Chapter

# Production and Application of Cellulose, Dietary Fiber, and Nanocellulose from Bamboo Shoot

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## Abstract

The cellulose from bamboo has excellent toughness, hygroscopicity, and high crystallinity. Bamboo shoot dietary fiber can modulate the gut microbiota to prevent high-fat diet-induced obesity and can be applied for food fortification. Bamboo shoot contains a low content of lignin and is extracted easily for nanocellulose, which is used to prepare all kinds of composite materials. In this chapter, lignification process of bamboo shoot shells will first be discussed to reveal the principle of lignification. Then, the preparation methods and applications of cellulose, dietary fiber, and nanocellulose from bamboo shoots that were successively generalized to further improve the exploration and application of bamboo shoots or bamboo shoot wastes such as bamboo shoot shells.

**Keywords:** bamboo shoots, cellulose, dietary fiber, nanocellulose, production, application

## 1. Introduction

Bamboo shoots (BSs) have long been used as food and in traditional medicine in many Asian countries because the tender BSs are rich in nutrients and bioactive compounds associated with health benefits against many chronic and degenerative diseases [1]. For example, bamboo shoot powder supplementation mainly consists of cellulose, hemicellulose, and lignin, which can reduce the levels of triglycerides, blood glucose, total cholesterol, high-density lipoprotein, and low-density lipoprotein in mice, and decrease the risk of fatty liver disease [2]. However, up to 70% of the harvested BSs have been discarded as waste biomass in China and other parts of the world. Therefore, it is of great importance for the exploration and application of BSs to develop the technologies and methods for novel products of BSs.

Presently, BSs and the processing residue have been studied as cheap sources of valuable nutrients and bioactive compounds for value-added products (e.g., food additives, functional foods, and pharmaceuticals) [1]. Dietary fiber (DF), defined as the seventh nutrient for humans by nutritionists, has many benefits for our health, such as improving the intestinal flora and decreasing the probability of obesity and cardiovascular disease [3, 4]. The total dietary fiber (TDF) in BSs ranges from 2.23 to 4.20 g/100 g fresh weight of shoots [5]. The DF from BSs increases food quality as well as organoleptic properties [5]. The cellulose from BSs has been described as having excellent toughness, hygroscopicity, and high crystallinity [6], and can be regarded as an ideal material for preparing BSs cellulose nanocrystals (BSCNC). Cellulose nanocrystal (CNC) has many interesting structural features and unique physicochemical properties, including magnificent mechanical strength, high surface area, and many hydroxyl groups for chemical modification, low density, and biodegradability. It has attracted great interest from researchers in such fields as biomedicine, electronic gadget, water purification, nanocomposite (NC), and membrane [7–9]. BSs have many advantages such as low content of lignin, fast growth, and wide distribution, which represent a favorable scenario for producing CNCs from BSs with low chemical and energy consumption [10]. Therefore, it is vital for the exploitation and utilization of BSs to produce BSC, BSDF, and BSCNC. Besides, the degree of polymerization and crystallinity of cellulose increased with the maturity of BSs, which positively correlates with the lignification [11]. Thus, an understanding of lignification process of BSs is helpful for the production of BSC, BSDF, and BSCNC.

## 2. Lignification process of bamboo shoot

Lignin is recognized as a limiting factor to biomass-to-products conversion, and thus it is required for efficient exploitation of BSs to understand the molecular mechanisms underlying lignin deposition. In general, the lignification of BSs takes place in the two stages of growth and storage.

During the growth of BSs, the lignification degree and lignin content increased with the height of BSs [12], and the lignin deposition increased with internode maturity and from bottom to top in each internode, except for the mature internode (8 m), which showed higher lignin levels in the lower portion as shown **Figure 1a**. In this stage, lignification is attributed to secondary cell wall (SCW) formation. The biosynthetic pathways are highly regulated by transcription factors (TFs). The network of TFs is mainly divided into two categories: those in the MYB family and those in the NAC family. NAC TFs act as "master switches" and regulate downstream levels of TFs to initiate SCW synthesis. MYB TFs play a central role in the transcriptional regulation of the deposition of plant SCW materials and have been reported to function as a link between upstream NAC TFs and downstream structural genes [14]. The lignification degree positively correlates with the content of lignin and cellulose. MYB20, MYB42, MYB43, and MYB63 may be positive regulators of both lignin and cellulose

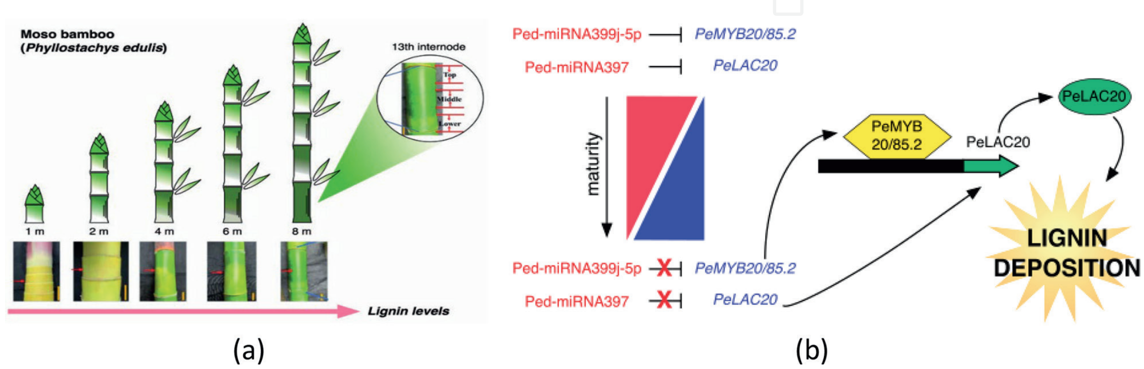


**Figure 1.**
*Lignification process of BSs (P. edulis) (a) and miRNA-mediated "MYB-PeLAC20" regulatory module for lignin polymerization of BS (b) [12, 13]. Internodes were also divided into three portions, named lower, middle, and top.*

