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Advancements in chemical pretreatment techniques for enhancing bamboo fiber quality in textile applications: a critical review

Abstract

Bamboo fiber has become a viable and environmentally beneficial option in the textile industry because of its sustainable qualities and appealing characteristics. Nevertheless, the inherent difficulties associated with untreated bamboo fiber, such as limited absorption of dyes and inadequate mechanical durability, need the use of efficient pretreatment methods to improve its suitability for textile purposes. This article critically analyses current improvements in chemical pretreatment procedures that seek to enhance the quality of bamboo fibers for textile applications. The usefulness of different pretreatment procedures, including alkali treatment, enzymatic treatment, bleaching, and mercerization, in changing fiber qualities is thoroughly assessed. This article examines the influence of pretreatment on many properties of bamboo fibers, such as their shape, mechanical strength, dye absorption, and process ability. In addition, the study outlines important areas of research that have not yet been explored and suggests future paths for the subject. It emphasizes the potential for innovation and cooperation to further enhance bamboo fiber pretreatment technology. In summary, this analysis enhances our comprehension of how chemical pretreatment improves the quality of bamboo fibers and encourages sustainable practices in the textile sector.

Keywords: bamboo, chemical, pretreatment, cellulose, hemicellulose, lignin

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Abbreviations: MWL, milled wood lignin; DTPA, diethylene triamine pentaacetic acid; LMwPF, phenol formaldehyde; ASE, ant shrink efficiency; MOR, mechanical modulus of rupture; SL, Semantan lignin; DMSO,dimethyl sulfoxide; SE, steam explosion; BFs, bamboo fibers; DES, deep eutectic solvent; PSA, Phenylsulfonic acid

Introduction

The textile industry has shown considerable interest in bamboo fiber because of its environmentally friendly characteristics, sustainable sourcing, and desired attributes such as softness, breathability, and antibacterial capabilities.[1] Bamboo fiber presents an appealing alternative to traditional textile materials due to the growing customer demand for ecologically aware products.[2] Nevertheless, the unprocessed bamboo fiber poses difficulties such as inadequate absorption of dyes, weak mechanical durability, and restricted capacity to undergo manufacturing processes, all of which hinder its extensive use in textile applications.[3] To overcome these constraints and fully use the capabilities of bamboo fiber, it is necessary to employ efficient techniques for pretreatment that will increase its quality and performance.[4] Considerable research and development have been conducted recently to improve chemical pretreatment methods especially designed for bamboo fibers.[5] The purpose of these procedures is to alter the surface qualities of the fiber, boost its mechanical strength, improve its capacity to absorb dyes, and optimize its overall adaptability for different textile processes.[6] A wide variety of pretreatment techniques, including enzymatic procedures, bleaching techniques, and alkaline treatments, have been investigated to address the special qualities and difficulties related to bamboo fiber.[7] This paper analyses the most recent developments in chemical pretreatment methods aimed at enhancing the quality of bamboo fibers for utilized in textile applications.[8] The present investigation looks for to give an understanding of the ideal techniques for maximizing bamboo fiber performance and usefulness in the textile sector by thoroughly assessing the effectiveness, benefits, and limits of various pretreatment methods.[9] In addition, the investigation identifies significant areas of research that have not been explored yet and suggests future possibilities in the field. It emphasizes the potential for creativity and cooperation to further enhance bamboo-fiber pretreatment technology.[10] This research contributes to the ongoing efforts to promote sustainable and ecologically responsible practices in the textile industry by conducting a comprehensive analysis of the latest pretreatment techniques and their impact on bamboo fiber qualities.[11]

Chemical composition of bamboo

Bamboo consists of three primary chemical components: cellulose, hemicelluloses, and lignin. These components are intricately interconnected inside a complex structure.[12] They account for around 90% of the overall bamboo biomass. The minor constituents consist of colors, tannins, protein, fat, pectin, and ash. Additional examples encompass resins, waxes, and inorganic salts. The elements mentioned have a significant impact on the physiological activity of bamboo. They can be located either in the cell cavity or in specialized organelles.[6] Bamboo contains a chemical structure comparable to wood, although it contains a greater proportion of minor components in comparison to wood.[13] Li et al.[14] provided the chemical composition of bamboo fiber, which may be seen in Table 1. Typically, the chemical makeup of bamboo varies based on its age. Significantly, the cellulose content of bamboo diminishes as it ages. Various scholars have examined various kinds and different components of bamboo. The bamboo from Kumamoto, Japan, has a cellulose content of 47%, hemicelluloses content of 23%, and lignin content of 28%.[15] The composition of bamboo consists of 43% cellulose, 15% hemicelluloses, and 26% lignin.[16] The bamboo species Dendrocalamus has cellulose at a concentration of 47%, hemicelluloses at 16%, and lignin at 18%.[17]

Moso bamboo (Phyllostachys heterocycla), with cellulose 2–47%, hemicelluloses 22–23% and lignin 23–31%.[18] The bamboo shoots shell fibre (BSSF) has 23% cellulose, 14% hemicelluloses, and 11% lignin. On the other hand, the bamboo stem and leaf (BSL) contains 21% cellulose, 12% hemicelluloses, and 12% lignin.[19]

Table 1 Chemical composition of bamboo fiber[14]

SL No	Chemical constituents percentage	Percentage
1	Cellulose	73.83
2	Hemicellulose	12.49
3	Lignin	10.15
4	Aqueous Extract	3.16
5	Pectin	0.37

