Research Progress on Functionalization Modification of Bamboo Fibers for Conductivity and Its Application in the Flexible Electronics Field

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Abstract. Bamboo resources hold significant potential for widespread application in the flexible electronics field after conductive modification. However, untreated bamboo has singular functionality and a limited application scope. By removing lignin to disrupt its inherent dense network and expose the active sites of bamboo fibers, conditions can be created for the conductive functionalization modification of bamboo. Currently, delignified bamboo fiber conductive functional materials have achieved diverse applications in fields such as energy storage devices and flexible wearable equipment, promoting the transformation of bamboo into high-performance, high-value-added materials. This paper first introduces the structural composition of bamboo, then delves into delignification pretreatment methods and the approaches for conductive functionalization modification of delignified bamboo fibers. Furthermore, it provides a comprehensive review of their research progress in the flexible electronics field, including supercapacitors and sensors. Finally, the current bottlenecks in the preparation and application of delignified bamboo fibers are summarized.

1 Introduction

Flexible electronic devices, capitalizing on their advantages of exceptional bendability, light weight, small form factor, and multi-functional capabilities, hold significant research value and application promise in areas such as wearable technology, energy storage solutions, and multi-purpose sensors. However, traditional flexible electronic materials are plagued by limitations including high production costs, unsatisfactory stability, and poor biological compatibility. Biomass materials, characterized by renewability, low cost, biodegradability, and high biocompatibility, are increasingly becoming a research hotspot in the flexible electronics field as alternatives to traditional materials.

Bamboo, a fast-growing, renewable, and abundantly available lignocellulosic resource, has transcended its traditional roles in construction and crafts to emerge as a highly promising feedstock for advanced functional materials. Its intrinsic multi-scale hierarchical structure—ranging from macroscopic hollow culms offering high strength-to-weight ratios to microscopic arrangements of cellulose microfibrils within fiber cells—provides a unique natural template for engineering. This structural arrangement endows bamboo with remarkable mechanical attributes, encompassing elevated tensile resistance and fracture toughness, together with a porous framework favorable for chemical functionalization and composite material development. The growing demand for sustainable and high-performance materials in sectors like electronics, energy, and environmental remediation has spurred extensive research into unlocking the full potential of bamboo, particularly its fibrous components. This review synthesizes current advancements, focusing on the processing of bamboo into functional fibers and their applications, with special attention to the field of conductive materials for flexible electronics as highlighted in recent research.

The transformation of raw bamboo into high-value fibers hinges on effective pretreatment to overcome the recalcitrance of its lignocellulosic matrix. The core challenge lies in selectively removing lignin, the amorphous phenolic polymer that acts as a "glue" and "cross-linker," binding cellulose and hemicellulose into a rigid composite. As detailed in recent works (e.g., Wang et al., 2025), delignification is crucial for exposing the reactive hydroxyl groups on cellulose and creating an accessible, porous network within the fiber. Common pretreatment methods include alkali cooking (e.g., using $NaOH/Na_2SO_3$ or $NaOH/NaClO_2$ systems), which effectively breaks lignin-carbohydrate complexes but often generates significant chemical waste; oxidative methods using H_2O_2 under acidic or alkaline conditions, which offer better environmental profiles and yield fibers with higher whiteness; and emerging green solvent systems like deep eutectic solvents (DES). DESs, composed of hydrogen bond donors and acceptors (e.g., choline chloride/lactic acid), have shown remarkable efficiency in fractionating bamboo into cellulose-rich solid residues, high-purity lignin, and recoverable solvents, enabling a near-zero-waste biorefinery approach. The choice of method significantly impacts the fiber's morphology, surface chemistry, and integrity, thereby dictating its suitability for subsequent functionalization. Beyond mere pulping, advanced processing like steam explosion or mechanical fibrillation can further disintegrate the fibers into micro- or nano-scale cellulose fibrils (bamboo cellulose nanofibers, BCNFs), which exhibit dramatically increased surface area, enhanced mechanical strength, and excellent dispersion capabilities in polymer matrices.

Building upon these processed bamboo substrates, functionalization strategies have diversified, with a significant thrust towards developing conductive materials for the burgeoning flexible electronics industry. This functionalization typically follows two parallel pathways: creating ionically conductive or electronically conductive composites. For ionic conductivity, the hydrophilic and porous delignified bamboo fiber network serves as an excellent scaffold for hosting ionic liquids, salt solutions, or conductive polymers like polyaniline (PANI) or polypyrrole (PPy) to form hydrogels or solid electrolytes. For instance, bamboo fibers reinforced with sodium alginate and soaked in ionic solutions have been developed into flexible strain sensors. The mechanism relies on changes in ion transport pathways during deformation, translating mechanical strain into measurable resistance signals. For electronic conductivity, the strategies involve integrating conductive nanofillers into the bamboo fiber matrix. Common approaches include in-situ synthesis, such as the electroless plating of silver nanoparticles (AgNPs) onto fiber surfaces or the in-situ polymerization of conductive polymers within the fiber's pore structure. Another viable strategy encompasses composite manufacturing through techniques like vacuum-driven filtration or stepwise layer assembly, whereby bamboo fibers are incorporated with materials such as reduced graphene oxide, carbon nanotubes, or MXenes to generate free-standing conductive films or paper-like substrates.A notable example from the literature involves creating alternating multilayer films of AgNP-decorated bamboo fibers with rGO/MWCNTs, achieving an electrical conductivity of 41.05 S/cm and effective electromagnetic interference shielding. The bamboo fiber here acts not only as a sustainable and robust substrate but also helps prevent the agglomeration of conductive fillers, ensuring a uniform and stable conductive network.

The application of these functionalized bamboo fibers is particularly prominent in two key areas of flexible electronics: energy storage devices and sensors. In supercapacitors, bamboo-derived materials play versatile roles. As electrodes, porous carbons derived from the direct carbonization of bamboo (bamboo charcoal) or composites of bamboo fibers with pseudocapacitive materials (e.g., Ni_3S_2, MnO_2, PANI) have been extensively studied. The natural pore channels of bamboo translate into a hierarchical porous structure in the carbon, facilitating rapid ion transport and yielding high specific capacitance. For instance, research demonstrates flexible electrodes based on bamboo fiber films supporting Ni_3S_2 nanosheets achieving high areal capacitance. As gel polymer electrolytes, bamboo cellulose nanofibers (CNFs) are incorporated into polymer matrices like PVA or polyacrylamide to create mechanically strong, ion-conducting membranes. Their hydrophilic nature and nanofibrillar structure help retain electrolyte and provide continuous ion transport pathways, which are critical for flexible solid-state supercapacitors or zinc-air batteries. In sensing, bamboo fiber-based conductive hydrogels and composites excel as flexible, wearable sensors. Their excellent mechanical properties, derived from the reinforcing effect of the fibers, allow them to withstand repeated bending and stretching. They can transduce various stimuli—such as strain, pressure, humidity, or even specific ions—into electrical signals. Sensors made from bamboo fiber/PVA/borax double-network hydrogels or bamboo fiber/SA/gelatin ionic hydrogels have shown high sensitivity (Gauge Factor >2), stability over thousands of cycles, and the ability to monitor human motions like finger bending and pulse. Beyond electronics, functionalized bamboo fibers find use in electromagnetic interference shielding, water purification adsorbents (e.g., after loading with magnetic particles

or activating into porous carbon), and as reinforcement in biodegradable composites to replace glass or carbon fibers.

In conclusion, the utilization of bamboo and bamboo fibers represents a compelling convergence of sustainability and high technology. Through tailored delignification and sophisticated functionalization—ranging from carbonization and nanocomposite fabrication to hydrogel engineering—this abundant biomass is being transformed into advanced materials with tailored electrical, mechanical, and chemical properties. The most promising and well-researched trajectory lies in flexible electronics, where bamboo fibers provide a unique combination of green credentials, structural robustness, and processability for creating next-generation energy storage and sensing devices. Future research is likely to focus on further greening the pretreatment processes (e.g., optimizing DES systems), achieving more precise control over fiber morphology and surface chemistry at the nanoscale, and exploring the multi-functional integration of sensing, energy harvesting, and storage within a single bamboo-derived platform. As the principles of circular bio-economy gain traction, bamboo stands poised to transition from a traditional material to a cornerstone of sustainable advanced manufacturing.

