Lignocellulosic Materials for the Biofuels, Biochemicals and Biomaterials

Subjects: Materials Science, Biomaterials

Contributor: Antonio M. Borrero-López , Concepción Valencia , José M. Franco

It is well known that with the increasing issues of climate change, waste management and unstoppable resource exhaustion, politics and research efforts need to be combined in the search for new materials and sources that can replace fossil fuels and non-renewable resources currently in use, which besides generally include hazardous/toxic manufacture protocols and problematic end-of-life. It is at this point that lignocellulosic sources can play a fundamental role as a consequence of their natural origin, ubiquitous production all over the world, minimum carbon footprint and the interesting properties of their main components.

lignocellulose biofuels biochemicals

1. Biofuels

Compared to petroleum-based fuels, biofuels possess advantages such as renewability, sustainability, availability, biodegradability, safety, neutral greenhouse effects and negligible SO_x and reduced NO_x gas emissions [1]. Lignocellulose represents the only sustainable, low-cost and scalable eco-friendly option for industrial fuel production [2]. Furthermore, it also represents a great opportunity for increasing the domestic energy production in those countries with large biomass supplies and/or land availability to produce energy crops [3]. The main drawback is found in lignin degradation, as it is considered the more energy-consuming step of the production process, due to the resilience of this biopolymer. Moreover, the cellulose efficiency, enzymatic and biomass costs and composition are other parallel parameters that critically affect the development of suitable technologies [2][3][4]. Furthermore, the obtaining of high-quality biofuels faces other problems, such as many of the most effective solvents for biomass pretreatment being simultaneously incompatible with enzymatic development, whereas those microbes with the highest yields in biofuel production do not often use the sugars present in hydrolysates as substrates [3]. Therefore, as mentioned before and widely discussed, massive attention has been paid to suitable pretreatments for advanced purposes.

Lately, effort has been focused on genome editing technologies as a powerful tool for understanding and developing an integrated system to produce fuels in fast and lower-energy-consuming processes [3]. Thus, some of the inhibitory compounds usually produced in natural plants, such as ferulic acid, can be substantially reduced by genomic editing; nonetheless, negative effects on crop yields, costs and environmental impacts can likewise take place. Another approach that has been substantially developed is the preferential growth of cellulose in detriment of hemicellulose and lignin, as most industrial microbes generally take advantage of hexoses instead of pentoses for biofuel production. Lignin content reduction and composition homogenisation have also been targeted, the latter

allowing less complex product mixtures to be generated, thus higher-value molecules are obtained. On the other hand, other strategies have been based on the incorporation of unusual monomers, which potentiates chain elongation or the incorporation of interchangeable linkages, resulting, once more, in higher saccharification yields [3].

Nevertheless, the use of lignocellulosic biomass as biofuel competes with the use as food supply. Hence, a step further can be taken when residual lignocellulosic biomass is considered, as it can be transformed into what is called advanced biofuels, i.e., biofuels which significantly reduce greenhouse emissions simultaneously with the preservation of the common use of landfills, and therefore do not compete with food or feed commerce [5]. In this sense, deep research and many industrial projects which range from aerospace to common fuels, biogas, bioethanol or biodiesel have been accomplished or are being carried out currently [2][5]. In order to obtain those products, three different routes have been targeted, i.e., thermochemical, biochemical and hybrid conversion. An overview of these alternatives can be found elsewhere [5]. Therefore, the action of microorganisms is once again taking the lead as a renewable and environmentally friendly pathway for the conversion of biowaste into biofuels [6].

The thermomechanical route includes a variety of thermal treatments, from relatively low severity to strong processes where high temperatures are applied. Hence, torrefaction, pyrolysis, hydrothermal liquefaction and gasification are found among them.

The biochemical route relies on the enzymatic digestion of the different biopolymers that comprise lignin, which has been thoroughly described in previous sections, by either fungi or bacteria. Biomass digestion can lead to the production of small sugars, which can be directly used as fuel. However, a suitable separation process is generally needed as a consequence of the huge variety of products involved in lignocellulosic degradation. In addition, by following the biological route, certain compounds that cannot be obtained by chemical routes are produced, opening new areas for advanced biofuels [3].

Often, the products from biochemical routes are further converted by catalytic or thermomechanical processes into higher-added-value fuels. Thus, the hybrid route is accomplished.

The main biofuels that have been studied up to date are summarised in **Table 1**, including the energy that could be obtained from them. More specific details about raw materials, final characteristics and conversion routes can be seen in the indicated references.

Table 1. Main biofuels, the associated energy and corresponding processing routes reported in the literature.

Biofuel	Lower Heating Value	References
Biodiesel	32.6 MJ/L	[7]
Bioethanol	21.2 MJ/L	[7][8]
Biocrude	35.0 MJ/kg	[7]

Biofuel	Lower Heating Value	References
Bio-oil	40 MJ/kg	[7][9]
Biogas	13–17 MJ/m^3	[1][10]
Biohydrogen	13 MJ/m^3	[1][10]
Biobutanol	27.8 MJ/L	[11]

As a consequence of the great variety of monomeric units and linkages that comprise the three biopolymers, the range of biochemicals that can be obtained from them constitutes an even wider range. These biochemicals critically depend on the original biopolymer, i.e., lignin generally provides outstanding aromatic-based compounds, whereas sugars resulting from the hydrolysis of cellulose and hemicellulose may produce valuable six- and five-carbon-derived products [12]. In addition, the biochemicals obtained are dependent on the processing protocol; therefore, multiple biological and chemical processes, as well as combinations of both, have been studied in order to formulate different chemicals. Special attention is being paid to the bioengineering of these microorganisms; thus, more specific compounds can be targeted. More detailed information about this topic can be found elsewhere [13].

