pulp molding technology, the multi-scale bamboo fiber system is formed into paper-based packaging boxes, whose performance can be comparable to that of petroleum-based plastic packaging boxes. This study clarified the reinforcing mechanism of bamboo fiber from the perspective of fiber scale effect and successfully prepared paper-based packaging boxes that can replace plastic

packaging boxes, providing a theoretical basis and practical path for the development of high-performance green packaging materials.

Experimental Section

Materials

The bamboo fiber (BF) was supplied by the National Engineering Research Center of Papermaking and Pollution Control of South China University of Technology. The MFC are produced in the laboratory.

Preparation of MFC

Fig 1 illustrates the bamboo fiber microfibrillation process. The MFC was produced by a multifunctional refining device (S210000001, FRANK-PTI, Germany). Bamboo fibers were first pre-treated for 24-hour at 0°C. Mechanical refining was then carried out at a pulp concentration of 5 wt%, using a refiner equipped with 20 grinding teeth, a tooth width of 3 mm, a cutting angle of 60°, and an edge load ratio of 1 J/m, corresponding to a specific energy input of 700 kW·h.

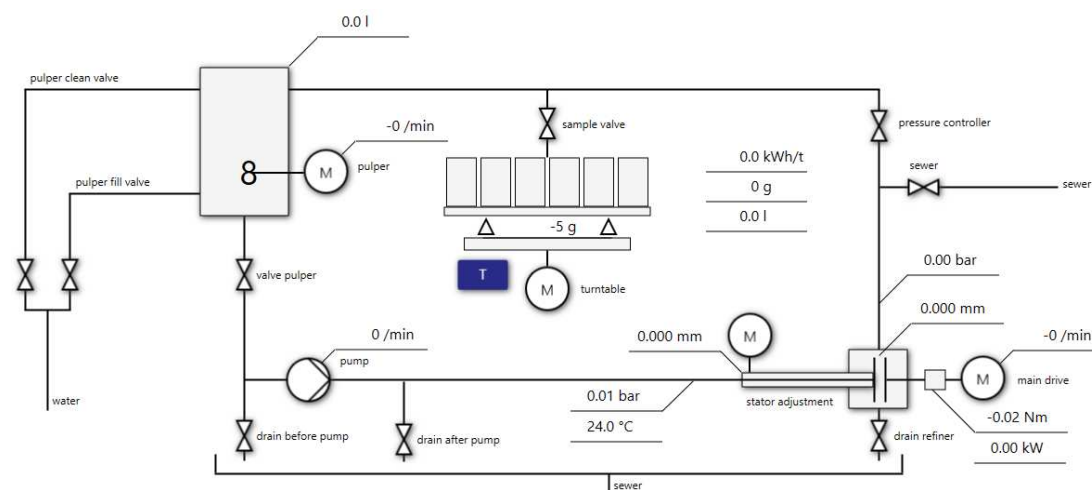


Figure1 Schematic of preparation of microfibrillated bamboo fiber

Preparation of bamboo fiber with different sizes

MFC was sieved using a Bauer McNett Fibre Classifier (S401800005, FRANK-PTI, Germany).

Specifically, the standard sieve was configured with 100, 200, 300, 400, and 500 mesh sieves. A 10 g

sample of bamboo MFC was dispersed in water and sieving at 580 rpm for 20 minutes. Six bamboo fibers samples were obtained, corresponding to the sieve intervals of <100, 100-200, 200-300, 300-400, 400-500, and >500 mesh. These samples were labeled as BF@R100, BF@P100-R200, BF@P200-R300, BF@P300-R400, BF@P400-R500, and BF@P500, respectively.

Preparation of handsheets with different MFC contents and bamboo fibers sizes

20% of different-sized MFC (0.2 weight%) was added to the BF and thoroughly mixed. Subsequently, use the rapid Köthen sheet forming machine (S958540016, FRANK-PTI, Germany) to form a handsheets with a weight of 120 g/m².

Microscopic characterization of bamboo fibers and handsheets

The bamboo fibers morphology was observed using an optical microscope (Olympus BX51, Japan). To achieve high-resolution imaging of surface morphology, samples were treated by supercritical CO₂ drying, followed by observation and fiber diameter measurement using a scanning electron microscope (SEM, HitachiSU5000, Japan). Fiber length distribution was determined using a fiber analyzer (ValmetFS5, Finland). SEM was employed to investigate the effect of composition on microstructure of handsheets.

Surface properties analysis

The surface charges of bamboo fibers were evaluated using a Zeta potential analyzer (SZP-10, BTG, Switzerland). Following supercritical CO₂ drying of bamboo fibers and handsheets, the specific surface areas were determined using a surface area and porosity analyzer (ASAP2460, Micromeritics, America). The bonding area of the handsheets was subsequently calculated according to Equation (1) (Wiggins et al., 1939).

$$\text{Relative bonded area (\%)} = \frac{\text{Fiber surface area} - \text{Paper surface area}}{\text{Fiber surface area}} \times 100\% \quad (1)$$

FT-IR analysis and calculation of hydrogen bonds

The chemical structure of handsheets were analyzed using a Fourier transform infrared spectrometer (FT-IR, TENSOR37, Bruker, Germany) in attenuated total reflectance (ATR) mode. The O-H stretching vibrations (3000-3700 cm⁻¹) was subsequently examined by fitting with PeakFit software (Huang et al., 2020). The relative proportions of intramolecular and intermolecular hydrogen bonds were calculated based on differences in sub-peak positions (Oh et al., 2005).