Chemical modification of bamboo

Bamboo fibers are being increasingly used as a sustainable substitute in several sectors because of their environmentally favorable characteristics. Nevertheless, in order to enhance their efficiency, chemical pretreatment methods are frequently utilized. The objective of these methods is to eliminate non-cellulosic elements like lignin and hemicellulose, thereby enhancing the flexibility of the fibers, their ability to absorb liquids, and their capacity to take up dyes. Furthermore, the application of chemical pretreatment can alter the surface characteristics of bamboo fibers, hence improving their compatibility with other materials and promoting adhesion in composite constructions. This technique guarantees that bamboo fibers satisfy the rigorous demands of several industries, such as textiles, construction, and automotive sectors.[20] Significant research and technological studies have been conducted to chemically modify bamboo fibers to enhance their qualities for specific uses. Chemical modification techniques includes alkali hydrolysis, acid hydrolysis, coupling, and other procedures.[21–24] Bamboo lignin is more reactive during pulping and other pretreatment processing because it has more phenolic hydroxyl groups than wood lignin.[25] The presence of these hydroxyl functional groups directly boosts the chemical reactivity of bamboo lignin in a range of chemical processes when combined with other appropriate substances. Moreover, it exhibits improved responsiveness throughout the extraction procedure.[26] There are several ways to carry out the lignin extraction process, including mechanical, chemical, enzymatic, and physical methods.

Different forms of lignin, such kraft lignin, klason lignin, hydrolytic lignin, organosolv lignin, alkali lignin, lignosulfonates, and milled wood lignin (MWL), can be created depending on the extraction techniques used. The technical lignin products' cross-linked structure and molecular weight distribution are influenced by the extraction procedure. Moreover, lignin may be utilized to create biopolymers and biochemical suchs as epoxy resins, polyurethane resins, carbon fiber surfactants, and dispersants.[27]

Alkaline pretreatment

Alkali hydrolysis is a conventional process. The procedure involves chemically treating raw cellulose fiber to eliminate lignin and amorphous areas. It generates a coarse texture on the fiber, stimulates hydroxyl groups, and enhances the tensile strength of the fiber. The primary step in this process is the use of an alkali solution sodium hydroxide (NaOH) to eliminate both the cellulosic and noncellulosic constituents, including hemicellulose, lignin, and pectin, present within the plant fiber.[28] The fibers that have been treated with alkali are then subjected to multi-phase bleaching. The majority of firms employ this procedure due to its efficiency in producing bamboo fibers in a short amount of time and at a lower cost, particularly when compared to mechanical processes. The authors Kumar et al.[29] in their study, soaked bamboo strips in 4% NaOH for 72 h to extract the fiber. This method removed 38–42% of the polysaccharides and lignin from the bamboo chips. The obtained pulp was cooled, filtered and washed, and then further treated with glacial acetic acid. Sodium chlorite was occasionally used to bleach the fiber to white. The treated pulp was called bleached bamboo fiber. The problem with this method was that fiber bundles with diameters of 100±10.4 μm were also formed during the extraction; therefore, the parameters were chosen to optimize separation of bamboo fiber by using a minimum amount of NaOH.[30]

Kumar et al.[31] conducted research and found that the distinctive qualities of mercerized bamboo fibers, which are utilized to make bamboo fiber-reinforced epoxy composites, make these bio composites economically viable for dielectric applications. In a separate and noteworthy investigation conducted by Kumar and Kumar,[32] it was shown that subjecting bamboo fiber to alkali treatment resulted in a significant enhancement of both the tensile and flexural strength of bamboo-epoxy nanocomposites. Specifically, the tensile strength rose by 60% and the flexural strength improved by 42% when compared to the strength of pure composites.

Several researchers have conducted studies on the physical, mechanical, and thermal characteristics of composites made from novolac resin reinforced with bamboo fibers that have undergone mercerization. These studies have focused on the weathering behavior, water absorption percentage, thickness swelling percentage, thermal stability, morphological qualities, and impact test of the composites. According to their findings, the alteration enhanced many characteristics of the composites, including fine structure, impact strength, wetting ability, interfacial strength, mechanical capabilities, weathering resistance, and thermal properties.[33–35] The study revealed the impact of acrylic acid-grafted bamboo rayon on the antibacterial properties of acrylic acid-grafted bamboo rayon silver nanoparticles.[36] An antibacterial composite fabric consisting of bamboo rayon and copper nanoparticles was created by using acrylic acid-grafted bamboo rayon. Both Gram-positive and Gram-negative bacteria exhibited durability up to 50 washings.[37]

A separate investigation documented the impact of alkaline and acetylating chemicals on the structure of bamboo fiber-polypropylene.[38] Their mechanical, thermal, rheological, morphological, and miscibility characteristics were thoroughly investigated. The alkaline and acetylating treatments resulted in better mechanical characteristics of bamboo fiber-polypropylene composites and improved adhesion between bamboo fiber and the polypropylene matrix.

A technique involving the use of HNO_3-$KClO_3$ has been employed to extract fiber from samples of bamboo. Prior to the introduction of $KClO_3$, the dried bamboo strands were soaked in a weak nitric acid solution.[39,40] Following a 24-hour treatment at a temperature of 50°C, the resulting suspension of bamboo fibers was subsequently cooled and subjected to dialysis using distilled water in order to eliminate low molecular weight molecules. The slurry was subsequently subjected to freeze-drying in order to get bamboo fiber in a dry state.