2 Basic Structure of Natural Bamboo

Bamboo is a biomass material characterized by a multi-scale gradient structure. From a macroscopic perspective, bamboo consists of periodically arranged hollow internodes and nodes that provide mechanical reinforcement. The internodes exhibit a cylindrical hollow structure, which significantly reduces the density of bamboo while endowing it with excellent bending stiffness and torsional resistance. The nodes are the connecting regions between internodes, forming solid transverse diaphragms internally, further enhancing the mechanical strength of bamboo. From a cellular composition analysis, bamboo is primarily composed of sclerenchyma fibers and parenchyma cells. Among these, sclerenchyma fibers are elongated with small lumens and are densely packed together, granting bamboo good toughness and mechanical strength. Parenchyma cells have thinner cell walls and larger lumens, primarily serving for nutrient storage. The vascular bundles constituted by sclerenchyma fibers are positioned within the honeycomb-configured ground tissue primarily consisting of parenchyma cells, manifesting a progressively decreasing concentration from the outer boundary toward the central hollow of the bamboo culm. This layered organization yields significant disparities in attributes such as tensile strength and rigidity between the exterior and interior portions of the bamboo stalk.
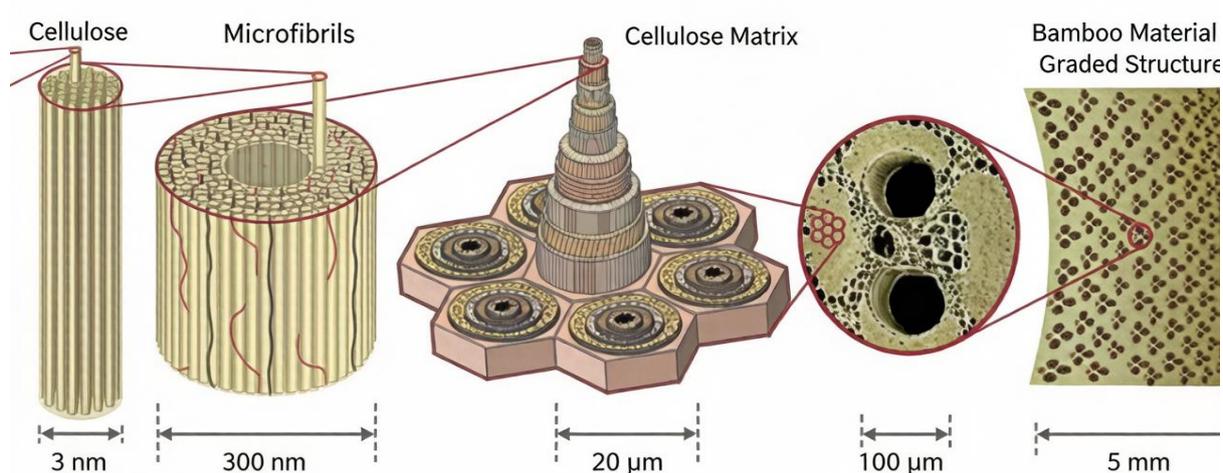

Figure 1 Multi-scale gradient structure of bamboo

Compared to raw bamboo, its tensile strength increased by nearly 2 times (560 MPa), toughness increased by 3.2 times (6.8 MJ/m³), and bending strength increased by 2 times (248 MPa). Li et al. treated raw bamboo with high-pressure steam and horizontal pressing equipment for softening and flattening. The treated bamboo was then immersed in a NaOH/Na$_2$SO$_3$ mixed solution for delignification. In the concluding stage, the bamboo

stripped of lignin was subjected to mechanical hot-pressing at 150°C under 5 MPa pressure for roughly 24 hours to produce densified bamboo (Fig. 2(b)). The fabricated material manifests a tensile strength of approximately 1 GPa, a toughness of 9.74 MJ/m³, and a specific strength reaching 777 MPa·cm³/g. This high-strength, low-density bamboo modification exhibits marked potential for deployment as a renewable, sustainable, and high-performance engineering substance (Fig. 2(c)).
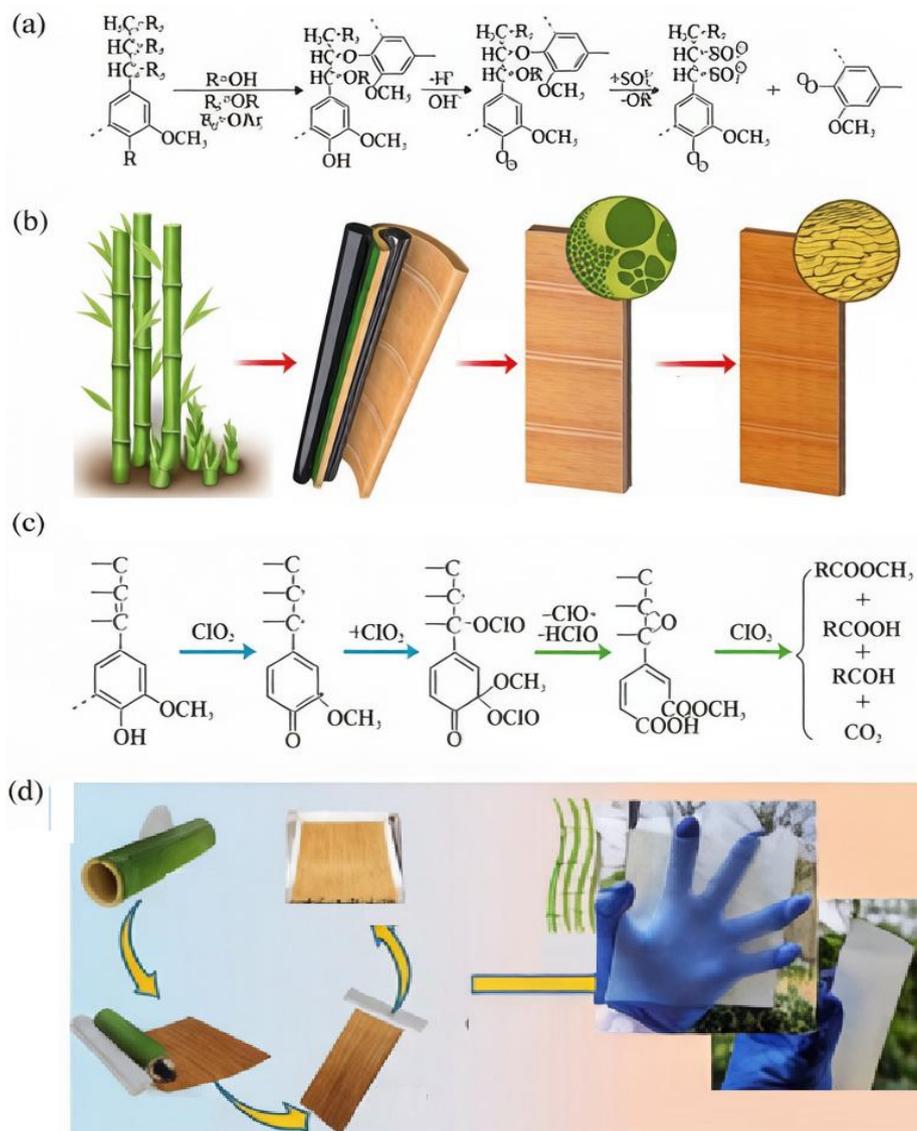

Figure 2 (a) Delignification chemical principle of the NaOH/Na₂SO₃ system [14], (b) schematic diagram of converting natural bamboo into densified bamboo [13], (c) comparison of tensile strength and stiffness of densified bamboo with other materials, (d) delignification chemical principle of acidic NaClO₂ system [14], (e) schematic diagram of the preparation of large-sized, flexible, and transparent bamboo boards

Analyzing from the nanoscale, cellulose macromolecular chains in bamboo aggregate into orderly arranged microfibrils, serving as the skeleton of bamboo. Lignin and hemicellulose act as a matrix filling the cellulose skeleton, thereby constituting the cell wall with a hierarchical structure (Fig. 1). Furthermore, similar to wood, lignocellulose in bamboo also exhibits anisotropy. Cellulose and hemicellulose in bamboo are arranged along the growth direction, while lignin has lower orientation and exhibits irregular arrangement. Therefore, from the macro to micro scales, bamboo demonstrates multi-scale and anisotropic characteristics.