X-ray diffraction analysis

The sample was characterized by the X-ray diffraction (XRD) using a Xpert-Pro diffractometer (X'Pert-Pro, Homelab, Rigaku, Japan) equipped with Cu K α radiation ($\lambda=1.5418$ Å). The generator was operated at 40 kV and 40 mA. The diffractogram was recorded in reflection mode over 5° and 60° (2 θ) at a scan speed of 12°/min with a step of 0.013°. The crystallinity index of samples was estimated by the Segal empirical formula (Segal' et al., 1959):

$$CrI = \frac{I_{200} - I_{am}}{I_{200}} \times 100\% \quad (2)$$

Where I_{200} is the maximum peak intensity at $2\theta=22.4^\circ$, I_{am} is the diffraction intensity of amorphous region, at the minimum intensity between the 1-10/110 peak and 200 peak (about $2\theta = 18.4^\circ$).

Testing of the physical properties of handsheets

All samples were conditioned at 50% RH and 23°C for at least 48 hours before testing. Paper density was calculated by the ratio of its mass to volume. Tensile strength, tear strength and burst strength was determined in accordance with ISO 12625-4 guidelines, SNI ISO 1974:2016 standards, and SNI ISO 2758:2014, respectively. The folding endurance test was evaluated by clamping one end of a paper strip and applying a constant load of 9.81 N to the other end, the number of double folds until failure was recorded. For the tensile test, strips (100 mm $\times$ 15 mm) were cut from the dry paper and tested at a

stretching speed of 20 mm/min. Toughness, defined as the energy required to induce fracture, was calculated as the area under the stress-strain curve.

Calculation of Paper Porosity

The porosity of handsheets was measured using the density method. The calculation is based on equation (3):

$$\text{Porosity}(\%) = \left(1 - \frac{\rho_1}{\rho_2}\right) \times 100\% \quad (3)$$

Where, ρ_1 is the density of the paper, in kg/m³; ρ_2 is the density of the bamboo fiber, in kg/m³.

The density of bamboo fibers was carried out by using a pycnometer for solids with distilled water as a liquid of immersion according to ASTM D8171-18. The density of bamboo fiber was calculated by the following equation:

$$\rho_2 = \frac{m\rho_{H_2O}}{m+m_1-m_2} \quad (4)$$

Where m is the absolute dry mass of bamboo fiber, m_1 is the total mass of the pycnometer filled with deionized water at 20°C, m_2 is the mass of the pycnometer filled with the fiber and deionized water and ρ_{H_2O} is the relative density of deionized water.

Fluorescent labeling and confocal microscopy observation

To investigate the spatial distribution and interfacial interactions between MFC and bamboo pulp fibers within a three-dimensional framework, fluorescent labeling was employed. bamboo pulp sulfate and MFC were labeled with distinct fluorophore and subsequently imaged using a white-laser confocal microscope. For MFC labeling, 5g of MFC was dispersed in 500mL of deionized water to prepare a 1 wt% suspension. 25mL of epichlorohydrin was then added to the suspension, and the mixture was stirred at 60°C for 2 hours. The resulting product was isolated by centrifugation and repeatedly washed with deionized water until the supernatant reached a neutral pH. Subsequently, amination was carried out by

redispersing the product and adding ammonium chloride-ammonia buffer solution (pH 10-11). The mixture was stirred for 2 hours, followed by centrifugation and washing with deionized water until neutral pH. Finally, 0.01g of rhodamine B isothiocyanate was added to a 1 wt% suspension of aminated MFC, and the mixture was stirred in darkness at 60°C for 24 hours. After centrifugation and neutral pH washing, fluorescently labeled MFC was obtained (Hobisch et al., 2021). The fluorescently labeling sulfate bamboo pulp was performed by immersing the fibers in a 1 wt% aqueous solution of 4,4'-bis(2-sulfostyryl) biphenyl disodium for 5 minutes.

Results and discussion

Morphological analysis of BF and MFC

The intrinsic morphology of BF and MFC is presented in **Fig.2a-f**. Supercritical CO₂ drying eliminates the structural distortion caused by water surface tension during drying, thereby preserving the native morphology of the samples (Shaodi Zhang et al., 2022, Zhang et al., 2025a). It reveals that refining induced significant morphology changes in bamboo fibers. Prior to refining, the fibers exhibited a round and columnar morphology with an intact structure and microfibrils on the surface(**Fig.2a、2c、2e**). The average diameter of 200 fibers, determined from SEM images using Image J software, was approximately $13.4 \pm 7.2 \mu\text{m}$ (**Fig 2g**). After refining, the resulting MFC exhibited a high degree of fibrillation(**Fig.2b、2d、3f**). Furthermore, compared with BF, the refined MFC exhibits a high specific surface area of 135.1 m²/g (Fig. 2h) and a high surface charge of -32.6 mV (Fig. 2i). This enables the MFC to have more abundant hydrogen bond binding sites and a larger fiber bridging area, thereby significantly enhancing the paper's reinforcement effect through an enhanced inter-fiber hydrogen bond network and physical entanglement. However, the diameter distribution of the MFC fibers remains uneven, and some of the fibers are still in a complete cylindrical shape. (**Figure 2b、2d**).