biosynthesis in *Phyllostachys prominens* shoots (HBSes), and MYB20 and MYB43 had a positive correlation with the lignin content in *Phyllostachys edulis* shoots (MBSes) [15]. It is commonly recognized that MYB20 plays an important regulatory role in the lignin biosynthesis pathway. As schemed in **Figure 1b**, the lignin polymerization of BSs based on the regulation of MYB20 was proposed: (1) in young internodes, higher expression of Ped-miRNA399j-5p and Ped-miRNA397 represses the expression of PeMYB20/85.2 and PeLAC20; (2) the expression levels of Ped-miRNA399j-5p and Ped-miRNA397 decrease with the maturity of BSs, resulting in the up-regulation of PeMYB20/85.2 and PeLAC20; (3) PeMYB20/85.2 binds to the promoter of PeLAC20, boosting its expression and inducing lignin deposition [12, 13].

Lignification has a close correlation with the relevant key enzymes in the growth of BSs. The phenylalanine ammonia-lyase (PAL) and peroxidase (POD) activities were progressively reduced from shoot base to top, and the contents of cellulose and lignin also decreased [16]. It follows that PAL and POD contribute to the lignification. Four key enzymes in lignin cell wall deposition are PAL, cinnamyl alcohol dehydrogenase (CAD), POD, and laccase. PAL is the first rate-limiting enzyme. CAD degrades hydroxy-cinnamaldehydes into the corresponding alcohols. POD and laccase catalyze the polymerization of cinnamyl alcohols into lignin in the last step of lignin synthesis. Accordingly, the accumulation of lignin in fresh tissue was positively correlated to the increasing activity of PAL, CAD, POD, and laccase [17, 18]. However, PAL and laccase activities first increased and then decreased with the growth of BSs [12]. The crystalline structure of cellulose fibers is surrounded by hemicellulose and lignin. Lignin is a heterogeneous aromatic polymer found as 10–35% of lignocellulose. The resistance of lignin to breakdown is a major obstacle in the bioconversion of lignocellulose. The microbial breakdown of lignin attracts considerable interest. White-rot fungi are known to break down lignin with the aid of extracellular POD and laccase enzymes [19]. Coculturing microorganisms (*Pleurotus ostreatus* and *Aspergillus niger*) have been adapted to decompose the lignocellulose of bamboo shoot shells (BSSs). During the degradation, there was a rise in the activities of enzymes carboxymethylcellulase (CMCase) and laccase [20].

After BSs are harvested, the storage is the second stage of BSs for lignification, which is also correlated with the expression of key enzymes such as POD, PAL, and CAD [18]. The contents of cellulose and lignin increased rapidly with storage time. In the first five days, cellulose increased rapidly, and in the next five days, it became to slow down apparently. However, the lignin content increased at an even speed during the storage time. Meanwhile, the activities of POD and PAL increased significantly with the storage time [18, 21]. The lignification during postharvest storage of BSs may be correlated with the up-regulated expression of the IFs of SND2, KNAT7, MYB20, and MYB85 from the NAC and MYB families. Application of melatonin effectively retarded the lignification, as well as reduced lignin and cellulose contents by inhibiting the activities of PAL and POD, but enhancing those of superoxide dismutase, catalase, and ascorbate peroxidase activities. This was mainly attributed to the inhibition of the TFs [14]. Therefore, lignification has been considered a typical characteristic of senescence of BSs during postharvest storage, which is affected by various factors to name a few. Cold storage can reduce weight loss, browning, respiration rates, and sugar degradation in BSs; decrease related enzymatic activities; and inhibit the increase in lignin and cellulose content. The increase in the degree of lignification and fibrosis is the main reason for senescence and for the decline in quality of BSs after harvest [22]. Low temperature (4°C) could decrease the activities of POD and PAL significantly, as well as decrease the contents of cellulose and lignin significantly [21].

However, the firmness, and lignin and cellulose content of BSs increased and accelerated by higher storage temperature. The increase in firmness of BSs during storage is a consequence of tissue lignification, a process associated with increase in the activities of PAL, CAD, and POD [18]. Hydrogen peroxide ($H_2O_2$) accelerates the programmed cell death process by upregulating DNase, RNase, and caspase 3-like activities and enhances the lignification of BSs. Therefore, endogenous $H_2O_2$ may play a vital role in the lignification process of BSs [23]. On the other hand, lignin biosynthesis has three stages: biosynthesis, transport, and polymerization of its precursors. Wherein, the transport activities for coniferin and β-glucocoumaryl alcohol depend on vacuolar type $H^+$-ATPase and a $H^+$ gradient across the membrane. Thus, the transportation is mediated by secondary active transporters energized partly by the vacuolar-type $H^+$-ATPase [24].