He et al.[41] proposed a complex technique for acquiring bamboo fiber. Crude fiber bundles of bamboo, derived from bamboo chips that were heated at 150°C for 30 minutes, were initially soaked in water at 60°C for 24 hours. They were subsequently dried in the air and impurities were eliminated via repetitive rolling. Afterward, the fiber bundles were subjected to heat treatment using solutions containing 0.5% NaOH (w/v), 2% sodium sulphite, 2% sodium silicate, and

2% sodium polyphosphate for about 60 minutes at a temperature of 100°C. The ratio of liquor to bamboo was 20:1. The fibers underwent a hot water wash, followed by treatment with 0.04% xylanase and 0.5% DTPA (diethylene triamine pentaacetic acid) at a temperature of 70°C for a duration of 60 minutes, maintaining a pH of 6.5. The fibers were subsequently subjected to a heat treatment at a temperature of 100°C for about 60 minutes, with the exception of employing 0.7% NaOH. During the bleaching process, the bamboo fiber was immersed in a polyethylene bag containing a solution of 4% hydrogen peroxide (H_2O_2), 0.2% sodium hydroxide (NaOH), and 0.5% sodium silicate (Na_2SiO_3) for a duration of 50 minutes. The alcohol concentration was 20, and the pH level was controlled at 10.5. The refined bamboo fiber was produced by subjecting it to a 0.5% Sulphuric acid solution treatment for 10 minutes, followed by emulsification for 5 days. Past investigations have shown that treating bamboo-epoxy composites with Maleic anhydride enhances their mechanical characteristics, namely the modulus of elasticity and flexural modulus. Additionally, it improves the water-resistant capabilities of the composites, as indicated by reduced water absorption.[42] The characteristics of polyester composites made of bamboo fiber and benzoylation and permanganate showed a similar pattern.[43] A separate research documented the process of creating polypropylene composites reinforced with short bamboo fibers. The bamboo fibers used in the study were chemically changed, and different percentages of these fibers were added to the composites.[44] The selection of maleic anhydride-grafted polypropylene as a compatibilizer was made in order to enhance the adhesion between the fiber and matrix.

Phenolic pretreatment

Anwar et al.[45] is provided. A study on bamboo strips treated with low molecular weight phenol formaldehyde (LMwPF) resin demonstrated considerable improvements in their physical and mechanical qualities. The strips were immersed in LMwPF resin for a duration of 1 hour, subsequently subjected to drying at a temperature of 60°C for a period of 6-9 hours, and finally subjected to hot pressing at a pressure of 14 kg/m² and a temperature of 140°C for a duration of 5-17 minutes. The treated bamboo exhibited a substantial enhancement in dimensional stability, particularly following a 5-minute pressing duration. The ant shrink efficiency (ASE) increased as the pressing duration was extended, reaching its maximum at 17 minutes. The mechanical modulus of rupture (MOR) and modulus of elasticity (MOE) both rose, but the compression strength parallel to the grain remained essentially unaltered. The study proposes that the application of LMwPF resin treatment has the potential to enhance the durability and stability of bamboo, hence expanding its suitability for a wide range of applications.[45]

Microwave-assisted organic acid pretreatment

Li et al.[46] examined the structure and antioxidant activity of bamboo lignin by means of microwave-assisted organic acid extraction. After allowing the bamboo stem to air dry, a solution was made by combining water, 6% HCl, acetic acid, and formic acid. The mixture was washed, dried, and microwaved. Lignin's molecular weight and carbohydrate content dropped as extraction increased, while its phenolic hydroxyl component increased. It was discovered that lignin had a greater antioxidant activity than butylated hydroxytoluene.[46]

Ethanol organosolv pretreatment

The structural change of bamboo lignin before and after ethanol organosolv pretreatment was studied by Bai et al.[47] To create powder, they utilized three-year-old Dendrocalamus brandisii bamboo, which they physically crushed. After that, the powder was treated in the Soxhlet apparatus with a 2:1 v/v mixture of toluene and ethanol to perform the extraction procedure for eight hours. Ethanol organosolv was used to pretreat the bamboo sample using a 70% (v/v) aqueous ethanol solution at 180 °C for two hours at a solid to liquid ratio of 1:10 throughout this process. After the bamboo had been processed, it was filtered and stored to dry. The lignin, cellulose, and hemicellulose residues were eliminated by the ethanol organosolv pretreatment. According to the study, the extracted MWL ideally has S, G, and H units arranged in a G > S ≫ H fashion. Spectroscopic observations revealed that bamboo's ethanol organosolv treatment consisted of β-aryl ether linkages. Most of the organized cellulose remains undigested throughout the ethanol organosolv pretreatment, with the main debased combinations being lignin, hemicelluloses, and less arranged cellulose. It was discovered that the processed wood lignin that was removed from the original bamboo was HGS lignin, which has a G > S ≫ H ratio. The spectroscopic results suggested that the cleavage of β-aryl ether securities is often elaborated by the ethanol organosolv treatment of the bamboo material.[48]

Formic acid delignification and alkaline hydrogen peroxide pretreatment

Li et al.[49] investigated the structural characterization of bamboo lignin separated using alkaline peroxide and formic acid using pyrolysis gas chromatography–mass spectrometry technology and gel permeation chromatography. They started by delignifying bamboo by treating it with an alkaline H_2O_2-formic acid solution to eliminate lignin, cellulose, and hemicelluloses. Formic acid (3000 ml, 88 wt %) was applied to the delignified bamboo and allowed to sit at room temperature for two hours. Next, the pulp was obtained by filtering.[49]

After that, the pulp was dried and cleaned using a solution of water and formic acid. The resultant residue is referred to as the formic acid pulp. After that, the previously produced formic acid pulp was treated for one hour at 80 °C with 20 ml/g by adding 1% H_2O_2 and 1% NaOH. Moreover, water and 1,4-dioxane were used to isolate the MWL. After the 100 ml water precipitation, the filtrate was heated to 40 °C and filtered using 10 ml of acetic acid (9/1, v/v). The resulting lignin, which corresponded to the isolated lignin produced by delignification with formic acid and H_2O_2 treatment, was then dried using 10 ml of ethanol.