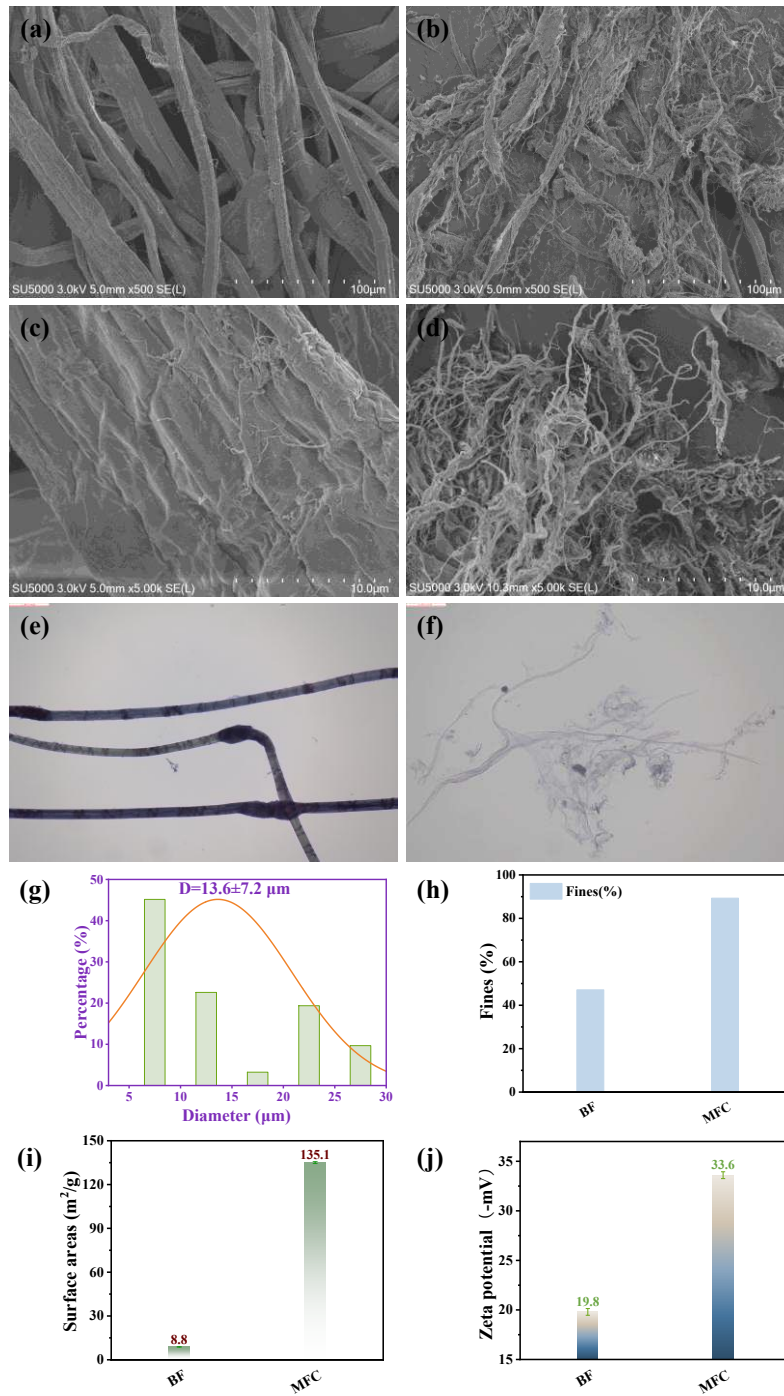


Figure 2 Characterization of BF and MFC: a SEM of BF; b SEM of MFC; c Higher-magnification SEM of BF; d Higher-magnification SEM of MFC; e Light microscopy image of BF; f Light microscopy image of MFC; g Fiber width distribution of BF; h Comparison of fines content between BF and MFC; i Specific surface area of BF and MFC; j Zeta potential of BF and MFC.

The morphology of MFC with different sizes

To conduct screening of MFCs based on their relatively uniform scale normalization. Subsequent sieving and processing yield six fibers fractions with narrowed size distribution (**Fig 3a-f**). A distinct morphology gradient emerged across the sieve fractions: the fibers retained on the 100-mesh sieve largely maintained a intact structure, although incipient fibrillation was evident (**Fig 3a**). With increasing mesh size, fiber fragmentation and fibrillation intensifies (**Fig 3a-f**). After 400-mesh sieving, intact fiber structures were nearly absent, with most material fully delaminated into fibril (**Fig 3e**). Furthermore, after sieving, the size of MFCs gradually became relatively uniform. As the sieve holes became larger, the size of MFCs decreased (**Fig 3a-f**). And after sieving with a 500-mesh sieve, the fiber diameter further reduced to the nanometer scale (**Fig 3f**).

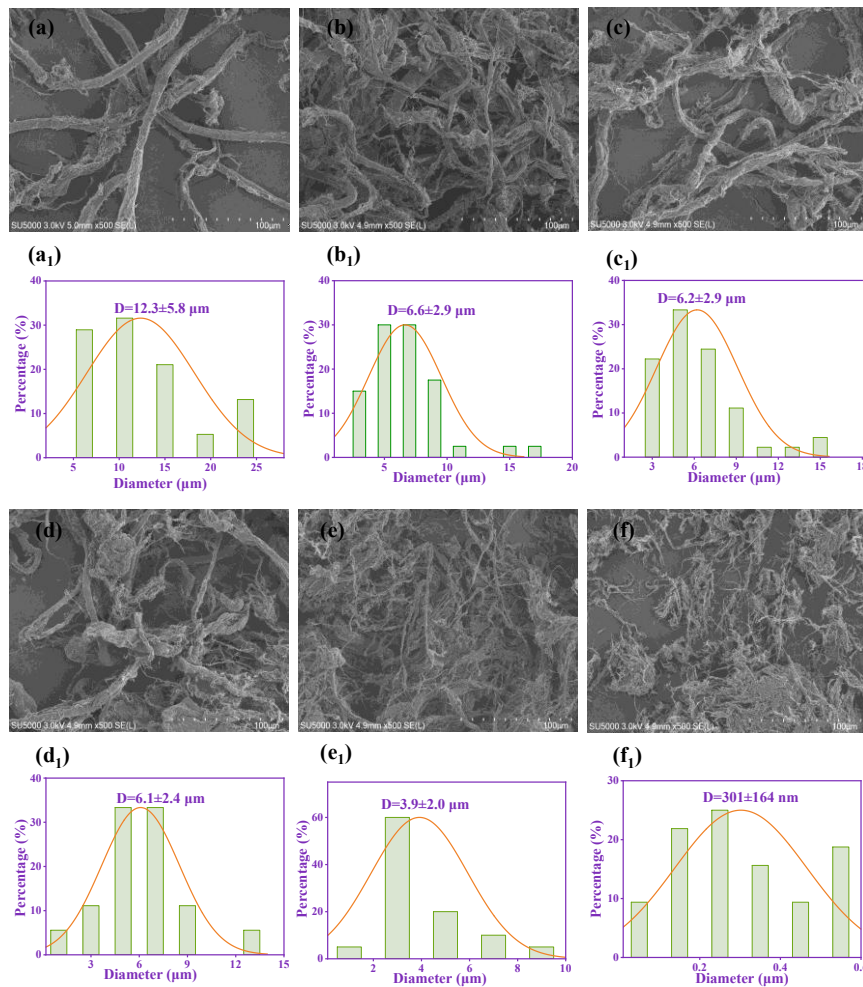


Figure 3 Morphological characterization of MFC at different scales and corresponding fiber diameter