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3 Common Bamboo Delignification Pretreatment Methods

Bamboo delignification treatment generally denotes the elimination of lignin and hemicellulose constituents from bamboo whilst preserving the intact cellulose framework.After delignification, bamboo forms richer porosity at the microscopic structural level, exposing more active sites; the abundant pore channels increase ion transport pathways, giving bamboo broad application prospects in fields such as energy storage and sensors. Currently, mainstream bamboo delignification methods broadly include the cooking method using sodium hydroxide (NaOH) as the main reagent, the oxidation method using hydrogen peroxide (H_2O_2) as the main reagent, and the environmentally friendly deep eutectic solvent (DES) method.

Although the $NaOH/Na_2SO_3$ system is a widely applied and relatively efficient delignification method, lignocellulose tends to have a darker color after delignification using this method. In contrast, the NaOH/sodium chlorite ($NaClO_2$) system is a delignification method widely used for producing transparent bamboo. $NaClO_2$ has a strong bleaching effect; it can destroy lignin's chromophoric groups, improving fiber whiteness. During use, $NaClO_2$ requires the dropwise addition of acid (e.g., acetic acid) to adjust the pH to an acidic environment. This acidic condition helps increase the rate of ClO_2 generation from the decomposition of $NaClO_2$, thereby further enhancing the delignification effect (Fig. 2(d)). Wang et al. employed pre-sectioned bamboo panels as starting material and fabricated scalable, large-format, highly pliable bamboo boards via an "alkali pretreatment-crosslinking-delignification" protocol (Fig. 2(e)).This substance demonstrates 80% optical transmittance, 72% haze, an elevated tensile strength reaching 78.5 MPa, together with diminished thermal conductivity of 0.35 W/(m·K) at a thickness of 1 mm.Wang et al. used a 1 wt% NaOH solution and a 3 wt% NaClO solution at pH=4.6 to treat natural bamboo for delignification. The fabricated transparent bamboo displayed elevated optical transmittance of 80%, considerable haze of 81%, together with reduced thermal conductivity of 0.203 W/(m·K).This transparent bamboo is capable of satisfying indoor illumination requirements while preserving privacy, thereby demonstrating considerable promise for the development of alternative energy-efficient residential glazing solutions.Overall, the cooking method using NaOH as the main reagent has broad applications in delignification pretreatment, but the large amount of waste liquid generated during the delignification process imposes an environmental burden, and its reaction process is energy-intensive.

3.1 Cooking Method

The cooking method involves using strong alkalis like NaOH for delignification under high temperature and pressure conditions. Among these, mixed cooking with NaOH and sodium sulfite (Na_2SO_3) is one of the most common systems. NaOH can interact with lignin in bamboo, weakening its bonding with cellulose and hemicellulose, disrupting its macromolecular structure, and converting it into smaller molecules that are easier to remove. Na_2SO_3 typically acts as a buffer to increase selectivity during delignification and prevent damage to cellulose (Fig. 2(a)). Chen et al. submerged bamboo within a $NaOH/Na_2SO_3$ blended solution to partially eliminate lignin and hemicellulose components from the bamboo matrix, subsequently employing microwave irradiation for drying and densification of the treated material. The prepared densified bamboo

3.2 Oxidation Method

The oxidation method refers to a method using oxidants such as H_2O_2 as the main reagent to achieve lignin removal through oxidation reactions. Compared to the cooking method, the H_2O_2 oxidation method has lower energy consumption, and the cellulose extracted from bamboo has high whiteness. Its main principle is that H_2O_2 decomposes under alkaline or acidic conditions, producing highly oxidative hydroxyl radicals (·OH) and superoxide anions (·O_2^-) and other reactive species. These reactive species attack the benzene rings and olefin side chain structures of lignin, disrupting its macromolecular structure and making it water-soluble, thereby achieving lignin removal (Fig. 3(a)). Li et al. successfully prepared bamboo fibers using a simple "top-down" method (Fig. 3(b)). First, bamboo was soaked in boiling water, then placed in a mixed solution of formic acid (HCOOH), H_2O_2, and H_2SO_4 for reaction, finally neutralized and cleaned with NaOH. The obtained bamboo fibers possess a Young's modulus as high as 120 GPa and an ultimate tensile strength of 2.22 GPa. The ultra-high strength allows the extracted bamboo fibers to serve as substitutes for glass fibers and carbon fibers. Wang et al. successfully prepared $CaCO_3$ mineralized bamboo boards using a "H_2O_2 pretreatment-vacuum impregnation-curing" process. After H_2O_2 pretreatment, the cellulose retention rate remained above 69.1%, and the liquid permeability of bamboo fibers increased, facilitating the penetration of flame-retardant materials. The prepared

CaCO₃ mineralized bamboo board exhibited excellent fire resistance, showing great potential in the construction field.
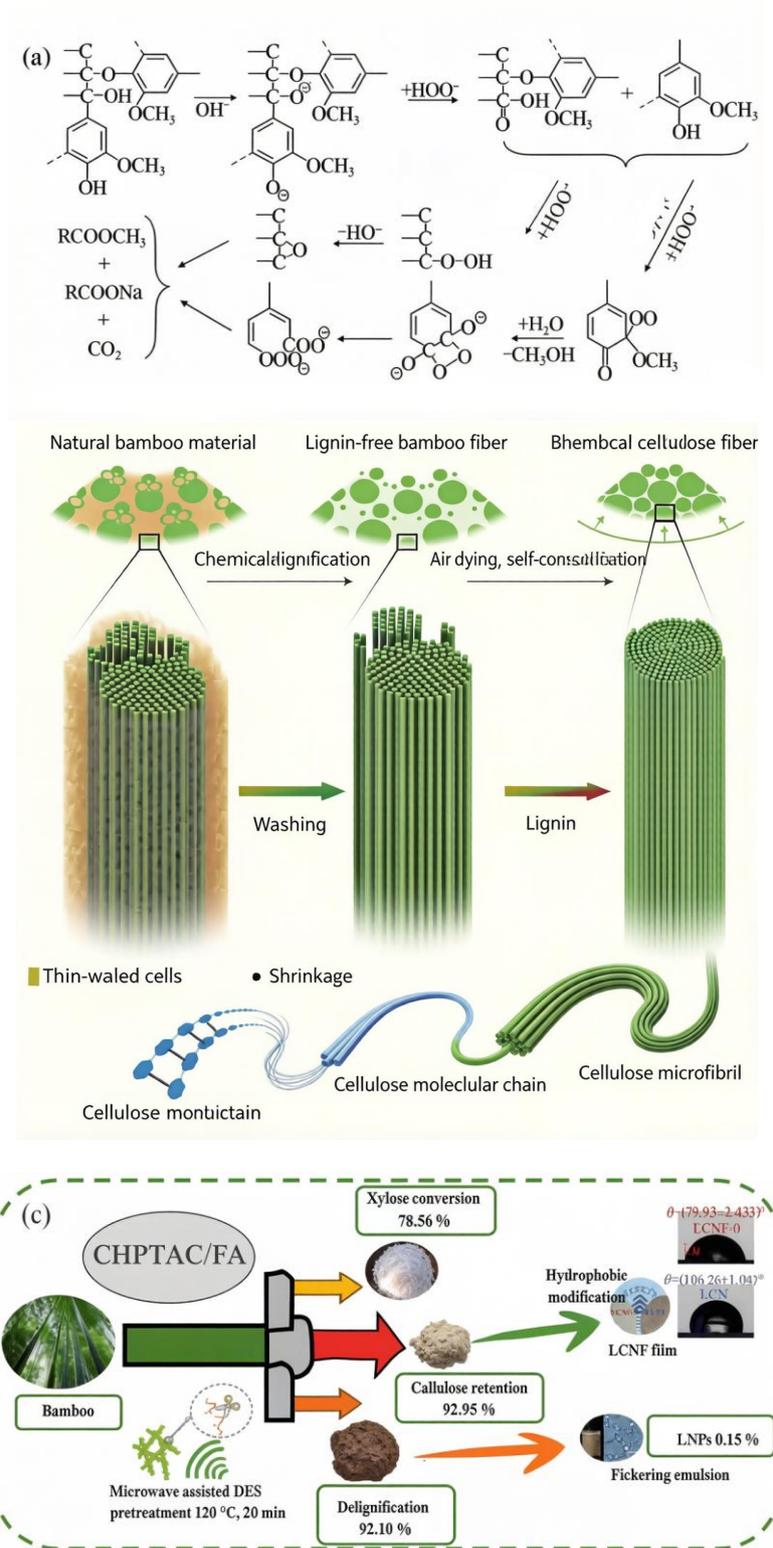