The lignin that was collected was examined using a number of advanced methods, including FTIR. The lignin recovered from the treated and untreated bamboo testing was subjected to FTIR spectra analysis, the results of which are presented in Figure 1. The range of the spectra showed that following the treatments, the lignin in the bamboo underwent certain changes. While the top at 1655 cm−1 is related to produced p-subbed aryl ketones, the bottom at 1719 cm−1 is assigned to the C=O stretch in carbonyl, un-formed ketones, and ester groups. The aromatic vibrations are associated with the band at 1510 cm−1, whereas the C–H deformation and asymmetrical vibration in CH_3 and CH_2 are related to the band at 1460 cm−1.The vibrations of the aromatic rings are the source of the sign at 1420 cm−1. The C and G ring condensation (G ring substituted in C-5 position) is seen in the band at 1326 cm−1. At 1224 cm−1, the top displays C–C, C–O, and C=O (G dense > G etherified) extensions. The aromatic in-plane C–H bending is predicted to be represented by the peaks at 1127 and 1034 cm-1. The signals in the range of 1597 and 836 cm−1 were identical, suggesting that the treatment had no effect on the lignin's core structure.

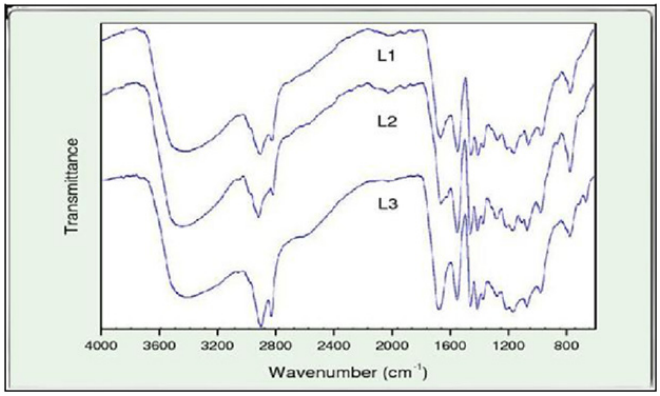

Figure 1 FTIR spectra of lignin isolated from bamboo.[49]

Hydrotropic pretreatment

Mou et al.[50] investigated After being treated with 30% (w/w) sodium xylene sulfonate and 2% (w/w) formic acid at 160°C for 90 minutes, the milling moso bamboo samples had an 8:1 solid to liquor ratio (S/L). 15% (w/w) fresh SXS was used to wash the solid substrate following pretreatment. Solution, followed by a distilled water wash. The cleaned sample was then kept for further enzymatic hydrolysis at -2°C. The process of recovering lignin from the wasted solution was previously discussed. To remove lignin and xylose from the cell wall of bamboo fiber, hydrotropic pretreatment is a workable technique. With pretreatment procedures, however, the effects on surface chemical compositions differed. Pretreatments altered the amount of surface lignin reduction, perhaps increasing enzymatic accessibility. Additionally, using various pretreatment techniques, the isolated lignin structure was altered.[50]

Enzymatic hydrolysis of avicel pretreatment

Wu et al.[51] investigated the impact of ethanol organosolv lignin from bamboo on the enzymatic hydrolysis of Avicel. They took 20 g of bamboo meals from Pleioblastus amarus (P. amarus) and Dendrocalamu sinicus (D. sinicus) and soaked them in ethanol solution (75%) and sulfuric acid (1%, w/w) for an overnight period. They then transferred the mixture containing bamboo meals and liquor to a micro autoclave and heated it for 60 minutes at 170 °C. They carried out an extraction process to isolate MWL by suspending the dioxane/water (96:4, v/v) and isolated at 25 °C in dark conditions for 24 hours. The mixture was then filtered and cleaned.

After that, the filtrate was placed on a rotator evaporator, dried, and subjected to an acidification procedure to produce MWL, which is similar to native lignin. It was reported on the enzymatic saccharification and the impact of ethanol on organosolv lignin's.[51]

Soda pulping method pretreatment

Osman and Ahmad et al.[52] used the soda pulping method in an autoclave with maximum pressure and temperature to extract lignin from two species of Malaysian bamboo: Semantan (Gigantochloa scortechinii) and Beting (Gigantochloa levis). According to SEM research, there are similarities between Semantan lignin (SL) and Beting lignin (BL) with regard to their functional groups, which are mostly made up of guaiacyl (G) and syringyl (S) types of lignin. Because of its strong durability at high temperatures combined with its relatively low glass temperature, bamboo lignin is likely a great source material for lignin phenol–formaldehyde fixatives, where phenol is partially replaced. The process for extracting lignin from bamboo is shown in Figure 2.

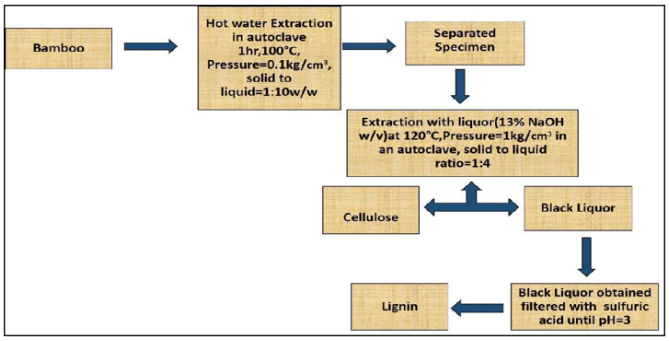

Figure 2 Bamboo fiber is extracted via soda pulping through two stages of treatment using hot water and 13% NaOH.[52]

The chemical and thermal properties of the lignin extracted from bamboo culms using the soda pulping process have been investigated. Different sources of lignin can have substantially distinct physicochemical characteristics.