distribution: a-f are the electron microscope images of BF@R100, BF@P100-R200, BF@P200-R300, BF@P300-R400, BF@P400-R500, and BF@P500; a₁-f₁ are the diameter distribution graphs of BF@R100, BF@P100-R200, BF@P200-R300, BF@P300-R400, BF@P400-R500, and BF@P500 .

The length and fineness of BF and fibers of various sizes were measured (**Table 1**). Refining the sulfurized bamboo pulp reduced the average fiber length from 2.06 mm to 0.53 mm and significantly increased in fines content. This indicated that refining not only shortened the fibers but also promoted fibrillation, resulting in a higher proportion of fines. Subsequent sieving revealed that fibers retained on coarser sieve were shorter and narrower and contained a higher proportion of fines. Notably, the fines content reached a maximum of 98.8% in the 400-mesh fraction. It indicated that the fines consist primarily of individual fibrils, implying that fibers retained on the 400-mesh sieve were largely converted into fibrillar structures.

Table 1 Fiber dimensions of different bamboo fibers

Sample	Average fiber length (mm)	Fines content (%)
BF	2.06	47.1
MFC	0.53	89.3
R100	0.69	51.5
P100-R200	0.67	51.7
P200-R300	0.57	58.2
P300-R400	0.51	68.6
P100-R500	0.43	98.8
P500	0.28	99.7

Paper properties

Fig 4a presents the data of paper density and porosity calculated based on mass, area and thickness parameters. The experimental results show that the reduction in MFC fiber size significantly increases the paper density while reducing the porosity. This phenomenon can be attributed to the compact stacking effect of nanoscale fibers. When the fiber diameter is reduced to the nanoscale level, the number of fibers per unit volume increases, and the fiber interstitial porosity decreases, thereby forming a more dense three-dimensional network structure. **Fig 4b** presents the typical tensile stress-strain curves of different MFC size samples. The tensile performance is negatively correlated with MFC size: when the MFC size is reduced to 30 nm, the tensile strength reaches a peak of 58.6 MPa, and the Young's modulus reaches 4.5 GPa (**Fig 4c**). This size-dependent enhancement effect is due to the high specific surface area of nanofibers promoting the formation of hydrogen bonds between fibers and enhancing the interface bonding strength; moreover, small-sized fibers can disperse stress more uniformly when subjected to force, delaying crack propagation. The toughness determined by integrating the stress-strain curve increases with the reduction of MFC size (**Fig 4d**).

Fig 4e shows that the reduction in fiber size leads to an increase in the content of fine fibers, thereby enhancing the tensile index. The maximum value of this index occurs in the BFP@P500 sample (corresponding to a MFC size of 300 nm), with the maximum tensile index of 95.11 N·m/g, indicating that the high aspect ratio characteristic of the nanofiber network effectively optimizes the stress transfer path. The tear is mainly related to fiber fracture and pull-out, influenced by both the fiber's own strength and the inter-fiber bonding force, especially the lateral hydrogen bonds mediated by hemicellulose (Merayo et al., 2016). The tear index changes in a rising-and-falling trend (**Fig 4f**), reaching the maximum value of 22.45 mN·m²·g⁻¹ in the BFP@P400-R500 (3.1 μm) sample. This non-monotonic change is due to the synergistic effect of fiber length and inter-fiber bonding force: medium-sized fibers

can maintain sufficient length to resist tear propagation while having a sufficient density of surface hydroxyl groups to form an effective hydrogen bond network; while too small-sized fibers lead to an easily penetrable tear path, and too large-sized fibers are prone to fiber slippage.

The bursting index is positively correlated with hydrogen bond density: higher density promotes a more compact inter-fiber bonding and greater fracture resistance(Tajik et al., 2018, Zulfiana et al., 2020). The change pattern of the blasting index is similar to that of the tear index (**Fig 4g**), but reaches a peak of $4.6 \text{ kPa} \cdot \text{m}^2 \cdot \text{g}^{-1}$ in the BFP@P300-R400 ($4.6 \mu\text{m}$). This is due to the aggregation and uneven distribution of small-sized MFCs, which disrupts the structure of tissue paper(Qiao et al., 2017). Fold durability, that is, the number of double folds required to reach failure, is affected by fiber strength, flexibility, length and inter-fiber bonding force. As shown in **Fig 4h**, fold durability increases monotonically with the reduction of MFC size. The number of folds reaches the maximum value of 1367 times in the BFP@P500 sample, which is 234% higher than that of BFP@R100. This is due to higher fiber content and stronger inter-fiber bonding force(Lin et al., 2024). This is attributed to the high interfacial bonding energy and physical entanglement density of the nanofiber network.