In the case of cellulose and hemicellulose, many different products can be obtained [13][14]. Werpy and Petersen [15] analysed more than 50 compounds, from which they found glycerol, acetic acid, levulinic acid, 3-hydroxybutyrolactone, glutamic acid, malic acid, itaconic acid, aspartic acid, oxalic acid, 3-hydroxy propionic acid, succinic acid, fumaric acid, 2,5-furan dicarboxylic acid, glucaric acid, sorbitol and xylitol/arabinitol to be among the more interesting ones. Most of them can also act as building blocks for the development of fine chemicals and derived compounds. **Table 2** depicts the main processes to obtain those species, together with the main derived products that can be obtained from them.

Table 2. Main building blocks and their derivatives obtained from cellulose and hemicellulose [15].

Compound	Production	Derived Products
Succinic, fumaric and malic acid	Biofermentation	Tetrahydrofuran (THF), 1,4-butanediol, 2-pyrrolidone, o-butyrolactone, N-methyl-2-pyrrolidone (NMP)
2,5-Furan dicarboxylic acid	Chemical (oxidative dehydration of glucose) and biological	(2,5-Bis(aminomethyl)-tetrahydrofuran, 2,5-dihydroxymethyl-tetrahydrofuran, 2,5-dihydroxymethyl-furan
3-Hydroxy propionic acid	Biofermentation	1,3-Propanediol, acrylic acid, acrylamide
Aspartic acid	Chemical and biological pathways	2-Amino-1,4-butanediol, aspartic anhydride, 3-aminotetrahydrofuran, amino-γ-butyrolactone
Glucaric acid	Chemical (starch oxidation by nitric acid or bleach)	Glucaro-γ-lactone, polyhydroxypolyamides, glucarodilactone, glucaro-δ-lactone

Compound	Production	Derived Products
Glutamic acid	Biofermentation	Glutaminol, glutaric acid, norvoline, 1,5-pentandiol, 5-amino-1-butanol
Itaconic acid	Chemical and biofermentation	3-Methylpyrrolidine, 3- & 4-methyl NMP, 3-methyl THF, 2-methyl-1,4-butanediol.
Levulinic acid	Chemical (acid decomposition of six-carbon sugars)	Diphenolic acid, 2-methyl-THF, b-acetylacrylic acid, 1,4-pentanediol
3-Hydroxybutyrolactone	Chemical (oxidative degradation of starch)	3-Hydroxytetrahydrofuran, 3-aminotetrahydrofuran, acrylate-lactone
Glycerol	Transesterification (via chemical or biological pathways)	Glyceric acid, 1,3-propanediol, propylene glycol
Sorbitol	Chemical (glucose hydrogenation)	Isosorbide, propylene glycol, ethylene glycol, 1,4-sorbitan
Xylitol/arabinitol	Chemical (hydrogenation of xylose and arabinose) and biological	Xylaric acid, propylene glycol, ethylene glycol, lactic acid

Other important cellulose- and hemicellulose-derived products are 5-hydroxymethyl furfural and furfural, which have been reported as being obtained by hydrothermal carbonisation of those biopolymers, respectively. Both derived furans can also be precursors of many other chemicals, biofuels and pharmaceutical and agrochemical products [12][14][16].

A detailed summary including the different chemical structures of both precursors and final products can be found elsewhere [14].

Regarding lignin, as mentioned above, a vast range of aromatic-based chemicals can also be obtained by its decomposition and transformation. However, the success of the suitable formation of chemicals from lignin relies on several main aspects, i.e., lignin fractionation from raw biomass, proper degradation, depolymerisation, transformation into high-value-added compounds and further separation. Depending on depolymerisation conditions, diverse products can be obtained, as shown in **Table 3**.

Table 3. Main procedures from lignin depolymerisation along with main products obtained.

Depolymerisation	Procedures	Products	Refs
Non-reductive depolymerisation	Thermal, hydrothermal, oxidative, acid and base catalysed, solvolytic	Vanillin, syringaldehyde, acetosyringone, guaiacylacetone, p-hydroxylated phenol acetovanillone, syringol, guaiacol, phenol, catechol, alkylcatechols, creosol, p-hydroxybenzaldehyde, vanillic, protocatechuic, syringic, homovanillic and p-hydroxybenzoic acid, aliphatic carboxylic acids (succinic, acetic and formic acid)	[12] [17]

Depolymerisation	Procedures	Products	Refs
Reductive depolymerisation	Hydroprocessing, liquid phase reforming	Cresol, xylenol, phenol with long alkyl chains, p-substituted methoxyphenols,	[17]

s depend on the procedure characteristics [17].

Similar to cellulose and hemicellulose, several of the compounds obtained can be considered end products, while many others can likewise act as building blocks for possible upgraded compounds [14][17].

3. Biomaterials

Due to the extensive variety of molecular species obtained from lignocellulosic degradation, the possibilities of derived biomaterials are massive. Werpy and Petersen [15] included in their work an exhaustive review of the biomass components, their primary degradation products, main intermediates and a brief description of derived bioproducts and uses. Hence, lignocellulose derivatives may play a significant role in areas such as general industry, transportation, textiles, packaging and other food vessels, environment, plastic replacers, stationery, house and leisure items, health and hygiene.

However, those biomaterials that make use of the interesting biopolymer network characteristics without further fractionation into derived products are not included among those uses; thus, they will be discussed separately. When considering lignocellulose, frequently research has taken advantage of lignin, cellulose and hemicellulose biopolymers separately; however, the whole biomass has also been considered.

3.1. Lignocellulose-Derived Biomaterials

There is an immense range of biosource applications currently, boosted by research possibilities, variety and exceptional properties. Some of them will be discussed further on in this section; nonetheless, a detailed revision of many of these applications is beyond the scope of this work.

As an example, for wheat and barley straw, advanced biomaterials for construction materials, phycoremediation of wastewater, cement properties enhancer and fibres in concrete were reported [18][19][20][21][22][23]. Straws and stalks from other sources were also focused on for board production, being potentially suitable for beaverboard, packing materials, one-use tableware or seeding devices [24][25]. Graphitised lignocellulose extracted from bamboo has also been used lately for electromagnetic wave absorbers [26].

