# Lignocellulosic Biomass and Conversion Technology

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**Abstract**

The research and development of alternative energy sources, especially bioenergy have become extremely important due to increasing demand for energy consumption and fossil fuel use, surged fuel prices, and significantly increased greenhouse gas (GHG) emissions over the last decade. Lignocellulosic biomass garnered public interest as a renewable alternative energy source because of its potential to mitigate greenhouse gas emissions, enhance national energy security, and bolster economic opportunity for rural communities. Nevertheless, its low energy density, high volatile content, low caloric value, and hydrophobic nature make it least preferable as it requires to undergo for a specialize pretreatment while converting it to the value-added energy products. The effectiveness and optimization of biomass to bioenergy conversion technique requires a careful pairing of advanced conversion technologies. For instance, lignocellulosic biomass can be converted to the value-added energy products via exploitation of diverse pathways that include but not limited to: (a) thermo/bio-chemical conversion routes, (b) microbial and enzymatic degradation techniques, and (c) consolidated bio-processing approach. In this chapter, we identified, compared, and assessed those conversion technologies, and further evaluated their applicability, efficiency, effectiveness, and limitations while developing the value-added energy

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R. Kothari et al. (eds.), *Biomass, Bioenergy & Bioeconomy*, Microorganisms for Sustainability 35, https://doi.org/10.1007/978-981-19-2912-0_5

products. We believed that the lignocellulosic biofuel will not replace the current use of fossil fuels; it rather complements and reduces their use while meeting the world's ever growing energy demand. To make lignocellulosic biofuel as a viable long-term energy strategy in the United States, there is a need to improve the conversion efficiency at a scale that is sufficiently large for commercial production. The diverse characteristics of lignocellulosic biomass, which requires unique conversion pathway, warrants future biologists, plant scientists, microbiologists, and enzymologists to prioritize the traits and advance the viable conversion pathway for the development and production of next generation of renewable energy for the 21st century.

**Keywords**

Thermochemical conversion · Bio-chemical conversion · Lignocellulosic biomass · Biofuel · Enzymatic · Microbial degradation

## 5.1 Introduction

The non-renewable fuels, in particular, fossil fuels (i.e. petroleum, coal, and natural gas) serve approximately 80–90% of today's global energy needs, both energetically and commercially (Hayes 2009). Nevertheless, they are non-renewable, are limited, and have reached to a "Hubbert Peak" in terms of their production and in some cases are in the verge of rapid depletion. Growing public interest and awareness on clean energy, the crude oil production is anticipated to decline from 1033 billion gallons in 2010 to 206.6 billion gallons in 2050 (Campbell and Laherrère 1998). Despite this projected decline in crude oil production, the reservoir of crude oil, natural gas, and coal are estimated to be exhausted in the next 50, 60, and 120 years, respectively (Tissot and Welte 2012).

Secondly, anthropogenic activities such as land use and land cover change, and fossil fuel combustion contributed an increased in concentration of greenhouse gases (GHG) in the atmosphere. In 2018, the USA accounted for about 5.42 billion ton of the total $CO_2$ emission (Lal 2004; Ritchie and Roser 2017). The liquid fuels from fossil fuels are projected to induce the carbon dioxide emissions from 14,740 Million Tonnes of Oil Equivalent (Mtoe) (2002) to 27,364 Mtoe (2030), which is in fact a very serious concern (Asia Pacific Energy Research Centre (APERC) 2007). According to United States Environmental Protection Agency (EPA) 2018 report on inventory of US greenhouse gas emission and sinks, total GHG emission has increased by 3.7% and $CO_2$ emission from fossil fuel accounts for 6.2% increase for the last 28 years (baseline year 1990).

As of 2007, the number of cars and light trucks on the road were about 806 million, which is projected to increase to 1.3 billion and over 2 billion by 2030 and 2050, respectively (World Business Council for Sustainable Development

(WBCSD) 2004; Balat 2011). This results in anthropogenic loading of GHG such as carbon dioxide, nitrogen oxide, and methane in the atmosphere will be a significant contribute towards climate change and global warming (Sun et al. 2012).

As such, the dwindling supply of commonly used traditional energy resources (i.e. fossil fuel), coupled with global warming as a foremost environmental concern have added new immediacy to the renewed interest in the pursuit of accessible, affordable, and eco-friendly sustainable energy source (Crutzen et al. 2016). Such challenges may be an opportunity for researchers and policy makers to promote renewable source of energy to meet our ever-growing energy needs, mitigate climate change, enhance environmental quality, uplift rural livelihoods, and strengthen global economy.