## 3. Preparation and application of BSC

Like wood, the cell walls of bamboo culms consist mainly of cellulose, hemicellulose, and lignin. Bamboo cellulose has excellent toughness, hygroscopicity, and high crystallinity [6]. Cellobiose is the basic repeating unit of cellulose. In the molecular structure of the cellobiose, strong intramolecular hydrogen bonds among the contiguous glucose segments in the chain and intermolecular hydrogen bonds with various other surrounding chains are formed, which are responsible for tight packing of crystalline regions of cellulose fibrils (**Figure 2a**). As shown in **Figure 2b**, the extensive orientation of the hydrogen bonding network and different possible directions of glucose units lead to various crystalline forms for cellulose, categorized into four types (Cellulose I, II, III, and IV) [26, 27]. Cellulose I has a parallel packing in the hydrogen-bonded cellulosic network, which is the typical crystalline form of native cellulose. On the contrary, cellulose II has an antiparallel packing of the hydrogen-bonded cellulosic network, which is either found in chemical recovery of cellulose I by solvating in some solvents (acid or base). Modification of Cellulose I & II using ammonia leads to cellulose III, whereas cellulose IV can be derived after heating cellulose III in glycerol at 260°C [28].

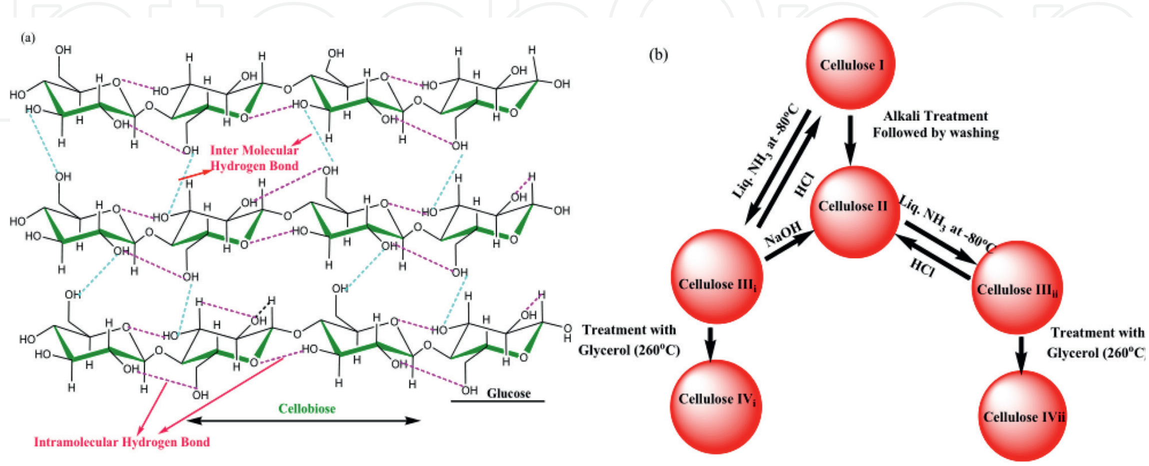


**Figure 2.**
*Possible inter as well as intramolecular hydrogen bonding between different cellulose units (a) [25] and different allomorphs of cellulose (b) [26, 27].*

As listed in **Table 1**, BSC has successfully been extracted from bamboo plants by chemical, physical, biological, and combinational methods to name a few. The hydrothermal treatment with NaOH and $NaClO_2$ has been found an effective method to prepare BSC, and these chemical reagents aim to remove hemicellulose and lignin of BSSF, and then BSSF was treated with alkali and bleached to produce BSC [34]. To protect environment, the environmental protection oxidant sodium percarbonate combined with alkali oxygen bath method was used to prepare BSSF. The method had a good effect on the degumming of BSSF, and most of the noncellulose components such as hemicellulose, lignin, and pectin had been removed. The degumming rate was 69.17% at the scouring temperature of 90°C, the alkali boiling time was 120 min, the dosage of sodium percarbonate was 24 g/L, and the dosage of $H_2O_2$ was 40 mL/L. The cellulose content and crystallinity were 73.19 and 61.40%, and the fiber had a smooth surface and a typical cellulose structure with better thermal stability [30]. The physical ultrasound-assisted method has often been coupled with some chemical methods to improve the preparation of BSC. The optimum parameters of alkali oxygen bath degumming were shown as follows: Scouring temperature of 95°C, alkali boiling time of 120 minutes, sodium hydroxide dosage of 20 g/L, and $H_2O_2$ dosage of 24 mL/L. The corresponding degumming rate was 70.07%. Pectin, lignin, and hemicelluloses were effectively removed from BSSF. The extracted BSSF presented a smooth surface, good quality, and high cellulose content, exhibiting a remarkable degumming effect of the ultrasonic pretreatment. The addition of a certain amount of sodium hydroxide in the ultrasonication process enhanced the "hollow effect" of the ultrasonic waves, improving the degumming effect [31]. The combinational use of acid and alkaline is more beneficial for BSC preparation than single use. As shown in **Figure 3**, acid pretreatment combined with alkali-oxygen bath degumming process removed most of pectin and non-cellulosic contents, and the prepared BSSF has a high content of 73.19% cellulose, exhibiting an excellent quality. The degummed fibers were separated from each other in a single fiber state, showing typical cellulose I structure, and with a large number of grooves on the surface [29]. By comparison, the acidic EtOH-$HNO_3$ process efficiently removed hemicellulose and lignin from bamboo, achieving

| Method | Traits of BSC | Ref. |
|---|---|---|
| Acid pretreatment combined with alkali-oxygen bath degumming process | The crystallinity increased from the control (43.53%) to final fiber (64.35%). 73.19% of cellulose content. | [29] |
| Oxidant sodium percarbonate combined with alkali oxygen bath method | The cellulose content and crystallinity were 73.19 and 61.40%. The degumming rate was 69.17%. | [30] |
| Ultrasound-assisted alkali-oxygen bath method | Degumming rate was 70.07%.<br>High cellulose content, smooth surface, and good quality. | [31] |
| Enzyme (cellulase and hemicellulose) coupled with LAB fermentation | The crystallinity and the thermal stability were improved. | [32] |
| One-step process (EtOH-$HNO_3$) | The highest purity of cellulose (96.8%) with the highest degree of polymerization (DP) value (815). | [33] |