One of the main applications that have been developed is the use of biomass as an adsorbent. In this sense, Rocha et al. [27] studied the adsorption of metal ions such as Cu(II), Zn(II), Hg(II) and Cd(II) on rice-straw-derived solutions. By the formation of biochar from rice straw, other metal ions such as Pb and Zn can also be adsorbed [28], as well as nitrogen and phosphorous [29]. Abdel-Aal et al. [30] reported the ability of rice straw in the treatment of wastewater including several commercial dyes instead. Likewise, banana peel- and palm-flower-waste-based derived products were also able to remove methylene blue and malachite green dyes from polluted solutions [31]

[32]. Other studies obtained proper adsorbents from residual products such as orange peel and sugarcane bagasse [33]. A detailed review of this matter has been recently published [34].

On the other hand, electrocatalytic activity was also studied on biomass-derived materials. Thus, Castro-Gutiérrez et al. [35] produced tannin-derived carbon materials, while Liu et al. [36] created soybean straw-based Fe-N co-doped porous carbons, both exhibiting excellent properties in electrochemical applications. Ma et al. [37] demonstrated that cornstalks and pomelos skins efficiently act as carbon sources for the construction of cathode catalysts for microbial fuel cells. Another biosource, watermelon, was used by Wu et al. [38] to create hydrogels and aerogels with electrochemical applications. Other biomass sources suitable for electrochemical applications are sawdust or grasses [39].

Composites containing residual lignocellulosic biosources have also been targeted. In those, lignocellulose acts as a reinforcing filler and avoids problems such as lack of flexibility or respiratory illnesses [40]. Bugatti et al. [41] showed how tomato peels could form proper composites with halloysite nanotubes for packaging applications. Ita-Nagy et al. [42] demonstrated that sugarcane bagasse fibres also properly reinforce composite structure. Pinhao and pecan nutshells were also used for reinforced composites preparation. The pinhao-nutshell-based composite exhibited lower water absorption capacity than the petcan-based one, based on the enhanced hydrophobic character of the pinhao-based composite [43]. Fibres from tropical maize and sweet sorghum bagasse were also studied as composite additives [44].

The use of biomass as catalysts or catalyst supports has also been deeply studied, as is the case for soybean and other biomass with high protein content [45].

In textile, bamboo fibres can provide comfortability, good dyeing and appealing characteristics. Hemp can also be utilised for textile application, as well as for making sacks and ropes, degumming, etc. [46].

In food, tomato peels have acted as an enhancer for colour and antioxidant properties for yoghurts [47], whereas tomato peel fibres have demonstrated the ability to produce a suitable network for edible gels, with enhanced stability and texture [48].

A singular case can be considered when lignocellulosic biomass acts as a hydrogel precursor, which has led to interesting applications being found in fields such as film formation, high-strength filaments, tissue engineering, among many others [49].

Nonetheless, the number of applications and studies is boosted when the different lignocellulosic biopolymers are considered separately. In the following sections, cellulose-, hemicellulose- and lignin-derived biomaterials have been examined.

3.2. Cellulose-Derived Biomaterials

The singular structure of cellulose, together with its possibilities of being modified by chemical reactions or converted into alkyl-derived or nanosystems, has made a great range of biomaterials available currently from this biopolymer.

The high number of hydroxyl groups present in cellulose has attracted research attention to the formation of cellulose-based hydrogels. Even though the cellulose ability to be dissolved in water is limited, the development of many suitable solvents has caused hydrogels with stunning properties to be obtained, with applications such as food packaging, smart swelling, controlled delivery and biomedical applications [50][51][52].

The well-known ability of some bacteria to produce cellulose (bacterial cellulose) has also been leveraged for the performance of hydrogels. In general, good tensile and compressive properties are shown, together with high water-absorption capacity, crystallinity and biocompatibility, which have caused bacterial-cellulose-based hydrogels to be focused on bio-applications such as dental and meniscus implants, or tissue engineering scaffolds [50].

Hydrogels from alkyl-cellulose-derived products have also been analysed, such as hydroxypropyl-, hydroxypropylmethyl-, carboxymethyl- or methyl-cellulose. The alkyl-derived chains introduce regions where physical crosslinking may be dampened; thus, chemical crosslinking has frequently been targeted, which has provided hydrogels with new characteristics, for instance, pH dependence in sorption capacity. These hydrogels have been shown to be valuable in water body elimination through the absorption of water in the stomach [53], dye elimination [54], food and drugs [50].

Nonetheless, the capacities of cellulose-based hydrogels can be further boosted by the combination of other synthetic or natural polymers. Hence, heavy metal elimination or food and tissue engineering applications have been targeted by the combination with chitosan, starch or alginate, respectively [50].

On the other hand, inorganic materials have also been added to the cellulose-based hydrogel structures, with applications in fields such as electricity, magnetics, optics and biology. A summarised insight on the potential applications of cellulose-based hydrogels can be found elsewhere [49].

However, not only hydrogels have been reported as being developed from cellulose. Aerogels, usually obtained by freeze-drying of hydrogels or supercritical drying with CO_2, have also been produced. In the same way as with hydrogels, cellulose, bacterial cellulose and many derived systems (from alkylated compounds to nanosystems) have been reported to produce aerogels, affecting both the synthesis process and final properties [55].

Aerogels possess characteristics such as very low density (up to 0.5 mg/mL), high specific surface area (up to 975 m^2/g) and highly porous structures (up to 99.9% porosity), while keeping good mechanical characteristics, which have propelled their use in applications such as shock absorbers, acoustic and thermal insulation, oil absorption, biomedical devices and implants, conductivity enhancers or carriers of metal nanoparticles and oxides [55][56][57].