Figure 3 (a) Delignification chemical principle of the H₂O₂ system [14], (b) extract high-performance bamboo fibers from natural bamboo materials [18], (c) separation effect of CHPTAC and FA on bamboo components

Wang et al. used H_2O_2 and acetic acid to treat bamboo for delignification, forming a porous structure; semi-transparent whole bamboo (entire bamboo culm), transparent bamboo slices, and ITO films were assembled together using UV resin. After UV-curing the resin, a multilayer device with high porosity, optical transparency, and high mechanical performance was obtained. Its maximum tensile resistance reached 46.40 MPa, surface rigidity attained 80.2 HD, and electromagnetic interference shielding performance across the 8.2–12.4 GHz frequency band achieved 46.8 dB.

3.3 DES Method

The deep eutectic solvent (DES) approach signifies a technique utilizing a two-component or three-component deep eutectic mixture produced by blending specific ratios of hydrogen bond acceptors (such as quaternary ammonium salts) and hydrogen bond donors (such as amides, carboxylic acids, and polyhydric alcohols) to process bamboo for lignin removal. This method offers advantages such as environmental friendliness, recyclability, and low energy consumption. Its core principle lies in the strong hydrogen bond interactions between hydrogen bond donors and acceptors within DES, which can effectively break the hydrogen bond connections within lignin molecules and between lignin and other components. Simultaneously, compared to cellulose and hemicellulose, lignin typically has higher solubility in DES. Based on these characteristics, DES can achieve efficient lignin removal.
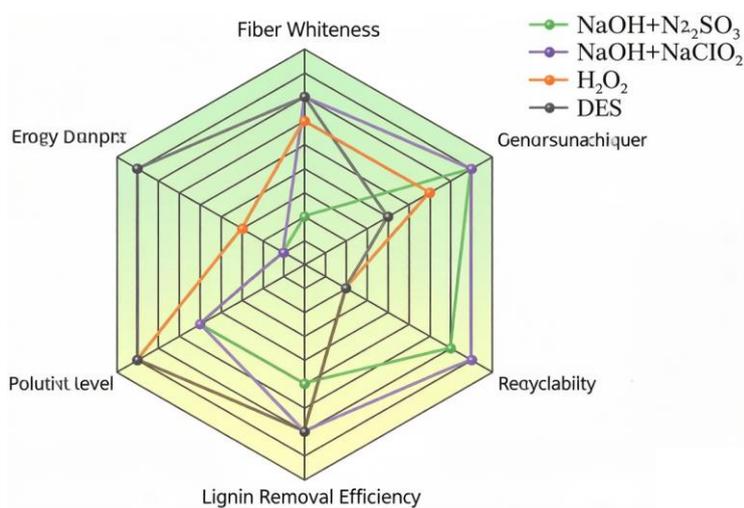

Figure 4 Comparison chart of comprehensive evaluation of different delignification pretreatment methods for bamboo

Xu et al. employed microwave-assisted DES (lactic acid/choline chloride) pretreatment technology to separate bamboo into three components: cellulose-rich residue, lignin, and recyclable DES. Through simple processing, the first two can be converted into biomass multifunctional nanomaterials. Under optimal pretreatment conditions of 130°C for 20 minutes, this method achieved a lignin removal rate of over 90%, with almost all cellulose retained. Hui et al. selected 3-chloro-2-hydroxypropyltrimethylammonium chloride (CHPTAC) as the starting material, reacting it separately with phthalic acid (FA) and acetic acid (AA) to create two different deep eutectic solvents. Using microwave-assisted DES pretreatment, they effectively isolated lignin nanoparticles (LNPs) and lignin-containing cellulose nanofibers (LCNF) from bamboo. The results showed that under optimal pretreatment conditions (120°C, 20 min), the CHPTAC/FA DES achieved a lignin removal efficiency of 92.10% along with a cellulose retention efficiency of 92.95% (Fig. 3(c)).Figure 4 summarizes a comprehensive evaluation and comparison of different bamboo delignification pretreatment methods based on fiber whiteness, delignification efficiency, environmental pollution level, energy consumption, the integrity of bamboo after delignification, and the recyclability of waste liquid.

4 Conductive Functionalization Modification of Bamboo

4.1 Ionically Conductive Bamboo Fiber Functional Materials

Bamboo, as a widely available biomass material, after treatment yields a bamboo fiber network with abundant pore channels and good mechanical properties, serving as a natural biomass template to provide channels for ion transport. Simultaneously, the hydroxyl groups abundant in cellulose facilitate chemical modification, enabling the preparation of ionically conductive bamboo fiber functional materials. Zhang et al. used a $NaOH/Na_2SO_3$ mixed solution to treat bamboo for delignification, then oxidized the chromophoric groups with H_2O_2 to obtain white nanocellulose. Utilizing stiff nanocellulose networks and flexible polyvinyl alcohol (PVA) networks as the supporting structure, together with borax acting as the cross-linking reagent, nanocellulose and PVA were bonded through diol complexation to construct a double-network hydrogel possessing a dense network configuration (Fig. 5(a)).This double-network hydrogel possesses excellent shape controllability, ionic conductivity, and high flexibility. It can not only sensitively detect minute masses in cold (0°C) and hot (60°C) environments (Fig. 5(b)) but can also be fixed on certain parts of the human body (such as wrists and fingers) to monitor human motion in real-time. Zhao et al. pretreated bamboo powder with a 4 wt% NaOH solution and an acidic $NaClO_2$ solution to obtain modified bamboo fibers. Then, the bamboo fibers were composited with sodium alginate, rapidly cross-linked into a gel under the action of calcium chloride, and subsequently immersed in a sodium chloride solution to obtain bamboo fiber-reinforced sodium alginate ionically conductive hydrogel. As the fraction of modified bamboo fibers increased, the hydrogel network framework became progressively more intricate and compact, considerably enhancing both the mechanical attributes and electrical conductance of the conductive hydrogel. Its tensile resistance reached 1.58 MPa, elongation at fracture attained 340%, and maximum electrical conductance achieved 4.94 S/m. The excellent flexibility and ionic conductivity give it potential in wearable electronic devices.