**Table 1.**
*Preparation method and traits of BSC.*

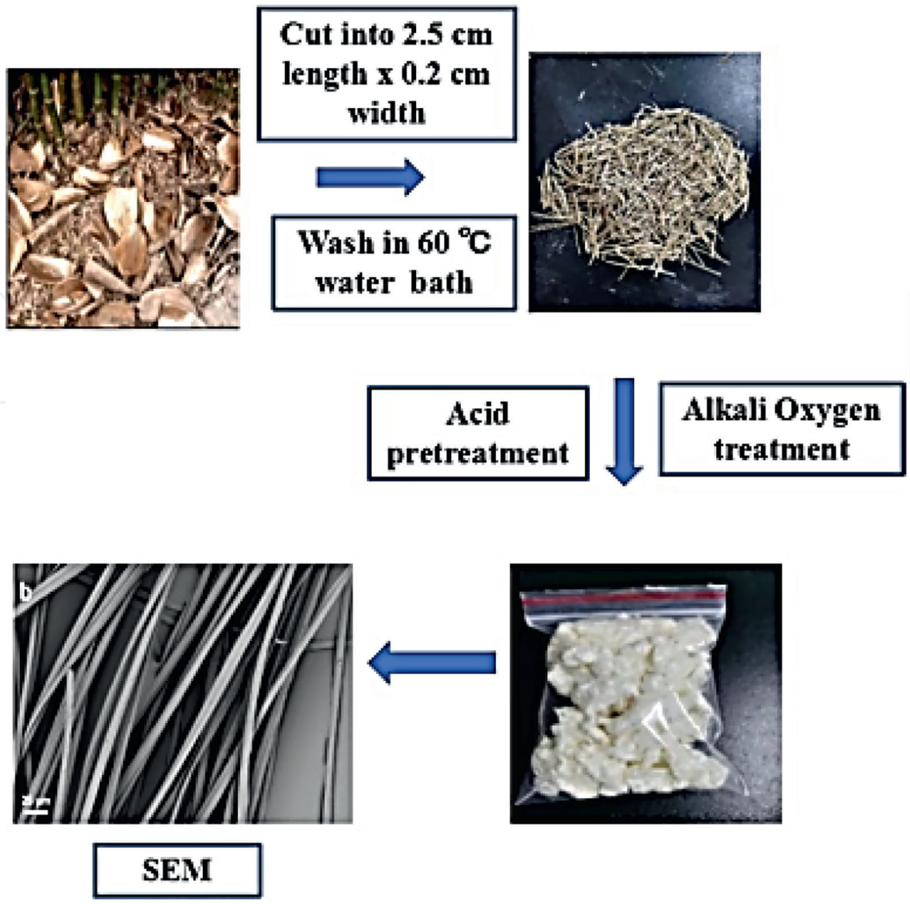


**Figure 3.**
*Degumming process of BSSF [29].*

the highest purity of cellulose (96.8%) with a high degree of polymerization (815) [33]. Bamboo shoot shells (BSS) were used as feedstock for the production of BSSF. Biological method is an effective way to improve the effect of BSS silage. Cellulase, hemicellulase, and lactic acid bacteria (LAB) can reduce the silage pH but increase the concentrations of dry matter and protein of BSS. The ensilaged fiber had an increased crystallinity and thermal stability [32].

BSC has been mainly applied as an ideal raw material in the synthesis of high-value-added material. Except for being used to prepare BSCNC, BSC, as a matrix, has often been explored to prepare many composites to name a few. BSSF was blended with starch/poly(lactic acid) (PLA) matrices to create a new low-cost biodegradable ternary composite. The mechanical strength, surface wettability, and water absorption of the composite have been increasingly improved with the rise of BSSF content from 0 to 20 wt% [35]. Also, it was used to cross-link with sodium alginate (SA) based on hydrogen bonding. The composite aerogels exhibited better encapsulation efficiency and *in vitro* antioxidant activity for the encapsulation and sustained release of bioactive compounds [36]. Besides, the modified BSC can exhibit some novel traits. The crude cellulose isolated from bamboo shoot processing by-products (BPSs) can be esterified using soybean oil to form esterified microcrystalline cellulose (E-MCC). The E-MCC had better dispersion and compatibility in starch film matrix. 5 wt% E-MCC can enhance the tensile strength and Young's modulus of TPS [37].

## 4. Preparation and application of BSDF

The major health benefits of DF are proper and regular bowel movement, prevention of constipation, diarrhea, diverticulitis, hemorrhoids, cardiac diseases, and cancer. Presently, many food products are being fortified with DF to provide an adequate amount in the diet. DF from BSs increases food quality as well as organoleptic properties [5]. DF is basically nondigestible and nonabsorptive parts of plants. DF is classified as insoluble dietary fiber (IDF) and soluble dietary fiber (SDF). From the same species, IDF showed better adsorption capacity than SDF. This is ascribed to that the surface of IDF is porous, whereas the SDF is relatively flat and compact, and stronger than IDF in the *Lactobacillus* and *Bifidobacterium* promotion effects [38]. As a cheap potential DF resource, fresh BS has a high content of TDF ranging from 2.23–4.20% [5]. Some methods to extract DF from BSs have been presented in **Table 2**, including physical method, chemical method, biological method, and combined method. Physical method is the most commonly used method to extract DF from BSs. High-temperature cooking (HTC), high-pressure homogenization (HPH), ultrasonic treatment (UT), and their combination (i.e., UT–HTC, HPH–HTC, and UT–HPH) have been applied to modify BSDF. The SDF content increased in all samples. UT–HPH could be a promising and alternative modification method to obtain high-quality BSDF. The modifications can destroy the hydrogen bonds between the lignin and hemicellulose of BSDF, significantly decreased the particle size of BSDF, and increased the SDF content, which increased oil holding capacity (OHC) and water swelling capacity (WSC) in BSDF by 55.35 and 91.47%, respectively. It is considered that combined modification technologies are effective methods to improve the quality of BSDF [42].