On the other hand, by the combination with oily systems, oleogels have also been prepared. Once more, prepared through the use of cellulose and cellulose-derived materials, a vast range of products has been documented. In the

food industry, it is ethyl cellulose which has attracted the most attention due to its appealing thickening properties, though pristine cellulose, methylcellulose and hydroxypropyl methylcellulose have also been studied [58]. Nonetheless, the rheology-modifier characteristics have been leveraged for its use in a wider range of applications such as binders, films, adhesives, lubricating greases and hot blends [59][60].

The case of lubricating greases remains especially appealing, as, regardless of the extensive work found in literature, the industry continues to employ almost entirely petroleum-based products and uses lithium- and other metal-based soaps as thickening agents. Hence, studies that explore the use of cellulose pulp as a thickener can be found [61][62][63], but also pristine cellulose [64][65] and cellulose derivatives [64][65][66]. A wide range of these systems has been demonstrated to impart suitable rheological and excellent tribological properties, along with appropriate mechanical stability comparable to lithium-based lubricating grease benchmarks.

As already introduced in this section, the formation of nanostructures from cellulose is also a very appealing approach for the development of potential systems with a broad range of applications. By the formation of nanofibres, excellent properties of water-based hydrogels have been shown, as only a very low concentration is needed in order to obtain good rheological properties. Furthermore, the formation of films and nanocomposites has also been extensively reported. Thus, applications such as reinforcing agent for paper, greaseproof paper, thermosetting resins, strengthened composites, obesity-precautionary thickener, suspension stabiliser, sanitary products, wound dressing, coatings, etc. can be found [67][68].

The formation of cellulose nanocrystals has also been extensively studied, with the majority of applications based on the formation of composites. Nonetheless, the suspensions containing these cellulose nanocrystals have shown nematic chirality, which boosts their applications in fields such as NMR spectroscopy and optical taggants [67][69].

In addition, not only mechanical and chemical processes have been documented to successfully produce cellulose nanostructures. Instead, some bacteria have also exhibited the possibility of directly obtaining cellulose nanostructures with the only presence of hydroxyl moieties as functional groups. The high yield for a biological process (up to 40%) and unique structure have propelled its use in fields such as regenerative medicine, wound healing, implants, membranes, films and barrier layers [67].

3.3. Hemicellulose-Derived Biomaterials

Even though hemicellulose does not possess the significance and properties of cellulose and cellulose derivatives, there are also many studies that take advantage of hemicellulose structure to produce interesting biomaterials. Due to the fact that hemicellulose is not formed by a single type of biopolymer, the possibilities are again raised. The main target of hemicellulose-based biomaterials has been based on the production of antioxidant agents, hydrogels and films for uses such as coatings, packaging or biomedicine; nonetheless, some other less common uses have also been studied.

Hydrogels have been mainly centred on drug delivery [70][71][72], tissue engineering and environmental protection, and have demonstrated pH, ionic strength, media composition and organic-solvent-dependent behaviour. Thus, the

removal of heavy metals such as Ni (II), Cu(II), Pb (II), Cd(II), Pd(II) and Zn(II) or sulfadimidine has been successfully achieved by these hydrogels [73][74][75]. On the contrary, good adhesion in tissues like liver has also been documented, in which they may play a good replacement role in detriment to more expensive and less available tissue and organ transplants [76]. In drug delivery, xylan- and galactomannan-based microcapsules have been shown to be excellent colon-specific carriers [71][77][78], while xyloglucan mucoadhesive and surface tailoring properties have led to the development of many specific studies [72]. Galactomannans have also been shown to be useful for drug delivery by the formation of an aerogel structure [79].

Hemicellulose-based films were also produced, whose significance is based on their outstanding properties against oxygen permeability, thus conforming to a great replacement for oxygen-sensitive food packaging. Xylan, arabinoxylan, glucomannan and galactoglucomannan, alone, modified or by combination with other biopolymers, are some of the biopolymers from hemicellulose which have shown suitable properties for film production [74][80][81].

The same oxygen permeability provides hemicellulose with interesting antioxidant and antimoisture properties, which make them good replacements as coatings for food packaging.

Between the less common uses, there is still a vast range to be found. Peng et al. [82] demonstrated that hemicellulose acts as a stabiliser for the formation of silver nanoparticles. Jiang et al. [83], instead, used hemicellulose for the synthesis of quantum dots to detect Ag(I) and L-Cysteyne in aqueous solutions. Farhat et al. [84] were able to produce hemicellulose from bleached hardwood pulp and switchgrass, which, crosslinked with zirconium, exhibited excellent adhesive properties. Xylan has been analysed by Ebringerova [85], who evaluated other potential applications such as textile printing, antimicrobial additive, plant growth regulator, inmunoenhancing supplement, additives and thickening agent in food. On the other hand, xyloglucan has also been reported as a texture enhancer, binder, dye absorption, emulsion stabilizer, syneresis control and food additive [86]. Some of these applications are shared by galactomannan-derived products, which have been shown to act as binders, texture modifiers, emulsifiers, lubricators or stabilisers, mainly in the food industry [87]. Galactoglucomannan has also been studied as a food additive because of its prebiotic properties [88].

References

1. Velvizhi, G.; Goswami, C.; Shetti, N.P.; Ahmad, E.; Pant, K.K.; Aminabhavi, T.M. Valorisation of lignocellulosic biomass to value-added products: Paving the pathway towards low-carbon footprint. Fuel 2021, 313, 122678.
2. Wi, S.G.; Cho, E.J.; Lee, D.-S.; Lee, S.J.; Lee, Y.J.; Bae, H.-J. Lignocellulose conversion for biofuel: A new pretreatment greatly improves downstream biocatalytic hydrolysis of various lignocellulosic materials. Biotechnol. Biofuels 2015, 8, 228.
3. Baral, N.R.; Sundstrom, E.R.; Das, L.; Gladden, J.; Eudes, A.; Mortimer, J.C.; Singer, S.W.; Mukhopadhyay, A.; Scown, C.D. Approaches for More Efficient Biological Conversion of

Lignocellulosic Feedstocks to Biofuels and Bioproducts. ACS Sustain. Chem. Eng. 2019, 7, 9062–9079.