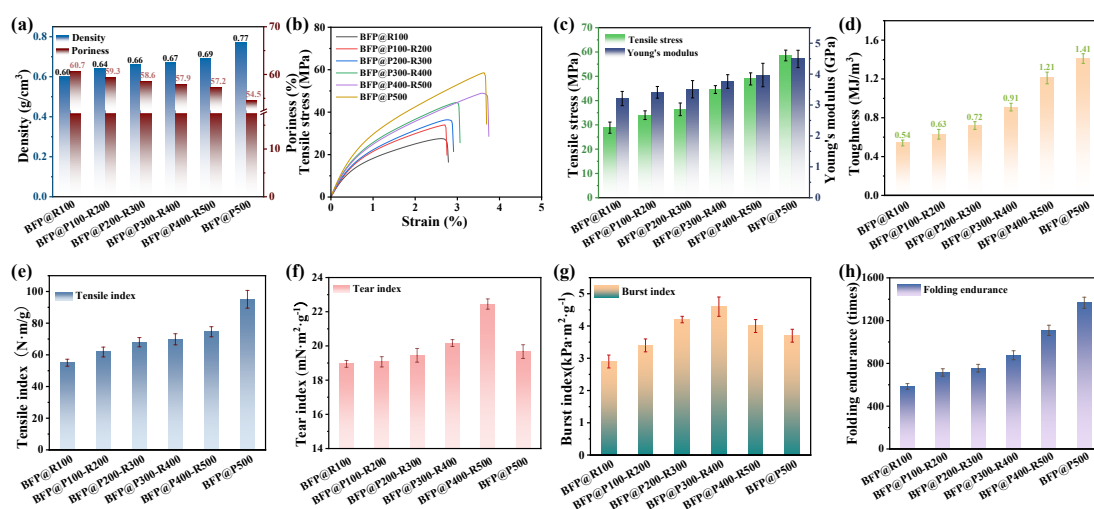


Figure 4 The influence of different sizes of MFC on the properties of Paper: (a) Density and porosity ; (b) Stretching curves; (c) Tensile strength and Young's modulus; (d) Toughness; (e) Tensile index; (f)

Tear index; (g)Burst resistance index; (h) Folding enduranceThe Mechanism of Microfibrillated Fibers

in Enhancing the Physical Properties of Paper

Mechanism analysis

Microscopic observation

Different diameters of bamboo pulp fibers and BF fibers were mixed in fixed proportions to prepare handmade paper, and the influence of fiber diameter on the paper structure was studied. With the addition of MFC (**Fig. 5a-f**), BF fibers maintained their role as the framework of the paper, while MFC effectively filled the gaps between the fibers, thus forming a dense and complex interwoven network. Scanning electron microscopy (SEM) observations showed that as the size of the bamboo pulp fibers decreased, the three-dimensional network inside the paper became denser, and the bonding between the fibers also significantly strengthened. This was mainly attributed to the smaller-sized fibers having a larger specific surface area and more bonding sites, which promoted hydrogen bond formation and mechanical entanglement, thereby generating a denser and more uniform handmade paper structure(Lin et al., 2024, Zhou et al., 2022, Sehaqui et al., 2011).

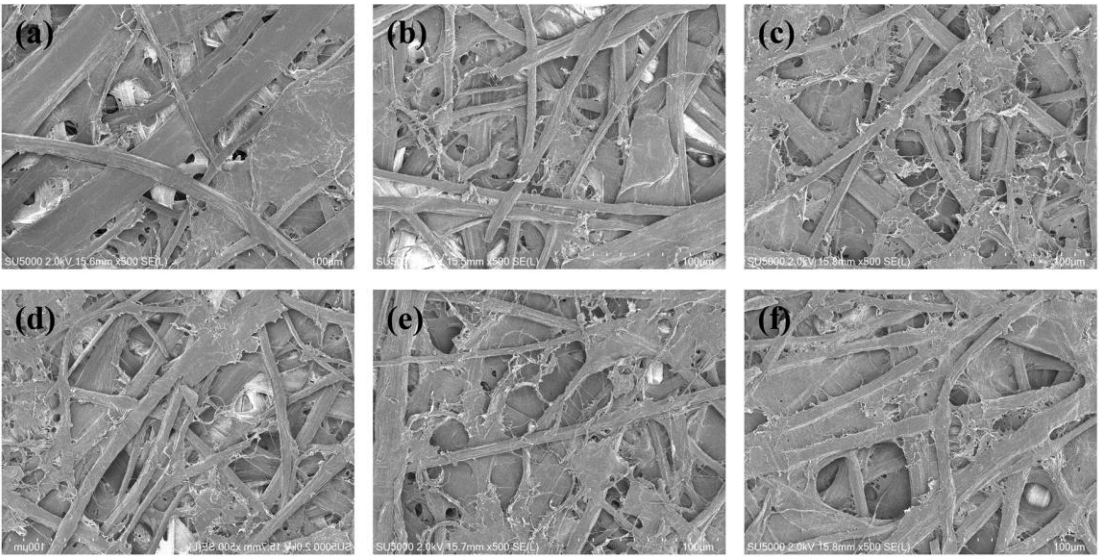


Figure 5 Surface morphology of paper made from different sized bamboo fibers: (a) BFP@R100; (b)

BFP@P100-R200; (c) BFP@P200-R300; (d) BFP@P300-R400; (e) BFP@P400-R500; (f) BFP@ P500

To visualize the spatial distribution and interfacial interactions of distinct fiber components in paper, BF fibers and MFC were fluorescently labeled and incorporated into handsheets. CLSM enabled direct three-dimensional visualization of their arrangement and binding behavior. Both components exhibited strong, uniform fluorescence, with BF fibers in blue and MFC in red. As clearly observed in **Fig 7**, the thicker MFC fibers were interwoven with BF fibers throughout the network, forming the primary load-bearing framework and establishing effective bridging junctions between fibers. Meanwhile, the finer MFC fractions predominantly occupied the pore spaces, filling and densifying the interstitial regions to enhance sheet cohesions(Hobisch et al., 2019, Mayr et al., 2017). This cooperative arrangement results in a dense, hierarchically structured three-dimensional network. The observations directly revealed the dual reinforcing role of MFC, it not only functioned as a reinforcing scaffold that participated in the stress-bearing network but also acted as a nanoscale filler that densified the structure. This provided compelling morphological evidence for the significant enhancement of paper physical properties by MFC and offered mechanistic insight into its reinforcing behavior.