Chemical method is also another important method to extract DF from BSs. The acid-alkali chemical method was used to prepare BSDF, which had higher TDF with a higher crystalline region [39]. Enzymolysis can improve the DF in the solubility by decomposing IDF, and producing SDF [39, 46]. With BSS as substrate, the extraction yields of IDF and SDF were 56.21 and 8.67%, respectively. The resulting fibers showed significant WSC, WHC, and *in vitro* binding capacities to fat, cholesterol, bile acids, and nitrites [46]. No-matter-chemical method and enzymolysis both improve functional properties of DF, which exhibits many good behaviors such as water retention capacity (WRC) (11.24–15.13 g/g), WSC (18.84–28.75 mL/g), OHC (6.71–10.15 g/g), glucose adsorption capacity (GAC) (0.08–6.89 mmol/g), and glucose retardation index (GRI) (3.57–40.92%). Thus, the functionalities of DF can be improved by manipulating its physic-chemical properties [39]. An effective solvent can also improve the extraction of DFs from BSs. Subcritical water (SW) and high-pressure homogenization (HPH) was used to treat BSs for the production of DF. The functions and the structural characteristics of DFs from BSs were significantly improved, and the SDF content was dramatically increased. SW modification enhanced WHC, OHC, and WSC of DFs better than HPH. The modified DF had increasing abilities to absorb cholesterol and nitrite ions [40].

The functional properties of DF change with the variation of extraction method. Alkali extraction (AE), enzymatic extraction (EE), ultrasonic-assisted enzymatic extraction (UAEE), and shear homogeneous-assisted enzymatic extraction (SHAEE) were applied to extract BSDF. The extracted BSDF by AE had the lowest protein content and crystallinity index, but the extracted BSDF by EE had highest protein

| Method | Traits of BSDF | Ref. |
|---|---|---|
| Acid-alkali method | Higher TDF and higher SDF, WRC (11.24–15.13 g/g), WSC (18.84–28.75 mL/g), OAC (6.71–10.15 g/g), GAC (0.08–6.89 mmol/g), and GRI (3.57–40.92%). | [39] |
| Modified AOAC enzymatic-gravimetric method | | |
| SW | The crystallinity decreased, but SDF content and the ability to absorb cholesterol and nitrite ions increased. | [40] |
| HPH | | |
| *Lactobacillus* and *Bifidobacterium* fermentation | Strong cholesterol-adsorption activity and prebiotic potential. | [38] |
| AE | The BSDF with the lowest protein content and crystallinity index. | [41] |
| EE | EE: The BSDF with the lowest OHC and highest protein content. | |
| UAEE | UAEE: The BSDF with the highest OHC and GAC | |
| SHAEE | SHAEE: The BSDF with the highest SDF content, WHC, α-amylase activity inhibition ratio, and the smallest particle size, and with a porous and loose structure.<br>Hypoglycemic activity of the four BSDF samples generally followed the order of SHAEE > UAEE > EE > AE | |
| HPH | The smallest particle size of BSDF | [42] |
| UT | A loose structure with a honeycomb appearance on the surface. | |
| Combinations (i.e., UT–HTC, HPH–HTC, and UT–HPH) | The lowest relative crystallinity.<br>UT-HPH: The particle size decreased, but the SDF content increased.<br>UT–HTC: SDF has a more porous, looser morphological structure, and increased content. | |
| LGG fermentation | The structure and composition of TDF changed, the proportion of IDF increased, and the TDF was decomposed into small pieces. Great WSC, stronger NIAC, the ability to produce SCFAs, and stronger anti-digestion ability. | [43] |
| Enzymatic hydrolysis | Particle sizes and the microstructure of IDF greatly changed. | [44] |
| DHPM | A honey-comb appearance and large cavities on the surface of modified fiber, which has increased crystallinity and thermal stability, higher WHC, and more promising binding capacities for oil, nitrite ion, glucose, and cholesterol. | |
| ME | The yields of IDF and SDF were 56.21 and 8.67%. The fibers showed significant WSC, WHC, and binding capacities to fat, cholesterol, bile acids, and nitrites. | [45] |

**Table 2.**
*Preparation method, traits, and applications of BSDF.*

content and the lowest OHC. The BSDF generated by UAEE had the highest OHC and glucose adsorption capacity (GAC). SHAEE obtained the highest SDF content (17.89%), WHC (8.81 g/g), and α-amylase activity inhibition ratio (19.89%) and the smallest particle size (351.33 μm). BSDF extracted by SHAEE and UAEE presented a porous and loose structure. In terms of *in vitro* hypoglycemic activity, the four

BSDF samples generally followed the order of SHAEE>UAEE>EE > AE. SHAEE is an innovative and promising method to obtain BSDF with excellent physicochemical and functional properties [41]. Therefore, the combination use of various methods is an effective road to change the functional properties of BSDF.