4. Baral, N.R.; Kavvada, O.; Mendez-Perez, D.; Mukhopadhyay, A.; Lee, T.S.; Simmons, B.A.; Scown, C.D. Techno-economic analysis and life-cycle greenhouse gas mitigation cost of five routes to bio-jet fuel blendstocks. Energy Environ. Sci. 2019, 12, 807–824.
5. Balan, V.; Chiaramonti, D.; Kumar, S. Review of US and EU initiatives toward development, demonstration, and commercialization of lignocellulosic biofuels. Biofuels Bioprod. Biorefin. 2013, 7, 732–759.
6. Bhujbal, S.K.; Ghosh, P.; Vijay, V.K.; Rathour, R.; Kumar, M.; Singh, L.; Kapley, A. Biotechnological potential of rumen microbiota for sustainable bioconversion of lignocellulosic waste to biofuels and value-added products. Sci. Total Environ. 2022, 814, 152773.
7. Demirbas, A. Competitive liquid biofuels from biomass. Appl. Energy 2011, 88, 17–28.
8. Danso, B.; Ali, S.S.; Xie, R.; Sun, J. Valorisation of wheat straw and bioethanol production by a novel xylanase- and cellulase-producing Streptomyces strain isolated from the wood-feeding termite, Microcerotermes species. Fuel 2021, 310, 122333.
9. Isahak, W.N.R.W.; Hisham, M.W.; Yarmo, M.A.; Hin, T.-Y.Y. A review on bio-oil production from biomass by using pyrolysis method. Renew. Sustain. Energy Rev. 2012, 16, 5910–5923.
10. Prasad, S.; Dhanya, M.S.; Gupta, N.; Kumar, A. Biofuels from biomass: A sustainable alternative to energy and environment, Biochem. Cell. Arch. 2012, 12, 255–260.
11. Gottumukkala, L.D.; Mathew, A.K.; Abraham, A.; Sukumaran, R.K. Biobutanol Production: Microbes, Feedstock, and Strategies. In Biofuels: Alternative Feedstocks and Conversion Processes for the Production of Liquid and Gaseous Biofuels; Elsevier BV: Amsterdam, The Netherlands, 2019; pp. 355–377.
12. Borrero-López, A.M.; Masson, E.; Celzard, A.; Fierro, V. Modelling the reactions of cellulose, hemicellulose and lignin submitted to hydrothermal treatment. Ind. Crop. Prod. 2018, 124, 919–930.
13. Lee, S.Y.; Kim, H.U.; Chae, T.U.; Cho, J.S.; Kim, J.W.; Shin, J.H.; Kim, D.I.; Ko, Y.-S.; Jang, W.D.; Jang, Y.-S. A comprehensive metabolic map for production of bio-based chemicals. Nat. Catal. 2019, 2, 18–33.
14. Isikgor, F.H.; Becer, C.R. Lignocellulosic biomass: A sustainable platform for the production of bio-based chemicals and polymers. Polym. Chem. 2015, 6, 4497–4559.
15. Werpy, T.; Holladay, J.; White, J. Top Value Added Chemicals from Biomass: I. In Results of Screening for Potential Candidates from Sugars and Synthesis Gas; U.S. Department of Energy Office of Scientific and Technical Information: Oak Ridge, TN, USA, 2004.

16. Mamman, A.S.; Lee, J.-M.; Kim, Y.-C.; Hwang, I.T.; Park, N.-J.; Hwang, Y.K.; Chang, J.-S.; Hwang, J.-S. Furfural: Hemicellulose/xylosederived biochemical. Biofuels Bioprod. Biorefin. 2008, 2, 438–454.
17. Schutyser, W.; Renders, T.; Van Den Bosch, S.; Koelewijn, S.-F.; Beckham, G.T.; Sels, B.F. Chemicals from lignin: An interplay of lignocellulose fractionation, depolymerisation, and upgrading. Chem. Soc. Rev. 2018, 47, 852–908.
18. Sharma, J.; Kumar, S.; Kumar, V.; Malyan, S.K.; Mathimani, T.; Bishnoi, N.R.; Pugazhendhi, A. Upgrading of microalgal consortia with CO2 from fermentation of wheat straw for the phycoremediation of domestic wastewater. Bioresour. Technol. 2020, 305, 123063.
19. Ahmad, M.R.; Chen, B.; Duan, H. Improvement effect of pyrolyzed agro-food biochar on the properties of magnesium phosphate cement. Sci. Total Environ. 2020, 718, 137422.
20. Chen, Y.-A.; Yang, H.; Ouyang, D.; Liu, T.; Liu, D.; Zhao, X. Construction of electron transfer chains with methylene blue and ferric ions for direct conversion of lignocellulosic biomass to electricity in a wide pH range. Appl. Catal. B Environ. 2020, 265, 118578.
21. Ahmadi, R.; Souri, B.; Ebrahimi, M. Evaluation of wheat straw to insulate fired clay hollow bricks as a construction material. J. Clean. Prod. 2020, 254, 120043.
22. Martos, S.; Mattana, S.; Ribas, A.; Albanell, E.; Domene, X. Biochar application as a win-win strategy to mitigate soil nitrate pollution without compromising crop yields: A case study in a Mediterranean calcareous soil. J. Soils Sediments 2020, 20, 220–233.
23. Luhar, S.; Cheng, T.-W.; Luhar, I. Incorporation of natural waste from agricultural and aquacultural farming as supplementary materials with green concrete: A review. Compos. Part B Eng. 2019, 175, 107076.
24. Chen, H. Lignocellulose biorefinery product engineering. In Lignocellulose Biorefinery Engineering, 1st ed.; Woodhead Publishing Limited: Cambridge, UK, 2015; pp. 125–165.
25. Basta, A.; El-Sayed, E.S.A.; El-Saied, H. Lignocellulosic Materials in Building Elements. Part IV—Economical Manufacture and Improvement of Properties of Light-Weight Agro-Panels. Int. J. Polym. Mater. Polym. Biomater. 2004, 53, 709–723.
26. Lou, Z.; Wang, Q.; Kara, U.I.; Mamtani, R.S.; Zhou, X.; Bian, H.; Yang, Z.; Li, Y.; Lv, H.; Adera, S.; et al. Biomass-Derived Carbon Heterostructures Enable Environmentally Adaptive Wideband Electromagnetic Wave Absorbers. Nano-Micro Lett. 2021, 14, 11.
27. Rocha, C.G.; Zaia, D.A.M.; Alfaya, R.V.D.S.; Alfaya, A.A.D.S. Use of rice straw as biosorbent for removal of Cu(II), Zn(II), Cd(II) and Hg(II) ions in industrial effluents. J. Hazard. Mater. 2009, 166, 383–388.