4.2 Electronically Conductive Bamboo Fiber Functional Materials

Bamboo fibers after delignification pretreatment have a larger specific surface area compared to natural bamboo, and bamboo fibers are easier to composite with other conductive materials (such as graphene, carbon nanotubes, metal nanoparticles) than whole bamboo, making them more suitable for preparing electronically conductive bamboo fiber functional materials, achieving high conductivity while meeting flexibility requirements. Currently prevalent composite methodologies encompass: direct blending, in-situ deposition, in-situ reduction, and in-situ polymerization. Wang et al. fabricated multilayer composite membranes incorporating conductive bamboo fibers, reduced graphene oxide (rGO), and multi-walled carbon nanotubes (MWCNTs) via an alternating vacuum filtration approach. TEMPO-mediated oxidation modification was employed to introduce reducible aldehyde functionalities onto the bamboo fiber surfaces. Silver nanoparticles (AgNPs) generated by the reduction of silver ammonia ions by these aldehyde groups were anchored onto the bamboo fibers via electrostatic interactions, yielding electronically conductive fibers (Fig. 5(c)). The multilayer film structure constructed by alternating vacuum filtration optimized the path and efficiency of electron transport, achieving an electrical conductivity of up to 41.05 S/cm (Fig. 5(d)), which is beneficial for enhancing interlayer electromagnetic wave multiple reflections. Zhao et al. successfully prepared GO-coated electronically conductive bamboo fiber materials through continuous steam explosion and in-situ coating technology. A pre-dispersed uniform PVA/GO dispersion and bamboo fibers were added to a screw extrusion steam explosion device. The enormous energy of the device was utilized to explode the bamboo fibers to the micron level, exposing more hydrogen bond binding sites on the bamboo fibers. Through intermolecular hydrogen bond interactions, the molten PVA would coat and uniformly adsorb graphene onto the bamboo fibers, forming conductive pathways, resulting in bamboo fiber/GO/PVA (BGP) composite conductive materials. As a consequence of the enlarged interfacial zone between graphene oxide and bamboo fibers, incoming electromagnetic waves encounter repeated boundary reflections, progressively diminishing in intensity or becoming completely absorbed. Accordingly, the bamboo-graphene hybrid material realizes substantial electromagnetic shielding performance attaining 51.51 dB.Additionally, Zhao et al. formed a bamboo fiber skeleton through acid hydrolysis of bamboo and performed in-situ polymerization of polyaniline on the fiber surface to prepare triboelectric materials with a unique hierarchical porous structure. The hierarchical porous structure of the bamboo fiber network not only provided abundant nucleation sites for the growth of polyaniline and served as a template for constructing a three-dimensional conductive network but also greatly increased the material's surface area, facilitating charge accumulation. The finally prepared bamboo fiber/polyaniline triboelectric material achieved a short-circuit current of 2.9 µA and an output power of 1.1 W/m² with only a 1 cm² working area. Lin et al. prepared electronically conductive bamboo cellulose fibers (BCF) via in-situ reduction of AgNPs. Bamboo cellulose fibers with interpenetrating porous structures and high surface

area, combined with AgNPs, formed rich and uniform conductive pathways. This BCF displayed high electrical conductivity up to 31.8 S/m and a tensile strength of 492 MPa. Moreover, it possessed outstanding flexibility, excellent mechanical stability, and wash resistance, maintaining over 96% of its conductivity after 1000 bending cycles and over 96% Ag retention after 50 washes. Gao et al. pretreated bamboo with an alkaline solution, then in-situ loaded AgNPs onto the bamboo surface through an electroless silver plating reaction, and finally deposited 1H,1H,2H,2H-perfluorodecanethiol (PFDT) on the bamboo surface. The prepared electronically conductive bamboo fibers exhibited high electrical conductivity of up to 530 S/m. Additionally, owing to the incorporation of silver nanoparticles and PFDT, these conductive bamboo fibers combined multiple superior characteristics, encompassing superhydrophobic behavior, self-cleaning capability,Additionally, as a consequence of the presence of AgNPs and PFDT, these conductive bamboo fibers integrated numerous exceptional attributes, including superhydrophobicity, self-cleaning functionality, Additionally, as a consequence of the presence of AgNPs and PFDT, these conductive bamboo fibers integrated numerous exceptional attributes, including superhydrophobicity, self-cleaning functionality, flame retardancy,andantibacterial properties.
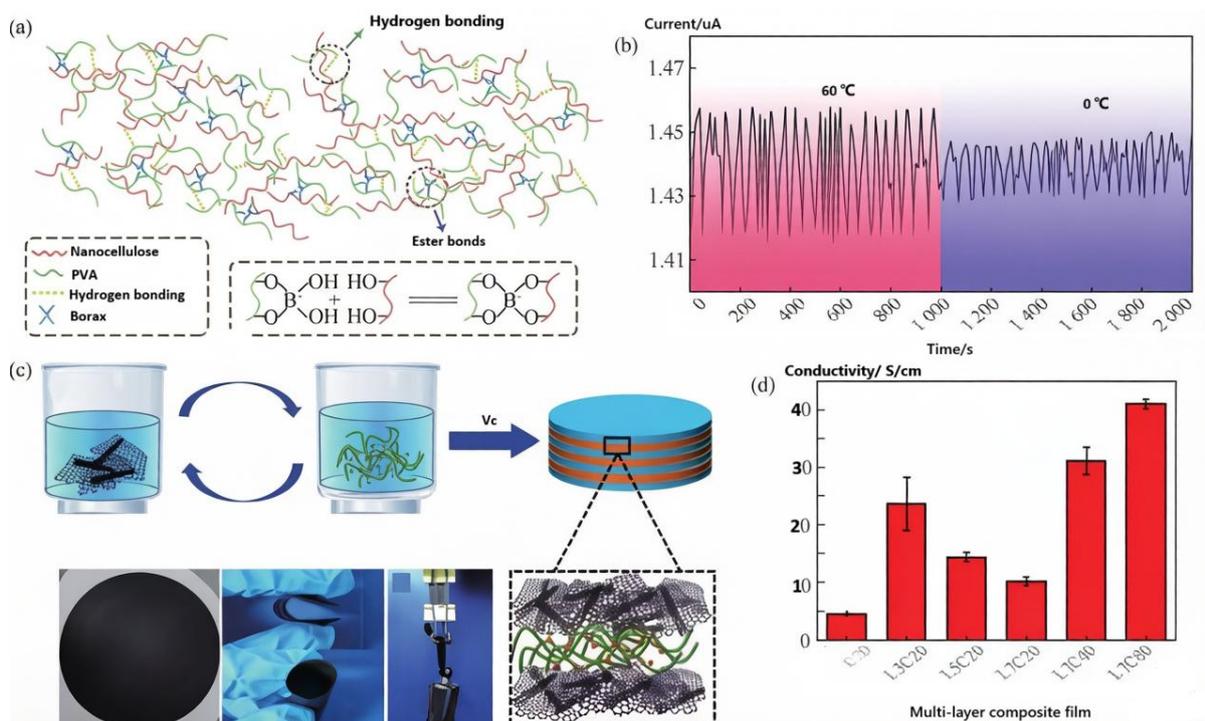

Figure 5　(a) Schematic diagram of the interactions among nanocellulose, borax, and PVA components in the double-network hydrogel [25], (b) stability tests of the NC-B-PVA double-crosslinked hydrogel under 0℃ and 60℃ [25], (c) schematic illustration of the preparation of alternating multi-layer composite films [27], (d) electrical conductivity of the multi-layer composite films

5 Application of Bamboo Fiber Conductive Materials in the Flexible Electronics Field

5.1 Supercapacitors

5.1.1 Electrodes

Compared to traditional electrode materials, environmentally friendly cellulose nanofibers (CNF) possess characteristics such as high aspect ratio, abundant chemically active sites, ease of combination with other electroactive materials, and their hydrophilic porous structure can serve as a buffer layer to mitigate volume changes of electroactive substances during charge/discharge cycles. CNF extracted from bamboo have a larger aspect ratio, higher mechanical strength, and excellent flexibility compared to wood fibers, and have been widely used in supercapacitor electrodes. Liu et al. extracted lignin-containing CNF (LCNF) from bamboo and composited it with carbon nanotubes, polyaniline, and PVA to prepare a functional ink suitable for 3D printing. By combining

a 3D printing bidirectional enhancement strategy, they successfully synthesized a biomimetic hierarchical porous nitrogen-doped electrode (Fig. 6(a)). The presence of LCNF promoted the uniform dispersion of carbon nanotubes, and the esterified lignin groups on LCNF reduced hydrogen bond formation, improving its colloidal stability. Shi et al. used bamboo fiber film as a template and combined electroless nickel plating with an in-situ sulfidation process to prepare a stable and high electrochemical performance flexible electrode (Ni$_3$S$_2$/BFF) (Fig. 6(b)). Among these, the bamboo fiber film served as a porous, flexible, and high-strength biomass-based support, providing rich active sites and structural support for electroless nickel plating (Fig. 6(c)). Electrochemical evaluations revealed that this pliable electrode exhibited an areal specific capacitance of 6116 mF/cm² at a current density of 36 mA/cm².Besides compositing bamboo fibers with other materials, directly carbonizing bamboo is also a method for preparing biomass-based electrodes. Compared to other conductive carbon materials, bamboo retains a hollow vessel structure partially similar to natural bamboo after carbonization. Furthermore, during the carbonization process, the decomposition of cellulose, lignin, and hemicellulose forms richer pore structures and larger surface areas. The retained carbon skeleton and abundant pores jointly form a hierarchical pore channel structure, providing pathways for electron/ion transport. Gontijo et al. produced bamboo-derived graphite devices possessing thermoelectric and electrochemical characteristics via low-temperature thermal processing of natural bamboo.The original high anisotropy of bamboo was retained during low-temperature heat treatment; by adjusting the treatment temperature, specific electrochemical properties can be imparted to the material. At 1000°C, this material exhibited high electrical conductivity of 839 S/m, showing great potential for application as a bamboo-based working electrode.