Microbial fermentation is composed of multiple enzymatic reactions. In view of the effect of enzymatically method on BSDF extraction, microbial fermentation ought to have an apparent effect on BSDF preparation. *Lactobacillus rhamnosus* GG (LGG) fermentation can change the structure and composition of TDF of BSs. The TDF was decomposed into small pieces, and the proportion of IDF increased [43]. The enzymatically SDF exhibited significantly higher glucose adsorbing capacity than those of IDF and TDF and showed similar inhibition potential against α-amylase with acarbose. TDF displayed the greater capacities for delaying glucose diffusion and inhibition of α-glucosidase than those of SDF [46]. The structure and properties of BSIDF can be changed for extensive applications by some modifications of enzymatic hydrolysis and dynamic high-pressure micro-fluidization (DHPM). The particle sizes of IDF powders significantly decreased, and the microstructure made marked changes. The treatments removed part of lignin and hemicellulose and increased the crystallinity and thermal stability of the modified fibers. Relative to the modification of enzymatic hydrolysis, the modification of DHPM better decreased BSIDF in particle size and porous structure, and the DHPM-modified BSIDF exhibited not only higher WHC but also more promising binding capacities to oil, nitrite ion, glucose, and cholesterol. It follows that DHPM could more effectively improve functional properties of BSIDF than enzymatic hydrolysis [44]. On the other hand, BSIDF was prepared and used as plant food particle stabilizer for oil-in-water (O/W) Pickering emulsions. The DFs from bamboo shoots had a soft nature and suitable shape to produce stable Pickering emulsions, which could be used as food-grade particles for applications in food and cosmetics industries. The BSDF suspensions and BSDF-stabilized O/W emulsions both exhibited shear-thinning behaviors; moreover, both viscosity and module were increased with the increase of BSDF contents. The surface coverage of emulsions was positively correlated with the content of BSDF suspensions. The obtained Pickering emulsions would have a wide application in food and cosmetics field [47].

BSDF has been mainly applied in food industry, especially in the field of healthy diet. BSDF has been shown to prevent high-fat diet-induced obesity through modulating the gut microbiota, which is a potential prebiotic fiber that modulates the gut microbiota and improves host metabolism and is the most effective in suppressing high-fat diet-induced obesity [48]. The administration of BSDF improved the lipid metabolism disorderly situation of hyperlipidemia mice. Compared with normal group, TDF supplement could exhibit the lowest body weight gain (2.84%) in mice [46]. Several potential mechanisms have been suggested to be responsible for the hypolipidemic effects of BSDF. (1) The fibers are not able to be digested in the gastrointestinal tract, resulting in greater satiety and less calorie intake. (2) The fibers present in gastrointestinal tract disturb lipid absorption due to their binding capacities. (3) The binding or adsorptive capacities of bile acids and cholesterol enhance their removal from enterohepatic circulation, leading to lower cholesterol in the various pools. In addition, the fibers might effectively regulate the transcription of certain genes involved in lipid catabolism and modulate the gut microbiota to improve lipid profiles. These mechanisms might work together to control the body weight gain and improve the lipid metabolism disorderly situation [45]. The administration of BSDF decreases total cholesterol, triglyceride, and low-density lipoprotein-cholesterol by 31.53, 21.35, and 31.53%, respectively [46], exhibiting a good potential as a cholesterol-lowering ingredient or an adjuvant for functional food with anti-obesity and hypolipidemic effects [49]. Besides, BSDF can be used to enhance the pasting viscosity and viscoelasticity of rice starch. BSDF was coated on starch granules to form a protective layer that restricts the accessibility of hydrolytic enzymes to starch and reduces the extent and rate of starch digestion, improving the properties of starch and facilitating its utilization [50]. BSIDF could be used to formulate desirable physicochemical properties of starchy foods. High content and appropriate size of BIDF could cause rice starch granules to aggregate *via* strong intra- and intermolecular hydrogen bonds to form a tight honeycomb-like and dense porous structure. As a result, peak viscosity, final viscosity, hardness, and the long-term retrogradation of rice starch paste increased [51]. BSDF can improve bread in texture properties except for hardness, and had good ability to absorb cholesterol and anti-digestion properties [43].

## 5. Preparation and application of BSCNC

CNCs have many interesting structural features and unique physicochemical properties, including magnificent mechanical strength, high surface area, and many hydroxyl groups for chemical modification, low density, and biodegradability, and thus have attracted great interest from researchers in various fields of biomedical, electronic gadgets, water purifications, NC, and membranes [7–9]. A persistent progression is going on in the extraction, modification, and application of CNCs as shown in **Figure 4**. BSs have many advantages such as low content of lignin, fast growth, and wide distribution, which represent a favorable scenario for producing CNCs from BSs in low chemical and energy consumption [10]. As indicated in **Figure 5**, the degree of polymerization and crystallinity of cellulose increased with the degree of maturity of the raw bamboo samples. The cellulose nanofiber (CNF) can be obtained from immature bamboo, which