28. Zhao, M.; Dai, Y.; Zhang, M.; Feng, C.; Qin, B.; Zhang, W.; Zhao, N.; Li, Y.; Ni, Z.; Xu, Z.; et al. Mechanisms of Pb and/or Zn adsorption by different biochars: Biochar characteristics, stability, and binding energies. Sci. Total Environ. 2020, 717, 136894.
29. Dai, Y.; Wang, W.; Lu, L.; Yan, L.; Yu, D. Utilization of biochar for the removal of nitrogen and phosphorus. J. Clean. Prod. 2020, 257, 120573.
30. Abdelaal, S.; Gad, Y.; Dessouki, A. Use of rice straw and radiation-modified maize starch/acrylonitrile in the treatment of wastewater. J. Hazard. Mater. 2006, 129, 204–215.
31. Nethaji, S.; Sivasamy, A.; Thennarasu, G.; Saravanan, S. Adsorption of Malachite Green dye onto activated carbon derived from Borassus aethiopum flower biomass. J. Hazard. Mater. 2010, 181, 271–280.
32. Liu, R.-L.; Liu, Y.; Zhou, X.-Y.; Zhang, Z.-Q.; Zhang, J.; Dang, F.-Q. Biomass-derived highly porous functional carbon fabricated by using a free-standing template for efficient removal of methylene blue. Bioresour. Technol. 2014, 154, 138–147.
33. Licona-Aguilar, Á.I.; Lois-Correa, J.A.; Torres, A.; Domínguez-Crespo, M.A.; Dorantes-Rosales, H.J.; Garcia-Zaleta, D.S. Sugarcane Bagasse-, Orange Peel-Derived Adsorbent Materials: Thermal and Morphological Studies. J. Nanosci. Nanotechnol. 2020, 20, 4563–4573.
34. Aragaw, T.A.; Bogale, F.M. Biomass-Based Adsorbents for Removal of Dyes from Wastewater: A Review. Front. Environ. Sci. 2021, 9, 764958.
35. Castro-Gutiérrez, J.; Díez, N.; Sevilla, M.; Izquierdo, M.; Celzard, A.; Fierro, V. Model carbon materials derived from tannin to assess the importance of pore connectivity in supercapacitors. Renew. Sustain. Energy Rev. 2021, 151, 111600.
36. Liu, Y.; Su, M.; Li, D.; Li, S.; Li, X.; Zhao, J.; Liu, F. Soybean straw biomass-derived Fe-N co-doped porous carbon as an efficient electrocatalyst for oxygen reduction in both alkaline and acidic media. RSC Adv. 2020, 12, 6763–6771.
37. Ma, M.; Dai, Y.; Zou, J.-L.; Wang, L.; Pan, K.; Fu, H.-G. Synthesis of Iron Oxide/Partly Graphitized Carbon Composites as a High-Efficiency and Low-Cost Cathode Catalyst for Microbial Fuel Cells. ACS Appl. Mater. Interfaces 2014, 6, 13438–13447.
38. Wu, X.-L.; Wen, T.; Guo, H.-L.; Yang, S.; Wang, X.; Xu, A.-W. Biomass-Derived Sponge-like Carbonaceous Hydrogels and Aerogels for Supercapacitors. ACS Nano 2013, 7, 3589–3597.
39. Gupta, G.K.; De, S.; Franco, A.; Balu, A.M.; Luque, R. Sustainable Biomaterials: Current Trends, Challenges and Applications. Molecules 2015, 21, 48.
40. Iqbal, H.M.N.; Kyazze, G.; Keshavarz, T. Advances in the Valorization of Lignocellulosic Materials by Biotechnology: An Overview. BioResources 2013, 8, 3157–3176.