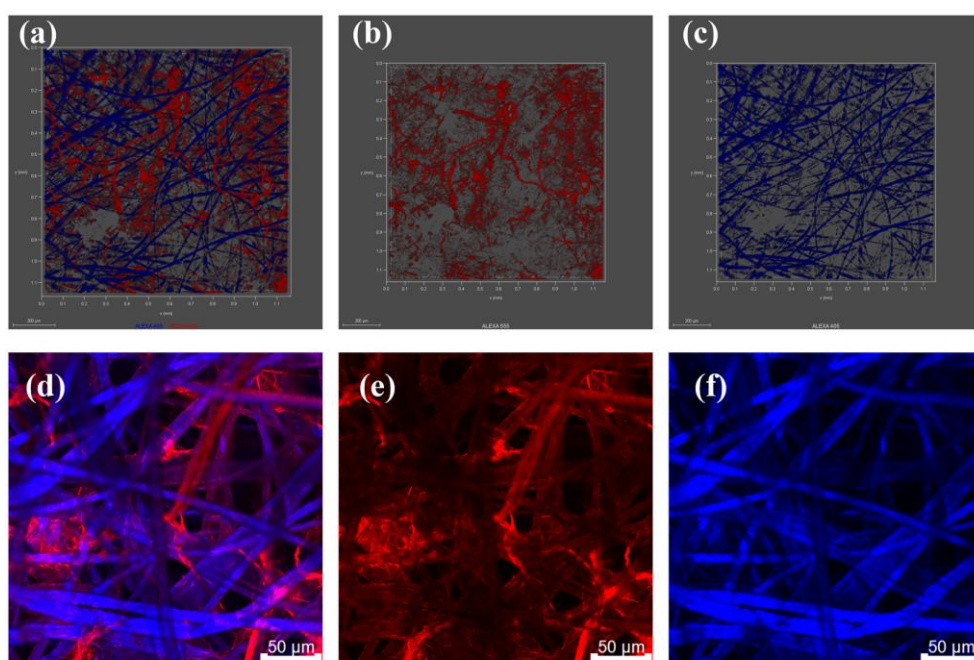


Figure 6 Laser confocal microscopic images of paper prepared with 20% MFC and 80% BF: (a) Full-field image of 20% MFC and 80% BF; (b) Full-field image of MFC; (c) Full-field image of BF; (d) High-magnification images of 20% MFC and 80% BF; (e) High-magnification image of MFC; (f) High-magnification image of BF

Surface properties

Fig 7a shows the BET specific surface area of different-sized MFCs. As the pore size decreases, the specific surface area gradually increases. Among them, BP@P500 has the highest specific surface area, reaching 145.9 m²/g. This result is attributed to the shortening of fiber length, the increase in fine powder content, and the improvement in surface roughness. The Zeta potential measurement results in **Fig 7b** indicate that the refinement and sieving treatment increase the surface charge, which may be due to the reduction in fiber size and the increase in specific surface area (Chu et al., 2020). These changes promoted uniform fiber dispersion and strengthen inter-fiber bonding during handsheets formation, thereby enhancing the mechanical properties (Perdoch et al., 2022, Anum, Mahyudin, 2022). The crystallinity index (CrI), calculated by peak deconvolution (**Fig 7c**), decreased after refining and further declined with increasing mesh size and fines content. This trend suggested a progressive disruption of crystalline domains during mechanical treatment. This trend indicates that the crystal structure is gradually damaged during mechanical processing, and the surface of MFC exposes more hydrogen bonds. (Midhun Dominic et al., 2022, C.S et al., 2016, Zhang et al., 2025b, Yuan et al., 2025).

The relative bonding area, defined as the ratio of bonded to total fiber specific surface area in paper, is a critical parameter of the inter-fiber bonding extent and is directly governed by the specific surface area of the fibers. To elucidate the effects of MFC content and bamboo fiber size on paper mechanical properties of paper, the relative bonding area was measured for all corresponding samples (**Fig 7d**).

Reducing bamboo fiber size led to an concurrent increase in relative bonding area and enhanced mechanical properties. This behavior was attributed to the fiber size effect: smaller fibers generated a higher fines content and possessed a greater density of surface hydroxyl groups. During paper formation, these fines not only fill inter-fiber voids but also form additional hydrogen bonds with adjacent fibers through their abundant hydroxyl groups, thereby significantly improving paper strength(Lavoine et al., 2012).

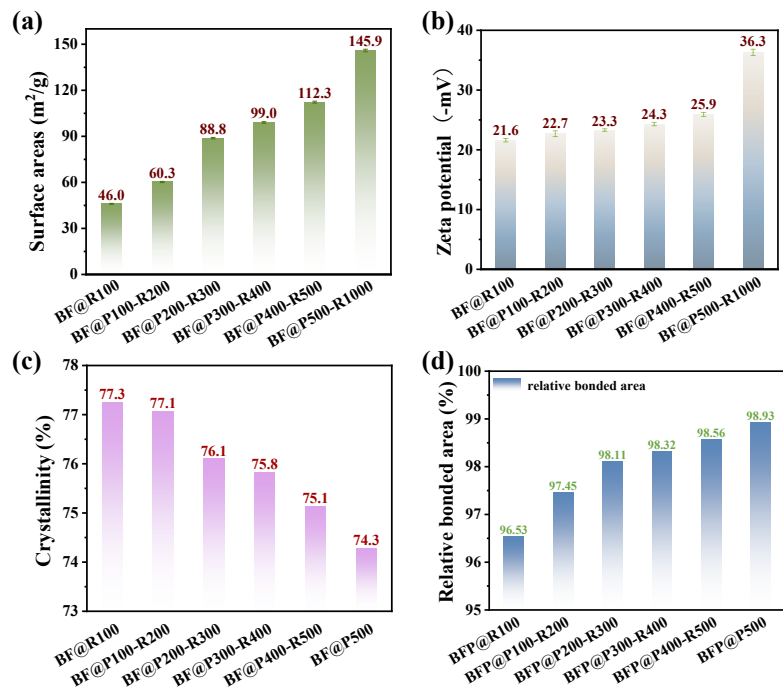


Figure 7 Physical and Chemical Properties of Bamboo Fibers: (a) N₂ adsorption capacity of different bamboo fibers; (b) Specific surface area of different bamboo fibers after supercritical drying; (c) Surface potential of different bamboo fibers; (d) and (e) Crystallinity of different bamboo fibers