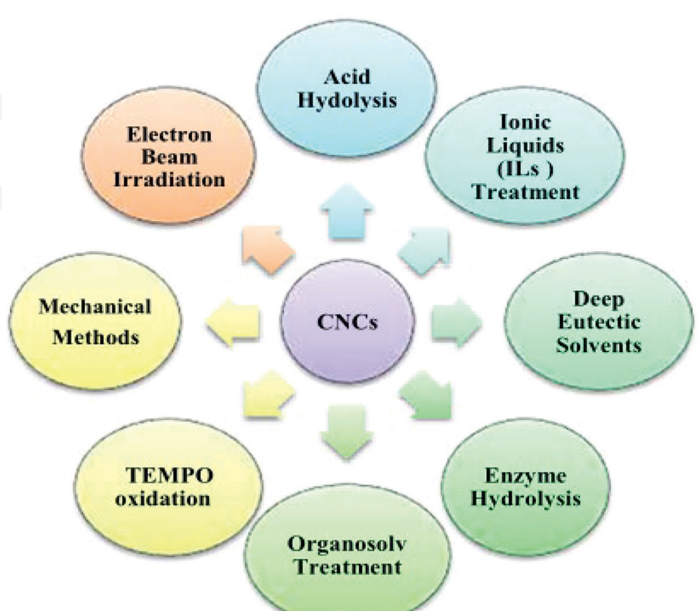


**Figure 4.**
*CNCs: Methodologies for CNCs preparation [7].*

contains <10 wt% of lignin by mild mechanical treatment. Immature bamboo can be a very promising source of raw material for the production of CNF [11]. Therefore, a biomass with less lignin may be advantageous to the production of high-performance CNF because the delignification step could be omitted from the

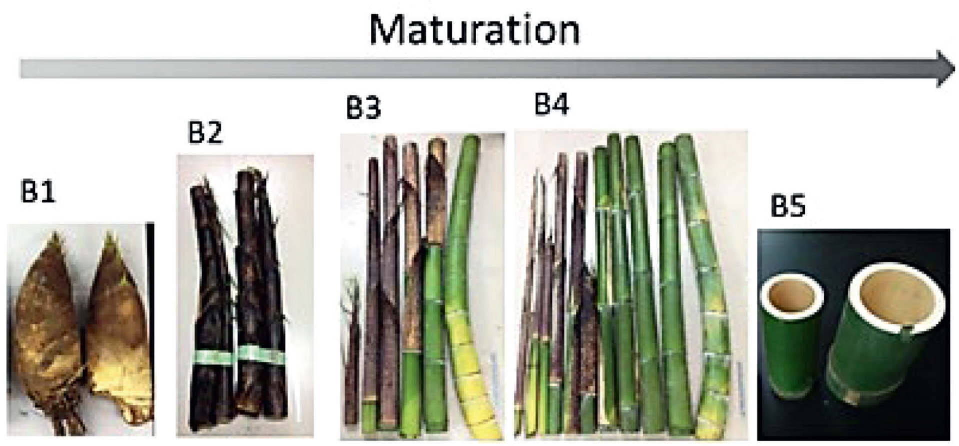


**Figure 5.**
*Pictures showing bamboo samples under different growth stages [11].*

| Method | Traits of BSCNC | Application | Ref. |
|---|---|---|---|
| Acid hydrolysis | 86.96% crystallinity and 22% yield of CNCs. | Biomedical and food packaging application | [54] |
| Combinational method (low content of sulfuric acid hydrolysis/ ultrasonic treatment) | Both CNF and CNCs displayed high crystallinity indexes of 68.51 and 78.87%. | Functional components or carriers in food and pharmaceutical fields. | [55] |
| TEMPO-mediated oxidation method | Good mechanical property and dimensional stability, 60–90 nm in the diameter of BSNC. The crystallinity increased, but the thermal stability decreased. | Filter and adsorption materials. | [56] |
| Hydrothermal treatment with NaOH and $NaClO_2$. | The least stability, its better crystallinity. | Paint formulation and nanocarriers in biomedical fields. | [34] |
| Alkali and hydrogen peroxide pretreatment | The yield of 50.67% with a crystals recovery of 77.99% | | [9] |
| Water, bleaching, and alkali treatment | 5.80 to 8.57 nm in diameter and 82.93 to 170.67 nm in length for BSNC materials. | Reinforcing PVA Films | [10] |
| Chemical and mechanical separate pre-treatment prior to sulfuric acid hydrolysis | Average widths of 134.2 + 34.33 nm. Crystallinity degrees of the nanofibrils and crystals were 49.47 and 56.92%. | Materials | [53] |

**Table 3.**
*Preparation method, traits, and applications of BSCNC.*

process [52]. However, mature bamboos contain more cellulose, which contributes to the isolation of CNCs and CNF with the use of different chemical and mechanical methods [6, 53].

As listed in **Table 3**, there are many methods to prepare CNCs from BSs. Acid hydrolysis is one of the traditional and universally used methods for the preparation of CNCs. Several mineral acids, for example, sulfuric acid ($H_2SO_4$), muriatic acid (HCl), hydrobromic acid, and orthophosphoric acid ($H_3PO_4$) were utilized for the preparation of nanocrystals [7, 10]. The mechanism for the formation of CNCs is schemed as in **Figure 6**. Non-crystalline regions of cellulose are removed by acid hydrolysis. As BSs were treated using 50% v/v $H_2SO_4$ at 50°C for 45 min, the resulting CNCs had 5.80 to 8.57 nm in diameter, 82.93 to 170.67 nm in length, and 11.89 to 21.97 in aspect ratio [10]. The extracted CNC by acid hydrolysis has a higher degree of crystallinity of 86.96% and a higher yield of 22% [54]. However, sulfuric acid hydrolysis decreased the thermal stability of CNCs [55], the extracted retained some lignin, and thus the chemical pretreatment is necessary to remove the purities prior to acid hydrolysis [53].