41. Bugatti, V.; Brachi, P.; Viscusi, G.; Gorrasi, G. Valorization of Tomato Processing Residues Through the Production of Active Bio-Composites for Packaging Applications. Front. Mater. 2019, 6, 34.
42. Ita-Nagy, D.; Vázquez-Rowe, I.; Kahhat, R.; Quispe, I.; Chinga-Carrasco, G.; Clauser, N.M.; Area, M.C. Life cycle assessment of bagasse fiber reinforced biocomposites. Sci. Total Environ. 2020, 720, 137586.
43. Engel, J.B.; Mac Ginity, M.; Luchese, C.L.; Tessaro, I.C.; Spada, J.C. Reuse of Different Agroindustrial Wastes: Pinhão and Pecan Nutshells Incorporated into Biocomposites Using Thermocompression. J. Polym. Environ. 2020, 28, 1431–1440.
44. Chen, B.; Luo, Z.; Chen, H.; Chen, C.; Cai, D.; Qin, P.; Cao, H.; Tan, T. Wood Plastic Composites from the Waste Lignocellulosic Biomass Fibers of Bio-Fuels Processes: A Comparative Study on Mechanical Properties and Weathering Effects. Waste Biomass Valorization 2018, 11, 1701–1710.
45. Chen, W.-F.; Iyer, S.; Iyer, S.; Sasaki, K.; Wang, C.-H.; Zhu, Y.; Muckerman, J.T.; Fujita, E. Biomass-derived electrocatalytic composites for hydrogen evolution. Energy Environ. Sci. 2013, 6, 1818–1826.
46. Chen, H. Integrated industrial lignocellulose biorefinery chains. In Lignocellulose Biorefinery Engineering; Elsevier BV: Amsterdam, The Netherlands, 2015; pp. 219–245.
47. Horuz, T.İ.; Belibağli, K.B. Encapsulation of tomato peel extract into nanofibers and its application in model food. J. Food Process. Preserv. 2019, 43, e14090.
48. Niu, Y.; Xia, Q.; Gu, M.; Yu, L. Interpenetrating network gels composed of gelatin and soluble dietary fibers from tomato peels. Food Hydrocoll. 2019, 89, 95–99.
49. Ajdary, R.; Tardy, B.L.; Mattos, B.D.; Bai, L.; Rojas, O.J. Plant Nanomaterials and Inspiration from Nature: Water Interactions and Hierarchically Structured Hydrogels. Adv. Mater. 2021, 33, e2001085.
50. Chang, C.; Zhang, L. Cellulose-based hydrogels: Present status and application prospects. Carbohydr. Polym. 2011, 84, 40–53.
51. Zhao, G.; Lyu, X.; Lee, J.; Cui, X.; Chen, W.-N. Biodegradable and transparent cellulose film prepared eco-friendly from durian rind for packaging application. Food Packag. Shelf Life 2019, 21, 100345.
52. Kabir, S.M.F.; Sikdar, P.P.; Haque, B.; Bhuiyan, M.A.R.; Ali, A.; Islam, M.N. Cellulose-based hydrogel materials: Chemistry, properties and their prospective applications. Prog. Biomater. 2018, 7, 153–174.

53. Sannino, A.; Madaghiele, M.; Lionetto, M.G.; Schettino, T.; Maffezzoli, A. A cellulose-based hydrogel as a potential bulking agent for hypocaloric diets: Anin vitro biocompatibility study on rat intestine. J. Appl. Polym. Sci. 2006, 102, 1524–1530.
54. Yan, L.; Shuai, Q.; Gong, X.; Gu, Q.; Yu, H. Synthesis of Microporous Cationic Hydrogel of Hydroxypropyl Cellulose (HPC) and its Application on Anionic Dye Removal. CLEAN—Soil Air Water 2009, 37, 392–398.
55. Long, L.-Y.; Weng, Y.-X.; Wang, Y.-Z. Cellulose Aerogels: Synthesis, Applications, and Prospects. Polymers 2018, 10, 623.
56. Tripathi, A.; Parsons, G.N.; Rojas, O.J.; Khan, S.A. Featherlight, Mechanically Robust Cellulose Ester Aerogels for Environmental Remediation. ACS Omega 2017, 2, 4297–4305.
57. Tripathi, A.; Parsons, G.N.; Khan, S.A.; Rojas, O.J. Synthesis of organic aerogels with tailorable morphology and strength by controlled solvent swelling following Hansen solubility. Sci. Rep. 2018, 8, 2106.
58. Pușcaș, A.; Mureșan, V.; Socaciu, C.; Muste, S. Oleogels in Food: A Review of Current and Potential Applications. Foods 2020, 9, 70.
59. Cortés-Triviño, E.; Valencia, C.; Delgado, M.A.; Franco, J.M. Thermo-rheological and tribological properties of novel bio-lubricating greases thickened with epoxidized lignocellulosic materials. J. Ind. Eng. Chem. 2019, 80, 626–632.
60. Gravelle, A.J.; Marangoni, A.G.; Davidovich-Pinhas, M. Ethylcellulose Oleogels. In Edible Oleogels; Elsevier BV: Amsterdam, The Netherlands, 2018; pp. 331–362.
61. Nuñez, N.; Martín-Alfonso, J.E.; Eugenio, M.E.; Valencia, C.; Díaz, M.J.; Franco, J.M. Preparation and Characterization of Gel-like Dispersions Based on Cellulosic Pulps and Castor Oil for Lubricant Applications. Ind. Eng. Chem. Res. 2011, 50, 5618–5627.
62. Núñez, N.; Martín-Alfonso, J.; Valencia, C.; Sánchez, M.; Franco, J.M. Rheology of new green lubricating grease formulations containing cellulose pulp and its methylated derivative as thickener agents. Ind. Crops Prod. 2012, 37, 500–507.
63. Cortés-Triviño, E.; Valencia, C.; Delgado, M.A.; Franco, J.M. Rheology of epoxidized cellulose pulp gel-like dispersions in castor oil: Influence of epoxidation degree and the epoxide chemical structure. Carbohydr. Polym. 2018, 199, 563–571.
64. Sánchez, R.; Fiedler, M.; Kuhn, E.; Franco, J.M. Tribological characterization of green lubricating greases formulated with castor oil and different biogenic thickener agents: A comparative experimental study. Ind. Lubr. Tribol. 2011, 63, 446–452.
65. Sánchez, R.; Franco, J.; Delgado, M.; Valencia, C.; Gallegos, C. Rheological and mechanical properties of oleogels based on castor oil and cellulosic derivatives potentially applicable as bio-

lubricating greases: Influence of cellulosic derivatives concentration ratio. J. Ind. Eng. Chem. 2011, 17, 705–711.