FT-IR analysis

The mechanical properties of handsheets were critically dependent on its hydrogen bond network, which was governed primarily by intermolecular hydrogen bonds formed between adjacent fibers, alongside intrinsic intramolecular hydrogen bonds (Szabó et al., 2023). To quantitatively assess the impact of different treatment methods on the hydrogen bonding, the O-H stretching vibration region (3700–

3000 cm^{-1}) was analyzed by FTIR (Huang et al., 2020). Spectral features in this region enable identification of hydrogen bond types and intensities. Deconvolution of O–H stretching band, guided by second-derivative, resolved three distinct components corresponding to specific modes (**Fig 8**). As shown in **Table 2**, the enhancement in tensile strength correlated with the increase in intermolecular hydrogen bonds. Although spectral features associated with intramolecular hydrogen bonds also intensified, the reinforcement of the hydrogen bond network was primarily driven by intermolecular interactions.

Specifically, in handsheets prepared with different fiber sizes, the areas of intermolecular hydrogen bonds assigned to the 6-OH $\cdots$ O-3 and 2-OH $\cdots$ O-6 linkages increased, from 19.40 to 24.15 and from 4.35 to 5.58, respectively. These results demonstrated that the enhancement in paper mechanical properties arised primarily from a substantial increase in density and strength of intermolecular hydrogen bonds within the three-dimensional cellulose network. The underlying mechanism involved the formation of denser and stronger hydrogen-bonded connections between fibers, leading to a highly integrated and robust network. This molecular-level insight established a theoretical and experimental foundation for the design of high-performance fibrous materials through targeted engineering of the hydrogen bond architecture.

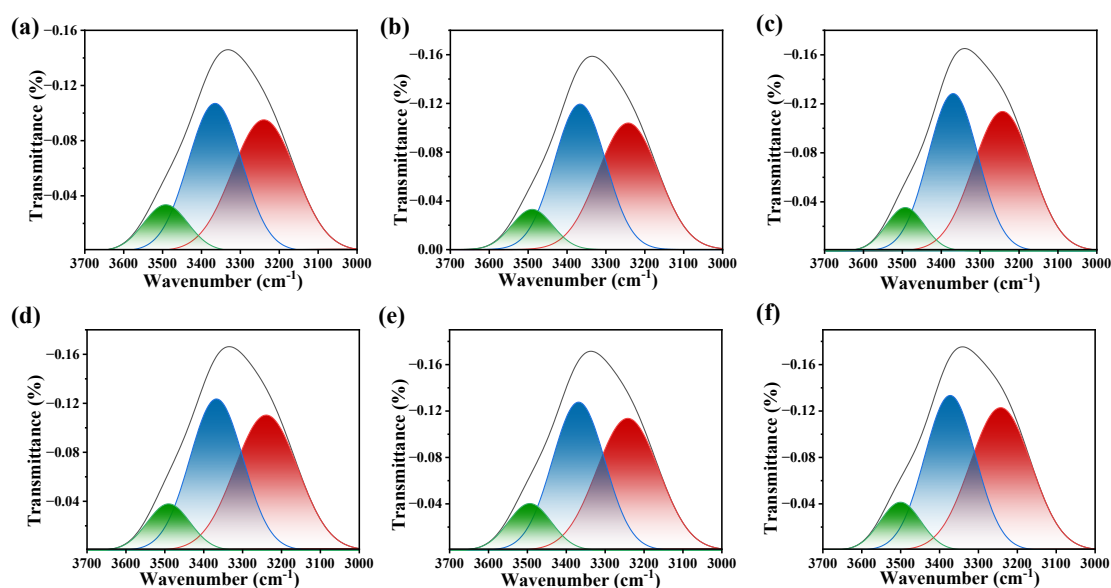


Table 2 Hydrogen bond content of paper under different sizes of MFC

Sample	6-OH···O-3 intermolecular hydrogen bonding			3-OH···O-5 intramolecular hydrogen bond			2-OH···O-6 intermolecular hydrogen bonding		
	wave number	area	Proportion	wave number	area	Proportion	wave number	area	Proportion
	/cm ⁻¹		/%	/cm ⁻¹		/%	/cm ⁻¹		/%
BFP @R100	3239.61	19.40	45.49	3365.15	18.50	43.38	3491.78	4.75	11.14
BFP @P100-R200	3242.75	20.31	45.68	3366.53	19.80	44.53	3489.63	4.35	9.78
BFP @P200-R300	3242.41	21.54	46.39	3369.44	20.62	44.41	3492.48	4.27	9.20
BFP @P300-R400	3239.19	22.43	45.93	3367.18	21.21	43.43	3490.31	5.20	10.65
BFP @P400-R500	3241.87	22.83	45.68	3368.31	21.57	43.16	3493.75	5.58	11.16
BFP @P500	3242.87	24.15	46.90	3372.66	21.94	42.61	3500.32	5.40	10.49

R²

Packaging box performance

In order to fully utilize the multi-scale effect and processability of MFC, the pulp molding process was adopted to manufacture paper packaging boxes. The mechanical properties, physical characteristics and environmental friendliness of the manufactured paper packaging boxes (**Fig 9a**) were systematically compared with those of the existing high-density polyethylene (HDPE) based plastic packaging boxes on the market (**Fig 9b**). In terms of dynamic impact reliability, a 25 kg weight was placed inside the box and subjected to multiple free-fall drop tests from a height of 3 meters. The results showed that the paper-based packaging boxes did not rupture or exhibit structural failure after multiple drops (**Fig 9c**), and their impact resistance was comparable to that of the HDPE plastic packaging boxes (**Fig 9d**). This result can be attributed to the high specific strength of the paper-based material and the energy dissipation characteristics of its fiber network structure, enabling it to effectively disperse stress and inhibit local damage when subjected to heavy impact (Caviness et al., 2023, Li et al., 2026). Additionally, the tensile strength of the paper-based packaging box was 42.2 MPa, and the Young's modulus was 1.26 GPa, which were significantly higher than those of the plastic packaging box at 29.3 MPa and 0.73 GPa (**Fig 9e–f**), indicating that the paper-based material has superior stiffness and strength under static tensile loading.

