**Lignocellulosic biomass: An economical and sustainable natural bioenergy source**

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**Abstract**

Lignocellulosic biomass is significantly important, cheap and abundantly available feedstock, comprising of agricultural waste or residues, forestry and solid wastes for the production of fuels and value-added chemicals. Lignocellulosic biomass assists in decreased requirement of fossil fuels thus reducing environmental pollution. From the economic point of view, lignocellulosic biomass can be produced quickly and at lower cost. Lignocellulosic biomass are promising substitutes to fossil fuels to fulfil the raw material needs of the manufacturing industry and help the transition from a linear to a circular economy, thereby meeting global sustainability criteria. In this book chapter, we have discussed structural complexity of lignocellulosic biomass and different biomass conversion methods. along with merits and demerits of pretreatment methods.

**Introduction**

Lignocellulosic biomass (LCB) is the utmost economical and renewable natural feedstock throughout the world. As a result, there has been increased interest in the development of chemicals derived from LCB. Technologies have been developed to produce various basic chemicals such as sugar alcohols, organic acids, furfural, oligo and polysaccharides using different biorefining technologies. The generation of renewable energy obtained from LCB as a substitute for fossil fuel is eventually essential for the persistence of the human race. LCB is generally divided into three types of waste: biomass, primary biomass and energy crops. Trees, shrubs, and sand grasses are classified as primary biomass, while agricultural residues, aggregates, and bagasse are classified as waste biomass. Energy crops are raw materials used for the production of second-generation biofuels because they offer high biomass productivity. These LCB can also be utilized for the generation of value-added products (Rahman et al. 2020). The application of LCB is expanded in several industries like biofuel production (Afolalu et al., 2021), paper industry (Limaye et al., 2017) and other pharmaceutical sectors (Bala et al., 2023). The LCB will be able to deliver approximately 38% of the direct fuel supply and 17% of the electricity worldwide by 2050 (Ong et al., 2021).

Bioenergy has attracted considerable interest as a sustainable energy source to replace depleting fossil fuels and help tackle rising fuel prices. In addition to the basic survival needs of food, water, and oxygen, human life requires supplemental sources of energy to sustain itself (Nanda et al., 2015). Although fossil fuels (oil, gasoline, coal, and natural gas) have accelerated global industrialization over the years, their adverse experiences cannot be denied. Direct effects of fossil fuel use include increases in greenhouse gases (especially CO2), air pollution, smog in urban areas, and water pollution from oil spills. Indirect effects include acid rain, global warming, climate change and other extreme weather conditions. Greenhouse gas (GHG) emissions, especially CO2, are directly proportional to the consumption of fossil fuels (Ehrenberg, 2012). Despite their rising prices, the demand for fossil fuels is increasing every day.

Bioenergy is seen as a promising resource as its ecological and economic benefits are becoming more apparent due to the improvement of technology. Due to this widespread awareness in the bioenergy sector, it is considered as one of the sustainable development agenda to achieve the Millennium Development Goals for 2015, especially in the area of ​​alleviating global hunger and poverty, adopted by the United Nations General Assembly in 2000 (Nanda et al., 2015). Most importantly, the introduction and production of such fuels should also have minimal impacts on the food web, water resources, land use pattern, ecosystem and environment (Chung, 2013). Waste biomass is one of the most promising sources of energy that supports the demand of a growing economy. It is therefore necessary to develop technologies that would enable the transformation of waste biomass into bioenergy with regard to thermodynamic efficiency and environmental impacts. In recent years, a significant amount of bioenergy research has been focused on biomass characterization, pretreatment, thermochemical and biochemical conversion, as well as biofuel refining.

In this book chapter, characteristics and structure of lignocellulosic biomass are primarily introduced. Afterward, the conversion or hydrolysis, which is one of the vital processes used to produce different kind of bio-energies, is introduced. This chapter makes an effort to evaluate the sustainability of LCB with respect to the production of next-generation biofuels.