66. Alfonso, J.E.M.; Núñez, N.; Valencia, C.; Franco, J.; Díaz, M. Formulation of new biodegradable lubricating greases using ethylated cellulose pulp as thickener agent. J. Ind. Eng. Chem. 2011, 17, 818–823.
67. Klemm, D.; Kramer, F.; Moritz, S.; Lindström, T.; Ankerfors, M.; Gray, D.; Dorris, A. Nanocelluloses: A New Family of Nature-Based Materials. Angew. Chem. Int. Ed. 2011, 50, 5438–5466.
68. Mittal, N.; Ansari, F.; Gowda, V.K.; Brouzet, C.; Chen, P.; Larsson, P.T.; Roth, S.V.; Lundell, F.; Wågberg, L.; Kotov, N.A.; et al. Multiscale Control of Nanocellulose Assembly: Transferring Remarkable Nanoscale Fibril Mechanics to Macroscale Fibers. ACS Nano 2018, 12, 6378–6388.
69. Peng, B.L.; Dhar, N.; Liu, H.L.; Tam, K.C. Chemistry and applications of nanocrystalline cellulose and its derivatives: A nanotechnology perspective. Can. J. Chem. Eng. 2011, 89, 1191–1206.
70. Farhat, W.; Venditti, R.; Mignard, N.; Taha, M.; Becquart, F.; Ayoub, A. Polysaccharides and lignin based hydrogels with potential pharmaceutical use as a drug delivery system produced by a reactive extrusion process. Int. J. Biol. Macromol. 2017, 104, 564–575.
71. Da Silva, A.E.; Rodrigues, H.; Gomes, M.C.S.; Eleamen, E.; Nagashima, T.; Egito, E.S.T. Xylan, a Promising Hemicellulose for Pharmaceutical Use. In Products and Applications of Biopolymers; IntechOpen: London, UK, 2012.
72. Pardeshi, C.V.; Kulkarni, A.D.; Belgamwar, V.S.; Surana, S.J. Xyloglucan for drug delivery applications. In Fundamental Biomaterials: Polymers; Woodhead Publishing: Sawston, UK, 2018; pp. 143–169.
73. Wan, J.; Liu, L.; Ayub, K.S.; Zhang, W.; Shen, G.; Hu, S.; Qian, X. Characterization and adsorption performance of biochars derived from three key biomass constituents. Fuel 2020, 269, 117142.
74. Peng, P.; She, D. Isolation, structural characterization, and potential applications of hemicelluloses from bamboo: A review. Carbohydr. Polym. 2014, 112, 701–720.
75. Ayoub, A.; Venditti, R.A.; Pawlak, J.J.; Salam, A.; Hubbe, M.A. Novel Hemicellulose–Chitosan Biosorbent for Water Desalination and Heavy Metal Removal. ACS Sustain. Chem. Eng. 2013, 1, 1102–1109.
76. Seo, S.-J.; Park, I.-K.; Yoo, M.-K.; Shirakawa, M.; Akaike, T.; Cho, C.-S. Xyloglucan as a synthetic extracellular matrix for hepatocyte attachment. J. Biomater. Sci. Polym. Ed. 2004, 15, 1375–1387.
77. Silveira, J.L.M.; Bresolin, T.M.B. Pharmaceutical use of galactomannans. Quím. Nova 2011, 34, 292–299.

78. Landin, M.; Echezarreta, M.M. Galactomannans: Old and new pharmaceutical materials. In Polysaccharides: Development, Properties and Applications; Nova Science: Hauppauge, NY, USA, 2010.
79. Rossi, B.; Ponzini, E.; Merlini, L.; Grandori, R.; Galante, Y.M. Characterization of aerogels from chemo-enzymatically oxidized galactomannans as novel polymeric biomaterials. Eur. Polym. J. 2017, 93, 347–357.
80. Hansen, N.M.L.; Plackett, D. Sustainable Films and Coatings from Hemicelluloses: A Review. Biomacromolecules 2008, 9, 1493–1505.
81. Prakobna, K.; Kisonen, V.; Xu, C.; Berglund, L.A. Strong reinforcing effects from galactoglucomannan hemicellulose on mechanical behavior of wet cellulose nanofiber gels. J. Mater. Sci. 2015, 50, 7413–7423.
82. Peng, H.; Yang, A.; Xiong, J. Green, microwave-assisted synthesis of silver nanoparticles using bamboo hemicelluloses and glucose in an aqueous medium. Carbohydr. Polym. 2013, 91, 348–355.
83. Jiang, X.; Huang, J.; Chen, T.; Zhao, Q.; Xu, F.; Zhang, X. Synthesis of hemicellulose/deep eutectic solvent based carbon quantum dots for ultrasensitive detection of Ag+ and L-cysteine with “off-on” pattern. Int. J. Biol. Macromol. 2020, 153, 412–420.
84. Farhat, W.; Venditti, R.; Quick, A.; Taha, M.; Mignard, N.; Becquart, F.; Ayoub, A. Hemicellulose extraction and characterization for applications in paper coatings and adhesives. Ind. Crop. Prod. 2017, 107, 370–377.
85. Ebringerova, A. The potential of xylans as biomaterial resources. In Polysaccharide Building Blocks: A Sustainable Approach to the Development of Renewable Biomaterials; Wiley: Hoboken, NJ, USA, 2006.
86. Martínez-Ibarra, D.M.; López-Cervantes, J.; Machado, D.I.S.; Sanches-Silva, A. Chitosan and Xyloglucan-Based Hydrogels: An Overview of Synthetic and Functional Utility. In Chitin-Chitosan—Myriad Functionalities in Science and Technology; IntechOpen: London, UK, 2018.
87. Prajapati, V.D.; Jani, G.K.; Moradiya, N.G.; Randeria, N.P.; Nagar, B.J.; Naikwadi, N.N.; Variya, B.C. Galactomannan: A versatile biodegradable seed polysaccharide. Int. J. Biol. Macromol. 2013, 60, 83–92.
88. Polari, L.; Ojansivu, P.; Mäkelä, S.; Eckerman, C.; Holmbom, B.; Salminen, S. Galactoglucomannan Extracted from Spruce (Picea abies) as a Carbohydrate Source for Probiotic Bacteria. J. Agric. Food Chem. 2012, 60, 11037–11043.

Retrieved from https://encyclopedia.pub/entry/history/show/55778