5.1.2 Electrolytes

Biomass-based materials, characterized by abundant sources, low cost, tunable mechanical properties, and ease of chemical modification, have been widely used in gel polymer electrolytes. Cellulose extracted from bamboo, as a biomass material, is typically introduced into polymer matrices through "bottom-up" or "top-down" strategies to enhance various properties of gel electrolytes.

The "bottom-up" strategy involves processing bamboo, extracting cellulose using mechanical or chemical methods, and treating it as functional macromolecules or nanomaterials. By compositing with other materials through methods like in-situ polymerization, new properties are imparted to bamboo fibers. Dou et al. used CNF derived from bamboo fibers as the basic building blocks. By intertwining hydroxide ion-conductive cellulose nanofibers (ICNF) with water-retaining cellulose nanofibers (WCNF), they successfully constructed a biomass solid-state electrolyte possessing ion transport and water permeation channels.Among these,
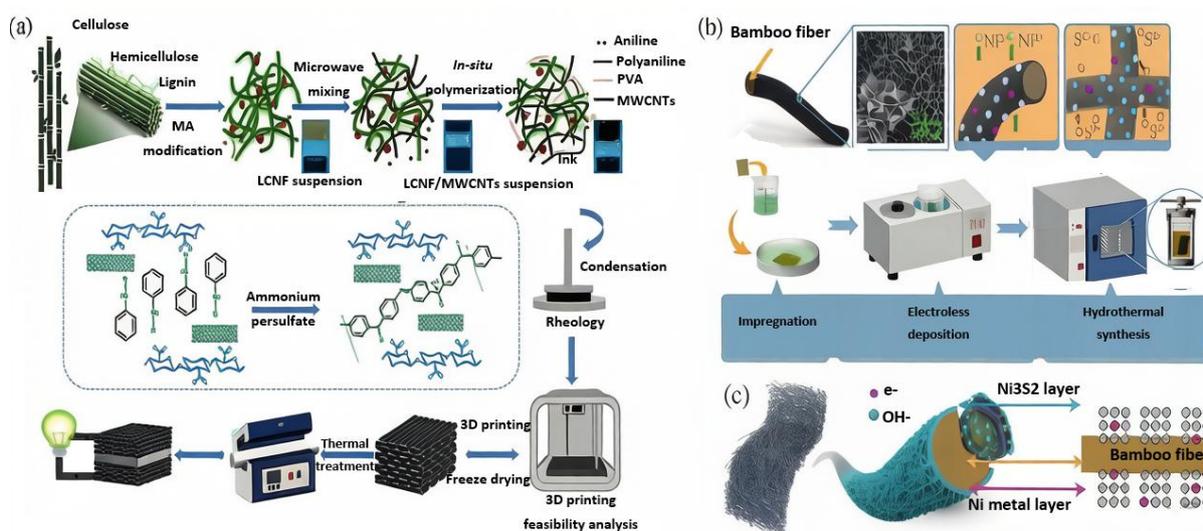

Figure 6   (a) Schematic illustration of a 3D-printed symmetric supercapacitor [33], (b) schematic diagram of the preparation process for Ni$_3$S$_2$/BFF [34], (c) electrode model of Ni$_3$S$_2$/BFF [34]

ICNF and WCNF were prepared by distilling precipitation polymerization, compositing poly(dimethyl diallyl ammonium chloride) (PDMC) with OH⁻ conductivity and superhydrophilic polyacrylamide (PAM) onto pristine

CNF, respectively. The physically entangled framework formed by ICNF and WCNF endowed this solid-state electrolyte with plentiful conductive channels and excellent mechanical attributes. The flexible zinc-air battery constructed based on this biomass solid electrolyte demonstrated exceptionally superior electrochemical performance, attaining a maximum power density as elevated as 126 mW/cm², a specific capacity of 748 mA·h/g, and a cycling lifetime surpassing 310 hours. Drawing inspiration from the natural tissue architecture of bamboo, Lin et al. devised a methodology to convert bamboo cells into fibrous supercapacitors employing conductive bamboo fibers and activated parenchyma cells as current collectors and active substances, respectively (Fig. 7(a)). The in-situ reduction of AgNPs endowed bamboo fibers with good conductivity and higher mechanical properties. Through carbonization and activation, the parenchyma cells of bamboo developed richer pore channels and larger specific surface areas, increasing the capacitance and energy density of the fibrous supercapacitor. The constructed supercapacitor displayed an elevated areal specific capacitance of 1454 mF/cm² at a current density of 0.64 mA/cm² (Fig. 7(b)). A 3D hydrogel architecture, designated PBPH, was engineered through the co-assembly of electroactive polypyrrole (PPy) and deformable polyacrylamide (PAM), as visualized in Fig. 7(c). The outstanding functionality of this hybrid gel arose from the concerted interplay of multiple structural elements—namely, the tiered porous morphology intrinsic to ABT substrates, the percolating conductive pathways established by PPy layering, and the cohesive entanglements pervading the PAM hydrogel lattice. Following systematic parameter refinement, wherein the PPy loading level was fixed at 0.1 mol/L and the substrate soaking extended over 6 hours, the resultant PBPH delivered striking electrochemical energy storage metrics alongside remarkable mechanical resilience. Direction-dependent capacitance measurements yielded 1377.28 mF/cm² axially and 101.73 mF/cm² radially (Fig. 7(d)). Complementing these electrochemical attributes, the construct sustained substantial mechanical loading, registering 104.82 MPa in tensile resistance and 1.95 MJ/m³ in deformation tolerance when probed along the fiber alignment trajectory.

5.2 Sensors

The demand for flexible wearable electronic devices has promoted the rapid development of gel-based sensing devices and imposed requirements such as high sensitivity, long-term usability, good biocompatibility, and the ability to withstand large deformations. Bamboo, as a biomass material, possesses high mechanical strength (can withstand significant external forces without damage), good flexibility (can adapt to large bending angles and other deformations), and good biocompatibility (harmless to the human body), making it an ideal material for preparing biomass-based gel sensors. Utilizing photocatalytic oxidation under ultraviolet irradiation, He and colleagues engineered chemically activated lignin derivatives. These functionalized moieties served as anchoring sites for the subsequent in-situ polymerization of compliant PAM macromolecular chains with surface-modified bamboo fibrils, culminating in the development of a mechanically robust, structurally anisotropic BPCH architecture (illustrated schematically in Fig. 8a).The modified photonic ABT endowed BPCH with axial tensile strength as high as 123.5 MPa and a Young's modulus of 3.46 GPa. Flexible sensors based on BPCH exhibited highly sensitive (GF = 0.72) and stable sensing behavior (Fig. 8(b)), capable of monitoring subtle limb movements, such as finger bending (Fig. 8(c)). Liu and co-workers assembled a trinary electroactive gel framework merging ionically crosslinkable alginate, mechanically reinforcing bamboo cellulose filaments, and thermoresponsive gelatin (designated SA/BF/Gel), which intrinsically exhibited tackiness toward contacting media and capability for crack autorecovery (portrayed in Fig. 8d). The resistance to mechanical fatigue and the spontaneous reparability of this swollen network were rooted in the coupled operation of proton-sharing interchain associations and dynamically exchangeable boron-mediated covalent junctions at phase perimeters, whereas the high areal density of electron-rich heteroatoms—including ionized carboxylates, pendant hydroxyls, and terminal amino groups—engendered vigorous interfacial anchoring across mismatched material classes. When the biopolymer formulation reached the critical gelatin dosage of 1.5 mass percent, the ensuing hydrogel demonstrated superior strain-gauging responsiveness quantified by GF = 2.21, concurrently maintaining invariant voltammetric signatures throughout thousands of polarization cycles (Figs. 8e–8f). Such distinguishing features qualify this architecture for integration into dermally mounted diagnostic instruments, specifically enabling millisecond-resolution tracking of metacarpophalangeal and radioulnar articulation dynamics, alongside cartographic visualization of contact pressure distributions across the gel-air interface.