**Lignocellulosic biomass structure and characteristics**

Lignocellulosic biomass includes numerous agricultural residues such as hardwood and softwood, pulp and paper industry waste, and energy crops. The structure of lignocellulosic biomass is complex, with recalcitrant and heterogeneous properties, and native holocellulose is resistant to enzymatic hydrolysis. The chemical characteristics and properties of the lignocellulosic components make them a suitable substrate of enormous biotechnological value (Nagar et al., 2022). The main components of these materials are 30%–50% cellulose, 20%–40% hemicellulose, and 15%– 25% lignin (Otieno & Ahring, 2012; Santibanez et al., 2021). The remaining fraction of lignocellulosic biomass includes proteins, oils and ash (Leng et al., 2010).

These three main components (cellulose, hemicellulose and lignin) are unevenly distributed in the cell wall and provide skeletal structure to plants (Ong et al., 2021; Bhagia et al., 2022). The connection between cellulose and hemicelluloses or lignin occurs mainly through hydrogen bonds, while the connection between hemicelluloses and lignin occurs through both hydrogen and covalent bonds (Liu et al., 2015; Galkin & Samec, 2016; Provost et al., 2022). In terms of structure, cellulose is a glucan polymer of d -glucopyranose units linked together by β-(1–4)-glycosidic linkages (Mansora et al., 2019). Meanwhile, hemicelluloses consist of polysaccharide polymers with a lower degree of polymerization compared to cellulose. Hemicellulose mainly contains sugars such as d-xylopyranose, d-glucopyranose, d-galactopyranose, l-arabinofuranose, d-mannopyranose, d-glucopyranosyluronic acid and d-galactopyranosyluronic acid etc. In addition, lignin has its own properties such as a three-dimensional, amorphous and highly branched phenolic polymer (Ong et al., 2021). Lignin is produced by an irregular process of biosynthesis composed of three basic phenylpropanoid monomers, p-hydroxyphenyl, guaiacyl and syringyl units (Katahira et al., 2018).

**Biomass conversion methods**

In general, the two most common methods used for biomass conversion include biological/biochemical and thermochemical conversion (Figure 1). In the biochemical conversion approach, enzymes are deployed to denature and decompose biomass materials to produce the desired products. Whereas during thermochemical conversion, high temperature is used with increased pressure to break down biomass in the presence of chemical catalysts to produce fine chemicals, chemical products, fuels and value-added products. Although, there is a third type of conversion, known as hybrid transformation, and it combines both thermochemical and biochemical methods (Inyang et al., 2022).

Each biomass conversion pathway has many of its own strengths and weaknesses; the appropriate conversion pathway is determined by many factors, including feedstock types, technology availability, the need for specialized enzymes and robust microbes for conversion, and energy requirements. The different types of conversion process are described here with their definitions.

**Figure 1:** Lignocellulosic biomass transformation methods

**Biochemical conversions of LCB**

***Fermentation***

Fermentation is the process of breaking down the sugar molecules into simpler compounds so as to produce substances that can be used in making chemical energy or the process during which sugars get transformed into a new product through chemical reactions supported/carried out by microorganisms. All the microorganisms employed in fermentation require the essential building blocks for their synthesis: carbon source, nitrogen source, salts, and different cofactors. Lignocellulosic biomass is extensively used in the field of xylanase production due to its low price and easy availability. Thus, xylanase secretion ability of Bacillus pumilus in submerged fermentation was tested using wheat bran as a substrate and a good xylanase titre was achieved (Tanwar et al., 2022). Another example of LCB conversion via fermentation is the production of second-generation bioethanol (Malik et al., 2022).

***Esterification***

Esterification is the chemical reaction in which two reactants generally an alcohol and an acid form an ester. It is an industrially important process applied for pharmaceutics, flavourings, and biodiesel production. An example of biodiesel production using oleic acid catalysed by the biomass-derived SPAC (Sulfonated polycyclic aromatic carbon) catalysts (Yadav et al., 2023).

***Anaerobic digestion***

It is a process of organic matter (animal manure, wastewater biosolids, and food wastes) breakdown through microorganisms or one can say that the sequence of processes by which microorganisms break down biodegradable substances in the absence of oxygen. Thermophilic anaerobic digestion process has been implemented worldwide mainly because to its pathogen-free method, in addition to increased biogas yield and decreased hydraulic retention time. Considering the high metabolic rate, thermophiles are widely investigated as an effective inoculum for LCB degradation and improved biomethane production (Singh et al., 2023).