ATR-FTIR spectroscopy revealed that all of the soda lignin derived from Malaysian bamboo had a high relativeness with respect to the functional groups. Semantan Gigantochloa scortechinii and Beting-Gigantochloa levis, two bamboo species used in this study, were initially obtained from Peninsular Malaysia and allowed to air-dry for two to three weeks. A 13% w/v aqueous sodium hydroxide solution was used to extract lignin. In an autoclave, hot water was used to isolate the bamboo specimens for a duration of one hour at 100°C. Following lignin separation, 13% NaOH was added and heated to 120 °C in a closed vessel for 1 hour, resulting in a 1:4 solid to liquid ratio. Additionally, the detection was carried out in an atmosphere full with N_2.[52]

Dioxane and dimethyl sulfoxide pretreatment

Xu et al.[53] investigated the structural characteristics of the lignin isolated from Dendrocalamus sinicus in order to gain large-scale practical applications in value-added goods. Following treatments with dioxane and dimethyl sulfoxide (DMSO), two lignin fractions were recovered from dewaxed and ball-milled bamboo samples: MWL (milled wood lignin) and DSL (dioxanesoluble lignin). Initially, the ball-milled and dewaxed bamboo was suspended in 96% dioxane for 48 hours at room temperature. To extract the MWL, the process was done in a N_2 atmosphere. Three volumes of 95% ethanol were employed in the rotary evaporator for the purification process in order to lower the hemicellulose level. In order to create biochemicals, polymeric materials, biofuels, and multifunctional polymer nanocomposites, it is a high-scale bio-imposed precursor. The results showed that 52.1% lignin could be obtained from the two-step treatment, depending on the total amount of lignin in the dewaxed bamboo test. P-hydroxyphenyl, guaiacyl, and syringyl units were the three basic components that made up bamboo lignin. Together with reduced amounts of β-β′, β-5′, and β-1′ links, the acquired bamboo lignin had considerable inter-unit connections introduced by the β-O-4′ aryl ether linkages. Subsequently, it was shown that tricin in bamboo was linked to the lignin polymer via the β-O-4′ bond.[53]

Dioxane and ethanol pretreatment

Zhu et al.[54] conducted research and proposed that the lignin content of bamboo varies with age, which is crucial for their application in a variety of industries. The bamboo used in the experiment was first peeled off and then squeezed to a size of 40 meshes. The resulting particles were then dried at 55 °C. The first step involved isolating

and drying 20 g of bamboo specimens of varying ages for 2.5 hours in a planetary ball mill set at 300 rpm with 1 cm of zirconium balls. Next, the dried bamboo was combined with 96% dioxane at a weight-to-volume ratio of 1:20 and heated to 100°C for 2.5 hours. After the reaction is finished, the liquid is separated from the solid by employing a concentrated rotatory evaporator. For a whole day, three volumes of 95% ethanol are poured dropwise in order to remove too much hemicellulose. Following the procedure, 10 liters of acid water (pH = 2, hydrochloric acid) were mixed with the concentrated liquid dropwise in order to precipitate the required lignin. The solid that precipitated was freeze-dried in order to extract the necessary lignin components.[54]

Biochar-catalytic degradation pretreatment

Tayier et al.[55] investigated the catalytic breakdown of lignin by bamboo biochar when heated to microwave temperatures. Initially, they combined 0.5 g of organosolv lignin with 20 ml each of ethanol and formic acid (1:1, v/v). After that, it was heated to 180 °C for 30 minutes while the microwave power was set at 650 W. Following the completion of the reaction, the samples were allowed to cool to room temperature. The filtrate was then washed by adding 100 milliliters of ethyl acetate until it turned colorless. The ethyl acetate result was once again cleaned with tetrahydrofuran until it lost color. After that, it was dried at 105 °C in a vacuum environment to extract the lignin residue.[55] The GPC spectra of lignin residue are displayed in Figure 3.

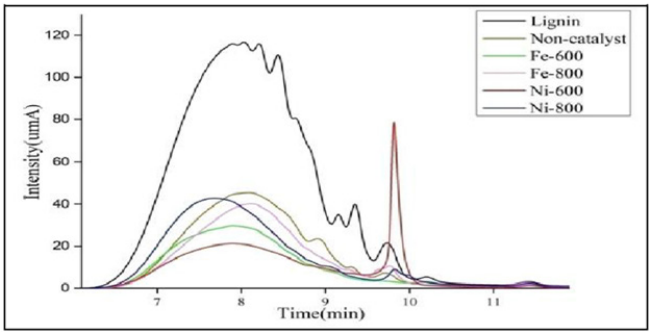

Figure 3 GPC spectra of lignin residue.[55]

Hydrothermal pretreatment

Using Pleioblastus amarus bamboo species, Yang et al.[56] examined the effects of hydrothermally processed bamboo lignin on cellulose saccharification for the synthesis of bioethanol. First, pretreated P. amarus was separated for 24 hours at 25°C using dioxane and water. After filtering, the mixes were cleaned. To prepare lignin, they dried, rinsed, and then dried it one more in a vacuum oven. Based on temperature, they designated the obtained lignins HPL160, HPL180, and HPL200, with total lignin contents of 89.1, 87.1, and 88.7%, respectively. They said that the resulting lignins had S/G units and that the hydrothermal pretreatment method had decreased the ratio, making the lignins hydrophobic. It was shown that HPL 200 had a significant concentration of phenolic hydroxyl groups. Additionally, it was observed that the lignin from bamboo had a negative effect on enzyme saccharification, which is advantageous for the production of biomaterials and biofuels.[56]