A combinational method has been proven to be better for the extraction of BSCNC than a single-acid hydrolysis method [55], and different combinations can lead to various effects to name a few. As BS was complexly treated by acid hydrolysis and the pretreatment using alkali and hydrogen peroxide, the optimum CNC yield of 50.67% with a crystals recovery of 77.99% was obtained at the sulfuric acid concentration of 54.73% and a temperature of 39°C. The sulfuric acid concentration has a more significant effect than the temperature. The crystals recovery of CNC higher than 70% was obtained at a sulfuric acid concentration of around 55–60%. The temperature has no significant effect on the crystals recovery of CNCs [9]. The dosage of $H_2SO_4$ is very high, which increases environmental burden. Ultrasonic treatment can reduce the dosage of acid. The combination of low-concentration acid hydrolysis and ultrasonic treatment was used to extract CNF and CNCs from BSs (*Leleba oldhami Nakal*). NFC and CNCs exhibited typical long-chain and needle-like structures, respectively.

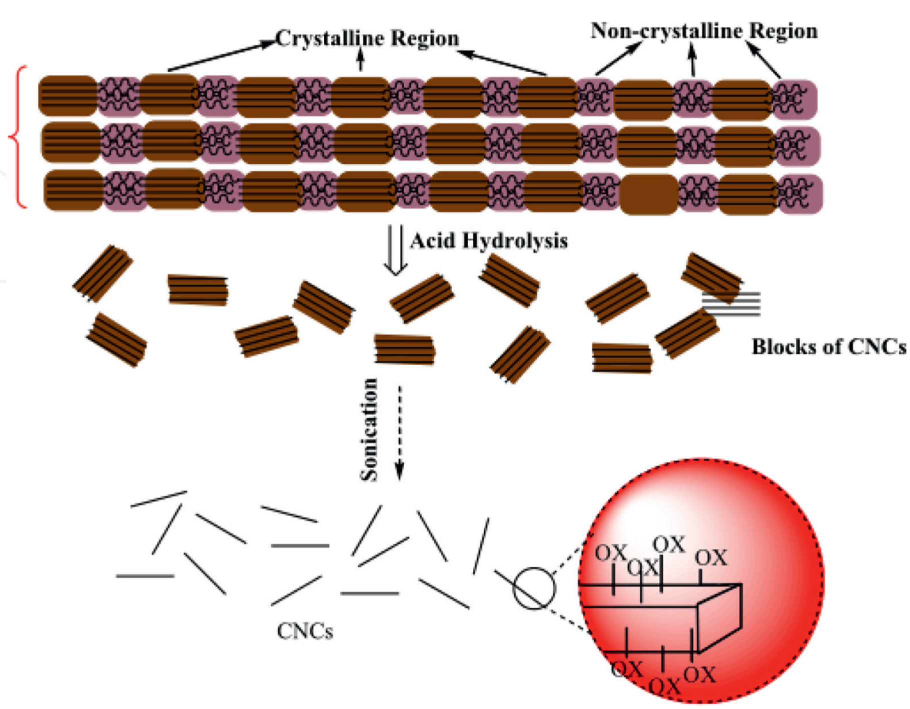


**Figure 6.**
*Schematic representation of CNC formation from cellulose acid hydrolysis [25].*

Lignin and hemicellulose were successfully removed, and both CNF and CNCs displayed high crystallinity indexes of 68.51 and 78.87% [55].

BSCNC can be potentially used in various fields. The CNCs prepared by acid hydrolysis has a high crystallinity value and a higher capability to enhance mechanical properties of polymeric composites, and thus is potentially applied in NC for biomedical and food packaging application [54]. The well-dispersed BSNC showed good reinforcement effects on the PVA matrix, and the BSNC-reinforced PVA films exhibited a tensile strength of 32.46 MPa, 53% higher than that of neat PVA film [10]. Besides, BSCNC has gained increasing interest due to its excellent properties and great potential as a functional component or carrier in food and pharmaceutical industries [55]. BSCNC showed great potential as an emulsifier in the Pickering emulsions [57]. With the increasing BSNC content, the emulsions presented increased droplet size, and even demulsification occurred. The surface coverage was above 100% for the Pickering emulsions. All emulsions showed elastic behaviors.

The modification of BSSF extends the application field. As raw material, BSSF was used to prepare self-reinforced NC composite by a simple method mediated with 2,2,6,6-tetramethylpiperidine-1-oxy (TEMPO) oxidation. Compared with the original fiber, the crystallinity of the composites increased, while the thermal stability decreased. The nanocomposite has good dimensional stability indicating the possibility for replacing hard-wood resources and the great potential for utilizing agricultural wastes. It provides a promising and convenient route to obtain film sheet materials with micro- or nano-structures from nature cellulose fibers [56]. Due to their hydrophilic tendencies, CNCs are modified to act as hydrophobic drug carriers. Rarasaponins (RSs) were attached onto BSCNCs to enhance their hydrophobicity. The curcumin uptake on CNCs-RSs reached 12.40 ± 0.24%, but it was slowly released until approximately 78% in three days [8].

## 6. Conclusion

There are increasing studies focused on the preparation methods and applications of cellulose, DF, and CNCs from BSs. The methods mainly include physical, chemical, biological, and combinations. As compared with every single method, the combinations exhibit more significant effect on the preparation and modification of BSC, BSDF, and BSCNC. With increasing emphasis on environmental protection, there will be increasing attention to novel technical processes to produce the products from BSs in order to efficient and green exploration and application of BSs. Due to various traits to be developed and applied, the extracted and/or modified BSDF have presently been applied as functional foods or food additives in food industry, and the extracted and/or modified BSCNC are used as materials in food, biomedical, pharmaceutical fields, and so on. In the future, novel modifications will continue to be created to discover some new traits of BSC, BSDF, and BSCNC, which will be developed into more new products that people need.

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