**Thermochemical conversions of LCB**

***Gasification***

Gasification is a process which utilizes heat, pressure, and steam to transform biomass or carbonaceous materials directly into a gas. The supercritical water gasification (SCWG) of lignocellulosic biomass for hydrogen production was reported earlier (Wang et al., 2023).

***Liquefication***

Liquefication is a thermochemical conversion of the carbonaceous matters of biomass into liquid products in the presence of a solvent at relatively low temperature (Li et al., 2022). The conversion of LCB to bio-oils is generally termed as direct liquefication. In a previous study, spent catalyst (V2O5-WO3/TiO2 was potentially utilized as the catalyst in hydrothermal liquefaction (HTL) to produce bio-oil (Qian et al., 2022).

***Pyrolysis***

It is a thermochemical process of biomass decomposition taking place in absence or limited supply of oxygen. Syngas or the synthesis gas is a valuable flammable mixture of hydrogen and carbon monoxide gases along with smaller quantities of methane, carbon dioxide and hydrocarbons (Awe et al., 2017). The use of thermochemical process pyrolysis was greatly employed previously (Ghodke et al., 2023; Sridevi et al., 2023).

***Combustion***

Biomass combustion is the most common process of consecutive heterogeneous and homogeneous reactions for converting the solid biomass fuels to energy (Mizakova et al., 2021). The co-combustion behaviours of coal and lignocellulosic biomass, and coal and hemicellulose/cellulose/lignin and their synergistic effects were investigated (Wang et al., 2022).

**Lignocellulosic Biomass Pretreatment**

The main objective of the pretreatment protocols is to deconstruct the complex structure of biomass to make each biopolymer easily utilized for the production of fuels, chemicals and power. Pretreatment is also considered as the central unit operation which affects the effectiveness of biomass processing techniques (Guragain and Vadlani, 2021). Several pretreatment methods are available such as physical, chemical, physico-chemical, and biological pretreatments. The pre-treatment set up determine the potency of the process; higher the yield produced better the process (Otieno and Ahring, 2012). Different advantages and disadvantages of the pretreatment methods are described in table 1. Some of the pretreatment methods are listed as follows:

* Physical methods: extrusion and microwave pretreatment.
* Chemical methods: acid pretreatment and alkali pretreatment
* Physico-chemical methods: steam explosion and ammonia fiber explosion
* Biological methods: use of microorganisms

Table 1: Different pretreatment methods and their advantages and disadvantages

|  |  |  |
| --- | --- | --- |
| **Pretreatment method** | **Advantages** | **Disadvantages** |
| Physical  | * No inhibitory compounds formation
* Easy process monitoring
* Continuous and controlled process
* Combined with other pretreatment methods
* No need of biomass washing
 | * Lack of data analysis
* Energy consuming process
* May lead to burning of material
 |
| Chemical | * Can be designed for separate hemicellulose and cellulose hydrolysate
* Effective delignification (alkali treatment)
* Cost saving for xylanase enzyme
 | * Production of unintended product
* Environmental concerns due to high use of chemicals
 |
| Physico-chemical | * Relatively less dilution of released materials
* High particle size biomass can be used
* High selectivity for delignification (AFEX)
* No use of additional chemicals (LHW)
* Minimum formation of inhibitory compounds
 | * Cost of solvent recovery
* Environmental concerns
 |
| Biological | * No inhibitory compounds are produced
* Environment friendly
 | * Strict control over the process is required
 |

\*AFEX: Ammonia fiber explosion pretreatment, LHW: Liquid hot water treatment

**Conclusion**

The lignocellulosic biomass contributes to economic value as the bioenergy production is without an increase of the agricultural areas. The development of efficient and economically feasible pretreatment method is vital for a sustainable bioenergy production. However, the development of a single pretreatment method for all types of input raw materials is almost impossible due to the substantial differences in the composition and complex biomass structure. Each pretreatment method is associated with its own advantages and limitations, which in turn depend on the composition and structure of the biomass. Therefore, the combination of two or more pretreatment methods with efficient energy integration would be a more effective option to develop a sustainable lignocellulosic industry.

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