Further comprehensive analysis was conducted on the density, mass, tensile strength, Young's modulus, and degradability of the packaging boxes (**Fig 9g**). In terms of density and mass, the density of the paper-based packaging box was only 0.65 g/cm³, with a total mass of 2.1 kg, while the plastic packaging box had a density of 1.1 g/cm³ and a mass of 3.7 kg, resulting in a weight reduction of approximately 43.2%. This lightweight and low-density characteristic not only helps to reduce energy consumption and carbon emissions during transportation, but also facilitates manual handling and storage management. What is particularly important is that the paper-based packaging box has complete

degradability, while the HDPE plastic packaging box is almost non-degradable in natural environments. This advantage enables the paper-based packaging box to be recycled through composting or biological treatment after disposal, significantly reducing white pollution and aligning with the development trend of green packaging materials. The paper-based packaging box developed in this study possesses high tensile strength, high Young's modulus, low density, and lightweight characteristics, as well as complete degradability advantages. It demonstrates great potential to replace traditional plastic packaging materials and exhibits excellent reliability in multiple drop tests. Its comprehensive performance can be comparable to that of the HDPE-based plastic packaging box, showcasing significant potential for substitution.

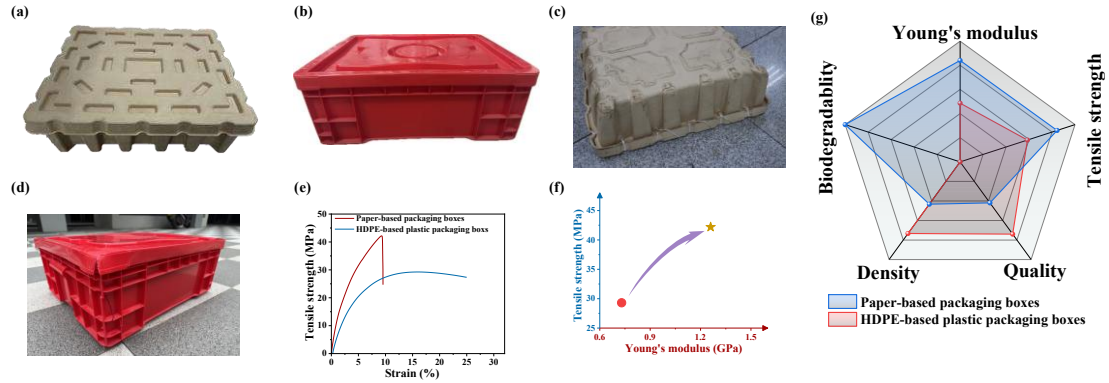


Figure 9 Performance characterization of packaging boxes: (a) plastic packaging box; (b) paper-based packaging box; (c) plastic packaging box after drop test; (d) paper-based packaging box after drop test; (e) tensile curves of plastic and paper-based packaging boxes; (f) tensile strength and Young's modulus of plastic and paper-based packaging boxes; (g) performance comparison between plastic and paper-based packaging boxes

Conclusion

This study, based on a multi-scale interface engineering strategy, fully integrates the advantages of micro/nano-fiber materials to successfully fabricate all-bamboo-based paper with excellent mechanical

properties. The successful preparation and separation of gradient-scale micro- and nano-fibers enable an in-depth understanding of how effectively scaled fibers significantly enhance paper performance and the underlying mechanisms. Through microscopic morphology observation, surface property analysis, and infrared spectroscopy characterization, the reinforcement mechanism of multi-scale MFC is revealed: the high specific surface area and abundant surface charge of MFC provide rich hydrogen bonding sites and extensive fiber bridging areas, enabling strong physical entanglement with BF and forming a dense hydrogen bond network. Meanwhile, smaller-scale fibers effectively fill the paper's pores, synergistically improving its mechanical properties, resulting in a tensile strength of up to 58.6 MPa and a Young's modulus reaching 4.5 GPa. To further exploit the multi-scale effects and processability of MFC, pulp molding technology was employed to successfully construct complex three-dimensional geometric, high-strength, and lightweight paper-based packaging boxes. These boxes demonstrated outstanding reliability in multiple drop tests, with overall performance comparable to HDPE-based plastic packaging, making them a promising low-cost, high-performance, and sustainable alternative. Furthermore, this multi-scale interface engineering strategy opens a practical pathway for scalable three-dimensional manufacturing of cellulose-based high-performance structural materials.

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Authors' contributions

The conception and design of the study were a collaborative endeavor, with invaluable contributions from all authors. Material preparation, data collection, and analysis were expertly executed by Zihao Hu, Junjun Chen, Lisheng Shi, Mengru Liu, Hai-Long Li and Jian Hu. The initial draft of the manuscript was written by Zihao Hu. All authors provided comments on the previous versions of the manuscript. Ultimately, all authors read and approved the final manuscript.

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Data availability

All data that was generated or analyzed during this study is included in the published article.

Conflict of Interest

The authors have no relevant financial or non-financial interests to disclose.

Declarations

Consent for participate

All the authors give explicit consent to participate and submit the article.

Consent to publication

All the authors explicit consent to publish the article.

Ethical approval

This study did not involve any experiments on human subjects or animals.

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