Consolidating the causal narratives threaded throughout this scholarly work, the optimization of deformable electronic system capabilities through the deliberate conductive engineering of bamboo-origin biopolymers admits interpretation as a sequenced, nested symbiotic evolution.

This process leverages the inherent structural advantages of bamboo, strategically modifies its composition, and integrates functional materials to create composites that excel in conductivity, mechanical robustness, and interfacial compatibility, which are critical for advanced flexible devices like supercapacitors and sensors.

The fundamental enhancement mechanism originates from the unique hierarchical and anisotropic architecture of natural bamboo, which is preserved and optimized through delignification pretreatment. Bamboo possesses a multi-scale gradient structure, from macroscopic hollow internodes for lightweight flexibility to microscopic arrangements of rigid sclerenchyma fibers and porous parenchyma cells. More importantly, its cellulose microfibrils are naturally aligned along the growth direction. However, the native lignin network acts as a barrier. Delignification methods (e.g., $NaOH/Na_2SO_3$ cooking, H_2O_2 oxidation, or Deep Eutectic Solvent treatment) selectively remove lignin and hemicellulose. This serves two crucial purposes: first, it breaks the dense lignocellulosic matrix, exposing the abundant hydroxyl groups on the cellulose surface, which are vital active sites for subsequent chemical modification and bonding; second, it creates a highly porous and interconnected microstructure within the bamboo fiber scaffold. This porosity drastically increases the specific surface area, providing numerous sites for the loading of electroactive materials and creating nano-to-micro channels that facilitate rapid ion diffusion and electrolyte infiltration—a cornerstone for high-rate electrochemical performance.
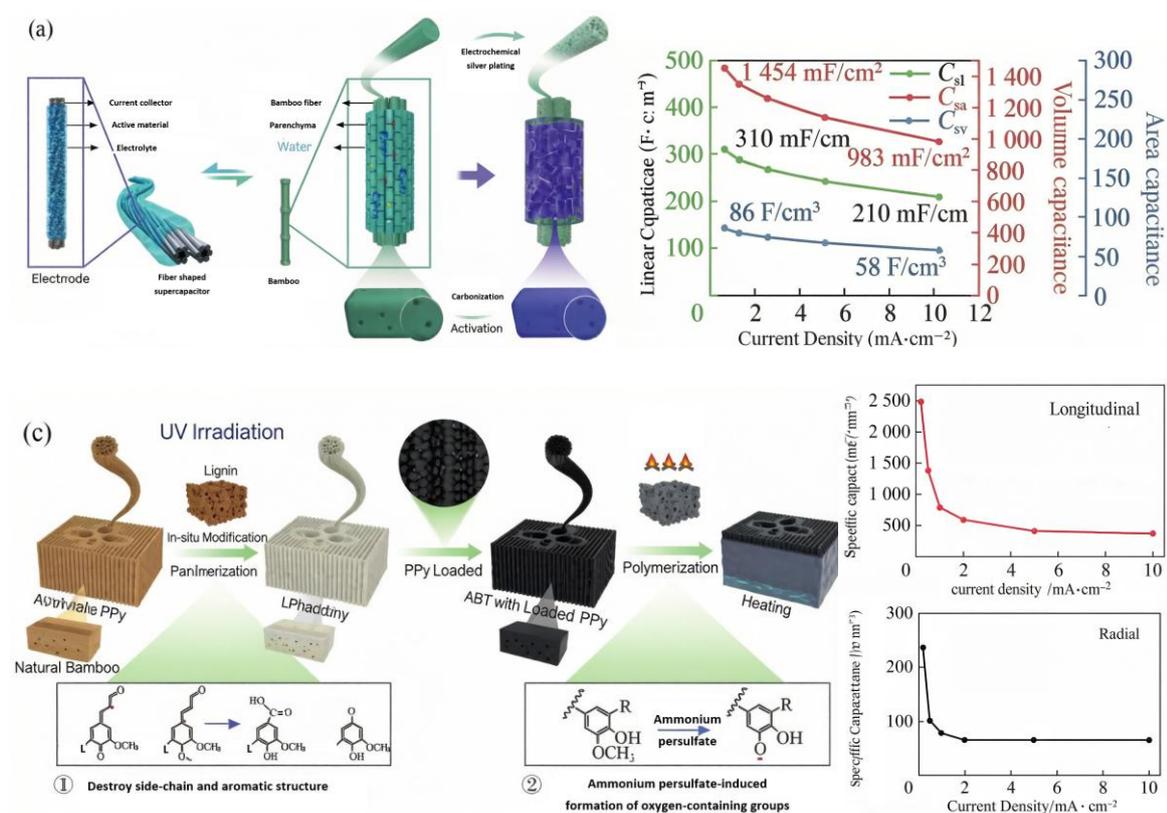

Figure 7 (a) Schematic diagram of the preparation process and (b) specific capacitance at various current densities of fiber-shaped supercapacitor based on the flexible bamboo structure [39], (c) schematic diagram of the preparation process and (d) longitudinal and radial areal specific capacitance of PBPH

The core performance boost is achieved through targeted conductive functionalization, which follows two primary pathways: ionic conduction and electronic conduction. For ionic conductive bamboo fiber materials, the delignified, hydrophilic cellulose network itself serves as an excellent natural template and reinforcing skeleton. When integrated into polymer matrices (e.g., PVA, polyacrylamide, sodium alginate) to form hydrogels or composite electrolytes, the bamboo fibers provide mechanical strength and shape integrity. The introduced ionic species (e.g., Na^+, Cl^-, OH^-) migrate freely through the water-rich phases within the hydrogel and along the

hydrophilic cellulose surfaces. The document highlights examples like double-network hydrogels for strain sensors and biomass solid-state electrolytes for zinc-air batteries, where the bamboo fiber network ensures mechanical stability while enabling efficient ion transport, leading to stable ionic conductivity and sensitive iontronic sensing capabilities. For electronically conductive bamboo fiber materials, the exposed surface and porous structure of delignified fibers are utilized to host conductive fillers. Techniques such as in-situ reduction (e.g., depositing AgNPs), in-situ polymerization (e.g., coating with polypyrrole or polyaniline), and direct compositing (e.g., with graphene, carbon nanotubes, or Ni_3S_2) are employed. Here, the bamboo fibers act as a dispersed, high-strength scaffold that prevents the aggregation of conductive nanoparticles or nanosheets. This results in the formation of a uniform, three-dimensional, and interpenetrating conductive network throughout the composite. For instance, the alternating multilayer films with AgNP-anchored fibers and rGO/MWCNTs achieve high electrical conductivity (41.05 S/cm) by optimizing electron pathways, while the in-situ grown Ni_3S_2 on bamboo fiber film creates a self-doped, interfacially coupled conductive network for flexible electrodes.