Steam explosion pretreatment

The investigation[57] examined the characteristics of bamboo fibers (BFs) that were prepared through the process of steam explosion (SE) subsequent to being subjected to pretreatment using enzyme, alkali, and salt. Various pretreatments prior to SE resulted in the partial elimination of lignin and hemicellulose from BFs, with alkali pretreatment showing the most favorable impact on lignin removal. The BFs exhibited the highest level of crystallinity when subjected to alkali pretreatment at a pressure of 2 MPa and a duration of 6 minutes. The crystal structure of the BFs did not undergo significant changes as a result of the pretreatment. Alkali and salt pretreatments led to a decrease in carbohydrate content and an increase in lignin and extractives content on the surfaces of BFs. With an increase in pressure holding time, the lignin content on the surface of BFs that were pretreated with alkali initially decreased and then increased, while the cellulose and hemicellulose content exhibited the opposite behavior. The findings suggest that the combination of alkali pretreatment and SE can effectively modify the characteristics of bamboo fibers, including lignin removal and alterations in crystallinity and surface chemical elements.[57]

Deep Eutectic Solvents (DES) pretreatment

Yan Su et al.[58] examined a viable pretreatment strategy that addressed the refractory character of poplar sawdust and enabled efficient enzymatic hydrolysis and lignin valorization. The strategy used a biomass-derived deep eutectic solvent (DES) made of choline chloride and lactic acid. The results demonstrate the high selectivity of DES in the removal of lignin and xylan, while maintaining the integrity of cellulose. The most effective parameters for pretreatment, including a DES ratio of 1:2, a temperature of 130°C, and a period of 1.5 hours, result in a significant glucose yield of 75.8% after enzymatic hydrolysis. The assessment of the extracted lignin demonstrates desirable attributes, such as a molecular weight range of 4000–6000 g/mol, low polydispersity (PDI < 2.0), limited presence of β-aryl-ethers without recondensation, and a significant amount of phenolic OH groups. Furthermore, the lignin demonstrates exceptional antioxidant prowess, suggesting its potential as a polyphenolic antioxidant. This study highlights the need of a developing biorefinery technology that efficiently separates and utilizes lignocellulosic biomass.[58]

Tailoring et al.[59] propose the use of Deep Eutectic Solvents (DES) as an environmentally benign method for pretreating bamboo. This strategy aims to selectively extract lignin and cellulose from biomass in a two-step process, promoting targeted and sustainable separation. Initially, a ternary deep eutectic solvent (DES) consisting of maleic acid (MA), choline chloride (ChCl), and ethylene glycol (EG) is employed for processing, leading to the production of lignin with a less compacted arrangement. The lignin produced has comparable characteristics to milled wood lignin (MWL) when subjected to particular circumstances (MA/ChCl/EG ratio of 1:5:15, temperature of 80°C, duration of 10 hours). Additionally, the recovered deep eutectic solvent (DES) showed favorable cycle performance. During the second phase, the cellulose-rich residue undergoes catalytic hydrogen lysis utilizing a solvent mixture of isopropanol and water, together with a catalyst called Raney nickel. This process yields cellulose with a purity level above 94%. The cellulose undergoes enzymatic hydrolysis, resulting in a glucose yield of 243.72 mg/g, which is 14.7 times more than untreated poplar. In summary, this study represents a notable progress in the efficient segregation of biomass constituents, with possible ramifications for the development of sustainable biorefinery procedures.[59]

Metal salt-based deep eutectic solvent (DES) pretreatment

The researchers Chen et al.[60] examined the capability of metal salt-based deep eutectic solvents (DES) to pretreat moso bamboo and improve its enzymatic hydrolysis. They focused on the limited development of this method and the unresolved issue of how

hydroxyl groups in choline chloride (ChCl) affect chloride ions. A type IV DES, consisting of a combination of metal salt and glycerol (Gly), was created. Its efficacy was evaluated using a Box-Behnken design to establish a relationship between enzymatic hydrolysis and the levels of hemicellulose and lignin. The results indicate that the FeCl3-based deep eutectic solvent (DES) demonstrates the most favorable performance compared to other compositions of DES. The FeCl3/Gly pretreatment has notable effectiveness in the removal of hemicellulose and lignin, resulting in a solid recovery rate of 55.54%. This is in contrast to the ternary DES pretreatment (with ChCl) conducted at mild circumstances (100°C, 3 hours). When exposed to high temperatures (specifically 120°C for a duration of 2 hours), a significant reduction in hemicelluloses (76.07%) and lignin (62.77%) takes place, resulting in extensive damage to the structure of the processed residue. As a result, the glucose production increases to 91.13% after enzymatic hydrolysis, suggesting that the hemicellulose concentration has a notable impact on enzymatic hydrolysis after the FeCl3/Gly pretreatment. This study explores the capability of metal salt-based deep eutectic solvent (DES) pretreatment to enhance the conversion of moso bamboo into valuable products under gentle settings.[60]

Phenylsulfonic acid (PSA) pretreatment

Xianqing Lv et al.[61] examined the potential of poly(N-vinylcaprolactam) (PNVCL) as a new addition to improve the efficiency of enzymatic hydrolysis in Phenylsulfonic acid (PSA) pretreated bamboo substrates. PSA pretreatment efficiently eliminates non-cellulosic constituents from bamboo, however the presence of deposited lignin can impede the effectiveness of enzymatic hydrolysis by causing non-productive adsorption of enzymes. PNVCL demonstrated superior performance compared to routinely utilized additions such as lignosulfonate and polyvinyl alcohol, and exhibited similar effectiveness to potent additives like Tween 20 and bovine serum albumin. When used at a concentration of 1.2 g/L in enzymatic hydrolysis, PNVCL resulted in an 80% conversion of cellulosic material by enzymes and decreased the amount of cellulose needed by a factor of three compared to not using any additive. PNVCL was shown to obstruct lignin residues by means of hydrophobic interactions. Consequently, the resultant PNVCL coating prevented cellulose adsorption by either electrostatic repulsion or hydration. This pragmatic methodology shows potential for improving the efficiency of enzymatic hydrolysis of lignocellulosic materials, thus leading to higher productivity and profitability in biorefineries.[61]

γ-valerolactone (GVL)/H_2O pretreatment

Yawei Zhan et al.[62] evaluated the performance of the pretreated bamboo substrates in terms of chemical composition, structural characteristics, and potential for bioethanol production. They investigated the effectiveness of the γ-valerolactone (GVL)/H_2O pretreatment system on bamboo (Neosinocalamus affinis) for enzymatic hydrolysis and ethanol fermentation. The findings demonstrate that the optimal cellulose-to-glucose conversion yield (CGCY) reached 73.39% and the cellulose-to-ethanol conversion yield (CECY) reached 67.00% when the reaction was conducted at a temperature of 140°C for a duration of 2 hours, using a GVL:H_2O ratio of 8:2. The output potential of bioethanol from bamboo is 183.5 kg per ton, which is a 9.71-fold increase compared to the conversion of untreated bamboo powder. Furthermore, these circumstances allow for the recovery of 50.60% of active lignin, which may then be used for high-value purposes. The highest concentration of fermentation inhibitors produced after pretreatment was around 140.9 mmol L−1, causing mild inhibition on subsequent processes. In summary, the study showcases the successful extraction of cellulose from bamboo and its subsequent transformation into bioethanol by the utilization of the GVL/H_2O pretreatment system.[62]

Synergistic pretreatment

Chang et al.[63] examined the process of fractionating lignocellulose into separate components with the goal of effectively using them. The technique entails utilizing hydrothermal pretreatment (HP) to break down hemicellulose, followed by delignification using a deep eutectic solvent (DES) made up of choline chloride and lactic acid. This process finally enables the enzymatic hydrolysis of cellulose residue. After subjecting the material to hydrothermal treatment at a temperature of 180°C for a duration of 35 minutes, a remarkable removal of 88.6% of hemicellulose was obtained. Additionally, the yield and purity of xylo-oligosaccharide reached 50.9% and 81.6%, respectively. Following the application of DES treatment at a temperature of 140°C for a duration of 2 hours, there was a significant reduction in lignin content, with 79.1% of lignin being removed. The regenerated lignin exhibited exceptional antioxidant activity, with a purity level of 96.8%. Although the radical scavenging activity of DES decreased somewhat after five recycling runs, this can be attributed to a drop in the ratio of Syringyl units to guaiacyl units. Nevertheless, the lignin still retained its exceptional antioxidant characteristics. Furthermore, the enzymatic digestibility of the residue treated with a two-step process was considerably higher than that of the residue treated with a single high-pressure process and the untreated green bamboo. This emphasizes the effectiveness of the combined pretreatment in overcoming the resistance of lignocellulosic materials and enabling their valuable usage.[63]

Current status and challenges

The chemical pretreatment of bamboo is a crucial field of study because bamboo has great promise as a sustainable and renewable resource for a range of uses, such as building, textiles, and composite materials. The present state of chemical processing of bamboo showcases notable progress in improving its physical and mechanical characteristics, rendering it a feasible substitute for conventional materials such as wood and synthetic fibers. One of the main difficulties in using bamboo is its natural qualities, including a high amount of lignin and strong bonding between fibers and the matrix. These properties restrict its ability to be processed and limit the variety of applications it may be used for. Chemical pretreatments, including as alkali treatment, bleaching, and acetylation, have been thoroughly researched and utilized to address these constraints. An alkali treatment has proven to be highly effective in strengthening the interfacial bonding between bamboo fibers and matrix materials in composites, hence improving the mechanical characteristics of the final products. Bleaching techniques are utilized to eliminate pigmentation and contaminants, hence enhancing the visual appeal and consistency of bamboo fibers for textile purposes. The chemical processing of bamboo is crucial for its incorporation into many industrial applications, capitalizing on its renewable characteristics and mechanical strength. Modern research has made significant progress in utilizing chemical pretreatments such as alkali treatment, bleaching, and acetylation to better the compatibility of bamboo with polymers, boost its mechanical qualities, and expand its applications beyond conventional usage.[64] These treatments enhance the surface qualities of bamboo, decrease the amount of lignin present, and change the crystalline structure of cellulose, resulting in improved adhesive properties and increased durability.[65] Notwithstanding these progressions, several obstacles impede the extensive use of chemically pretreated bamboo. An important issue is the environmental impact of

chemical pretreatments, which frequently employ harmful solvents and produce dangerous by-products, therefore

requiring the investigation of more environmentally friendly options.[66] The diversity of bamboo, which is affected by variations in species and growing circumstances, introduces difficulty to the standardization of pretreatment procedures, so affecting the uniformity of the final products.[67] Furthermore, the capacity of various pretreatment procedures to be scaled up presents economic difficulties, since many processes need a significant amount of manpower and are not financially viable for large-scale manufacturing.[68] The careful equilibrium between efficient pretreatment and the conservation of bamboo's innate structural integrity is crucial, since too forceful chemical treatments might deteriorate its mechanical characteristics.[69]