The culmination of these mechanisms is manifested in the enhanced performance of specific flexible electronic devices, primarily through structural-electrochemical-mechanical synergy. In flexible supercapacitors, when used as electrodes, bamboo fiber-based composites (e.g., with polyaniline, carbon nanotubes, or metal sulfides) benefit from the combined effects of high electronic conductivity (from the added fillers), abundant electroactive sites, and a porous structure for ion access. The bamboo fiber skeleton mitigates the volume change of active materials during charge/discharge, enhancing cycling stability. As gel polymer electrolytes, bamboo-derived cellulose nanofibers (CNF) can be engineered to create dedicated ion and water transport channels (e.g., ICNF and WCNF), which not only provide high ionic conductivity but also excellent mechanical strength and flexibility, preventing short circuits in bending states. In flexible sensors, the mechanism revolves around translating mechanical deformation into stable electrical signals. Ionically conductive bamboo fiber hydrogels exhibit resistance changes when stretched or bent due to the distortion of ion transport paths. The high strength and anisotropy inherited from the bamboo template (as in photonic anisotropic bamboo template hydrogels) allow these sensors to withstand large and repeated deformations without failure, enabling the monitoring of human motion. Electronically conductive composites can also function as piezoresistive sensors. Furthermore, the native biocompatibility and biodegradability of bamboo fibers add a critical safety and sustainability dimension for wearable and implantable electronics, reducing interface irritation and environmental impact. In summary, the enhanced performance is not due to a single factor but the orchestrated outcome of: (1) Structural Templating: Using bamboo's natural hierarchy to create optimized porous and anisotropic frameworks; (2) Interfacial Engineering: Exploiting cellulose's chemistry for strong bonding and uniform dispersion of functional materials; (3) Multi-modal Conduction: Establishing efficient pathways for either ion or electron transport; and (4) Mechanical Reinforcement: Providing the necessary toughness, flexibility, and durability that pure conductive materials often lack. This integrated approach positions conductive bamboo fibers as a versatile and high-performance platform for the next generation of sustainable flexible electronics.
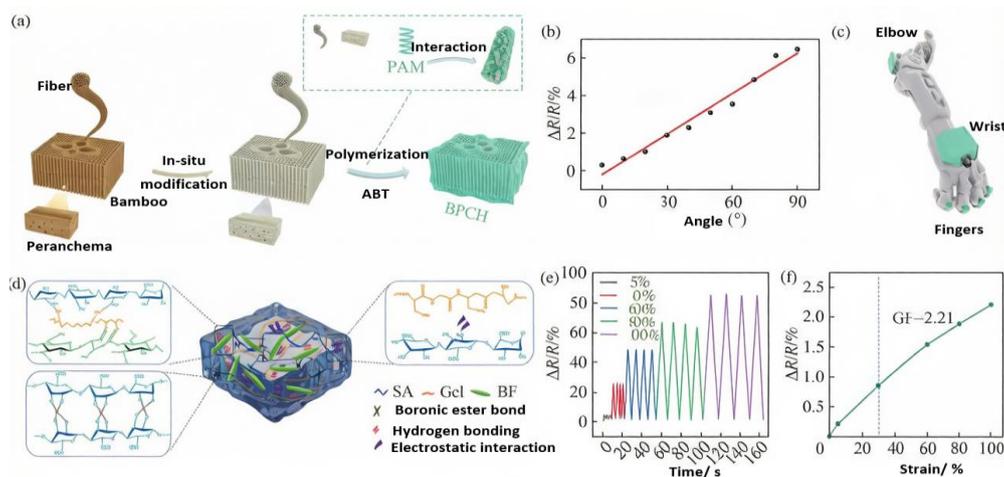

Figure 8 (a) Schematic diagram of the preparation process for photonic anisotropic bamboo template and BPCH [41], (b) relative resistance changes of BPCH at bending angles of 0~90° [41], (c) BPCH used as

"electronic skin" for working robots [41], (d) schematic illustration of the structure, (e) relative
resistance changes at different strains, (f) sensitivity factors at different strains of SA/BF/Gel composite
conductive hydrogels

Based on the comprehensive review provided in the document, the future application prospects for conductive functionalized bamboo fibers in flexible electronics are vast and strategically aligned with global demands for sustainable, high-performance, and intelligent materials. The immediate and most critical development will focus on overcoming the current bottlenecks to enable industrial-scale production. This involves pioneering truly green delignification processes, such as optimizing solvent-recyclable deep eutectic solvent (DES) systems or developing catalytic oxidation methods, to minimize energy consumption and wastewater. Concurrently, the concept of a full-component bamboo biorefinery will mature, where extracted lignin and hemicellulose are not waste but are converted into value-added products like lignin nanoparticles for UV shielding or hemicellulose-derived binders, thereby enhancing overall economics and sustainability. Furthermore, precision in delignification and modification will be achieved through advanced process control and in-situ characterization techniques, allowing for the tailored fabrication of bamboo fibers with specific porosity, surface chemistry, and mechanical properties for targeted applications.

Building on a more robust and sustainable production foundation, the performance and functionality of bamboo fiber-based devices will see significant enhancement. In energy storage, we will see the rise of all-bamboo structural supercapacitors and batteries, where bamboo-derived porous carbon serves as the electrode, a bamboo nanocellulose-based membrane as the separator, and a bamboo fiber-reinforced hydrogel as the solid electrolyte, creating fully integrated, biodegradable energy storage devices with exceptional mechanical flexibility for wearable and implantable electronics. For sensors, the future lies in multifunctional, self-powered e-skin. By integrating the ion conductivity of bamboo hydrogels with the triboelectric or piezoelectric properties of modified bamboo fibers (e.g., with polyaniline), sensors will not only detect strain, pressure, and humidity with high sensitivity but also harvest energy from body movements to power themselves, enabling long-term, maintenance-free health monitoring systems. The inherent anisotropy and hierarchical structure of bamboo will be further exploited to create directionally sensitive sensors and actuators. Beyond capacitors and sensors, transparent conductive bamboo films, with their excellent electromagnetic interference (EMI) shielding properties, low thermal conductivity, and high strength, are poised to become a sustainable alternative to indium tin oxide (ITO) and plastics in smart windows for energy-saving buildings, flexible displays, and aerospace interiors, providing simultaneous functions of transparency, thermal insulation, and EMI protection.

Ultimately, the convergence of these advancements will position bamboo fibers as a cornerstone material for the next generation of eco-friendly flexible and wearable electronics. The future will likely witness the seamless integration of bamboo-based functional components into Internet of Things (IoT) ecosystems, from self-powered environmental sensors made from waste bamboo to flexible health monitoring patches that are biocompatible and compostable. The transition from lab-scale innovation to commercial products will require concerted efforts in standardization, lifecycle assessment, and integration with existing manufacturing lines (e.g., roll-to-roll processing). By addressing the current challenges in green processing and multi-level resource utilization, conductive bamboo fibers have the potential to catalyze a paradigm shift towards a circular bio-economy in the electronics industry, offering a powerful combination of high technical performance, environmental sustainability, and economic viability that is currently unmatched by most conventional synthetic materials.

6 Conclusion

As a biosourced feedstock, bamboo presents distinctive value propositions encompassing planetary abundance, fiscal affordability, carbon-neutral renewability, inherent orthotropic mechanical behavior, and topologically ordered multiscale void architectures, establishing its preeminence among vegetative substrates for imparting electrical conductivity via chemical or physical functionalization approaches. Currently, multifunctional conductive bamboo fibers have been extensively researched in fields like energy storage and flexible sensing, but they still face many challenges. Achieving greening of delignification technology. Most current delignification methods are energy-intensive and generate significant wastewater and exhaust gases during the reaction process, causing substantial environmental harm. Future research should focus on developing industrialized green delignification methods that combine low cost and low pollution. Improving the utilization rate of bamboo

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DOI:

resources. Currently, the utilization of removed lignin and hemicellulose is low, resulting in resource waste. Efforts should be made to strengthen the recovery and utilization of waste liquid after delignification, further realizing the high-value utilization of bamboo. The precision of delignification degree needs enhancement. Excessive delignification treatment can destroy the natural structure of bamboo and reduce cellulose utilization, while insufficient delignification limits the functionalization degree of bamboo fibers. Methods similar to in-situ lignin modification should be developed to achieve lignin removal while preserving the structure and high strength of bamboo.

In the future, with continuous breakthroughs in modification and functionalization technologies, bamboo fiber conductive functional materials are expected to achieve green alternative of traditional materials in more fields.

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