The main obstacles in bamboo usage are its inherent natural characteristics, including a high lignin concentration and strong fiber-matrix bonding, which restrict its ability to be processed and limit its variety of applications. Chemical pretreatments, including as alkali treatment, bleaching, and acetylation, have been thoroughly researched and utilized to address these constraints. Alkali treatment, for instance, has demonstrated substantial effectiveness in increasing the interfacial bonding between bamboo fibers and matrix materials in composites, boosting the mechanical characteristics of the final products. Bleaching procedures are utilized to eliminate pigmentation and contaminants, enhancing the visual appeal and consistency of bamboo fibers for textile purposes. Nevertheless, there are still several obstacles that remain in the chemical preparation of bamboo. An important concern is on striking a balance between ensuring adequate treatment and maintaining the natural strength and flexibility of bamboo. Excessive treatment can cause a deterioration of mechanical qualities, whilst insufficient treatment may not effectively address the constraints. Moreover, the utilization of aggressive chemicals and the management of waste products generated during the pretreatment procedures provide substantial environmental obstacles. Hence, the investigation of environmentally safe and sustainable chemical pretreatment techniques is an essential and active field of study. Chemical pretreatment procedures present additional difficulties in terms of scalability and cost-efficiency. Several of the existing techniques require significant manual effort and may not be financially feasible for widespread use in industrial settings. Moreover, the diversity among bamboo species and their distinct characteristics necessitate customized pretreatment methods, which makes standardization attempts more challenging.

Future work

A significant amount of research has been conducted on the advancement of pretreatment methods to enhance the digestibility of biomass, hence facilitating the conversion of biomass into cellulosic pretreatment. An optimal, economically efficient pretreatment process may possess several desirable attributes.[70]

1) Achieving the highest possible recovery of fermentable carbohydrates;
2) Minimizing the production of inhibitors resulting from carbohydrate degradation during pretreatment;
3) Ensuring minimal negative impact on the environment;
4) Reducing the need for post-pretreatment processes such as washing, neutralization, and detoxification;
5) Minimizing water and chemical usage;
6) Keeping the capital cost of the reactor relatively low;
7) Requiring a moderately low amount of energy input;
8) Achieving a relatively high treatment rate; and
9) Generating via Therefore, future research on pretreatment will concentrate on the subsequent domains.

The primary objective is to decrease the amount of water and chemicals used. The second objective is to extract carbohydrates and create additional valuable by-products in order to enhance the economic viability. Furthermore, the advancement of a clean delignification process leads to the advantageous co-fermentation of hexose and pentose sugars, resulting in enhanced economic viability of pretreatment. Fourthly, a comprehensive comprehension of the mechanisms involved in pretreatment and the correlation between the structural characteristics of biomass and enzymatic hydrolysis. Furthermore, it is important to minimize the production of inhibitors such as furfural, 5-HMF, and acetic acid, as these compounds can greatly impede the enzymatic breakdown and fermentation of biomass. Valuable by-products with high added value.[71]

Conclusion

The review study emphasized the significance and worth of bamboo as a very valuable and adaptable resource, sometimes referred to as "green gold." It underlined the numerous benefits of bamboo over other resources, particularly in comparison to bamboo itself. In addition, the study emphasizes the scientific aspects. Due to its versatility, bamboo has garnered significant attention in the field of study. However, lignin has several multifunctional capabilities and has shown itself to be an exceptional natural substance. The database has generated significant attention among scholars and scientists. This review paper concluded various pretreatment methods of Bamboo like Alkaline pretreatment of Bamboo, Phenolic pretreatment of Bamboo, Microwave-assisted organic acid pretreatment, Ethanol Organosolv pretreatment. Formic acid delignification and alkaline hydrogen peroxide pretreatment, Hydrotropic pretreatment, Soda pulping method Pretreatment, Dioxane and dimethyl sulfoxide pretreatment, Dioxane and ethanol pretreatment, Biochar-catalytic degradation pretreatment, Hydrothermal pretreatment, Steam Explosion pretreatment, Deep Eutectic Solvents (DES) pretreatment ,Metal salt-based deep eutectic solvent (DES) pretreatment, Phenylsulfonic acid (PSA)-pretreated bamboo, γ-valerolactone (GVL)/H_2O pretreatment, Synergistic pretreatment. Bamboo pretreatment techniques differ greatly in that they all aim to improve the materials processing for different uses by focusing on its intricate lignocellulosic structure. Alkaline pretreatment efficiently eliminates lignin and hemicellulose, enhancing the accessibility of cellulose. Phenolic pretreatment alters the structure of lignin, improving the process of enzymatic hydrolysis. Microwave-assisted organic acid pretreatment expedites the degradation of bamboo's composition by employing organic acids and microwave heating. Ethanol organosolv pretreatment utilizes ethanol, typically with an acid catalyst, to solubilize lignin, resulting in the production of cellulose of superior quality. The pulp is subjected to formic acid delignification, which is then followed by alkaline hydrogen peroxide treatment to further remove lignin and enhance the brightness of the pulp. Hydrotropic pretreatment use compounds like as xylene sulfonates to dissolve lignin at elevated temperatures. Soda pulping utilizes sodium hydroxide to dissolve lignin, which is commonly found in paper production. Dioxane and dimethyl sulfoxide (DMSO), together with dioxane and ethanol, are solvent-based techniques used to dissolve cellulose and lignin. Biochar-catalytic degradation employs biochar as a catalyst to facilitate the breakdown of lignin and hemicellulose. Hydrothermal and steam

explosion pretreatments employ high-pressure hot water and steam, respectively, to break down hemicellulose and alter the structure of lignocellulose. Deep eutectic solvents (DES) and metal salt-based DES provide novel and perhaps more environmentally friendly methods for dissolving bamboo components. Phenylsulfonic acid (PSA) and γ-valerolactone (GVL)/H_2O pretreatments break down hemicellulose and dissolve lignin, respectively. Synergistic pretreatments include the combination of several procedures to provide numerous advantages, such as enhanced removal of lignin and preservation of cellulose. Every approach offers a distinct combination of effectiveness, ecological consequences, and appropriateness for certain uses, with continuous study aimed at enhancing these procedures for economic feasibility.

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Conflicts of interest

Authors declare that there is no conflict of interest.

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