In regard to the above-mentioned scenarios, hydroelectric, geothermal, wind and solar approaches are some of the current methods to satisfy the renewable power needs through electricity generation. According to the International Energy Agency (IEA) report 2019, these sources account for 25.6% of total electricity generation (IEA, International Energy Agency 2019). Hydropower has the highest shares of 63% to global electricity generation among these approaches, followed by Wind (18.1%) and solar photovoltaic (8.3%) (IRENA, International Renewable Energy Agency 2020). The electricity generated through hydropower is supposed to reduce 4 billion tons of GHG emission per year (Association 2019). Similarly, another approach of electricity generation—geothermal approach has very low (103 g $CO_2$e/kWh) GHG emission from power generation compared to coal (1235 g $CO_2$e/kWh) and natural gas (485 g $CO_2$e/kWh) (Sullivan et al. 2010). While looking over the statistics provided by World Wind Energy Association (WWEA), the total global wind power energy has reached 650.8 GW in 2019 ultimately resulting to lowest GHG emission (8 g $CO_2$e/kWh) and air pollution after hydropower (5 g $CO_2$e/kWh) (Sullivan et al. 2010). Also, it is productive to state that the solar energy provides $2.5 \times 10^{21}$ Btu/year (1 British thermal unit (Btu) = 1055.05585 joules), more than 12,000 times the current human requirement of $2.0 \times 10^{17}$ Btu/year and approximately 4000 times the energy projection expected to use by humans in 2050 (Demain et al. 2005; Kumar et al. 2008). The energy obtained from the sun is utilized via photovoltaic conversion or by exploiting plant biomass as solid or liquid fuels (Armaroli and Balzani 2007). Regardless of it, none of these approaches can suffice the global energy needs. Thus, unlike merely a single technology, a basket of complementary technologies is helpful to stimulate the production of eco-benign renewable fuel sources. The best alternative method to strategically substitute the consumption of fossil fuel and meet energy demand is through the use of biomass (Piemsinlapakunchon and Paul 2019). The production of renewable liquid fuels from cellulosic biomass is considered to be the utmost effective approach. As a further matter, the microbial conversion of cellulosic biomass into ethanol is an often-touted route in an alternative fuel industry (Alper and Stephanopoulos 2009; Das et al. 2020).

Biofuels evolved over time, and they are classified as first, second, third and fourth generations based on the feedstock production and use. Biofuels produced from edible food crop feedstocks that contain starch are first generation biofuels

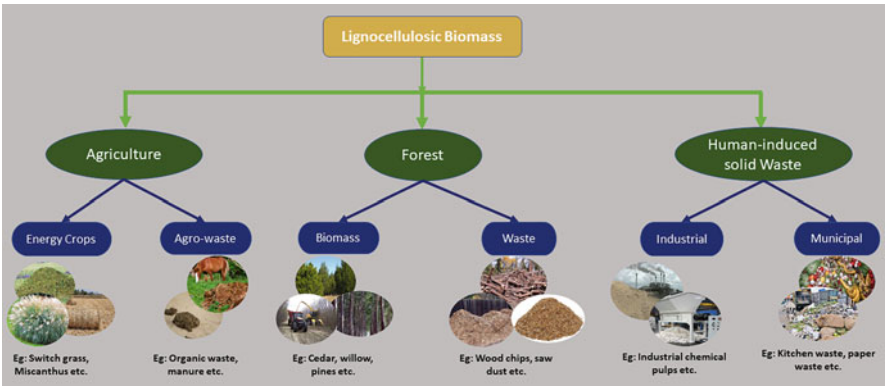


**Fig. 5.1** Sources of lignocellulosic biomass

(Bhatia et al. 2017). High cultivation cost and competition with foods make the first generation biofuel feedstocks unreliable and unsuitable alternative for fossil fuels (Alalwan et al. 2019). Inedible lignocellulosic biomass mainly from forest, agricultural residues and industrial waste are second generation biofuels. These sources of biomass have higher possibility to become best alternatives for fossil fuel despite their limitations in scaling up the production (Alalwan et al. 2019). Third generation biofuels are produced from the algae that lead to the high yielding biofuel (Bhatia et al. 2017). Fourth generation biofuels are produced from genetically engineered, low lignin and cellulose containing feedstocks to solve the possible limitations of second and third generation biofuel feedstocks production. The metabolic engineering pathways used for the fourth generation feedstock production which can be a prominent strategy for high yielding biofuel in near future (Dutta et al. 2014).

Out of all types, biofuels from second generation feedstocks are found to be feasible and environmentally sustainable. While looking over the abundance of the feedstock to produce these different generations of biofuels, second generation biofuels are found to be ubiquitous, eco-friendly, and easily accessible. Also, they are derived from the non-food sources and do not compete with food production. A sustainable production of lignocellulosic biofuel minimizes the risk of environmental problems that include but not limited to deforestation and land degradation, unsustainable land and water use, global warming, and natural resources depletion. Also, forest and crop residues, major sources of feedstock of second generation biofuels are found to be carbon neutral and have high carbon capturing ability. They do not add additional carbon to the atmosphere while burning. The heating value is about $3 \times 10^6$ kcal/Mg, which is twice of that of coal and thrice of that of diesel (Larson 1979).

Lignocellulosic biomass is a carbon rich biodegradable plant and animal materials, especially obtained from agricultural, industrial and municipal wastes, substantial forest residues, and wastewater treatment plants as explained in Fig. 5.1 (Deublein and Steinhauser 2011; Yousuf et al. 2020). The paucity of global energy (from fossil fuels) in the near future, the global warming and environmental concerns

have propelled to a resurgence in the production of sustainable fuel sources. Biomass receives notable significant concern as an alternative viable and environmentally sustainable feedstock for the production of biofuel in an industrial scale. The singular attributes of biofuel from cellulosic biomass such as environmentally benign, lower hygroscopicity, and competitiveness with the existing transportation fuels can circumvent the associated problems due to fossil fuels (Sakimoto et al. 2016).

Cellulosic biomass is the most ubiquitous class of biomass available on earth and it is the forest that accounts for about 80% of the world's plant biomass (Sakimoto et al. 2016). Perlack et al. (2005) stated that forest-based woody biomass represents nearly 370 million tons per annum of cellulosic biomass in the USA. Hadar (2013) proposed that 154 l of bioethanol can be produced from 1 ton of fiber representing municipal solid waste. Kim and Dale (2004) suggested that 491 Gallon/year can be produced from the crop residues. Taking into consideration a viable conversion technology, the biofuels from cellulosic biomass could replace about 30–40% of the total annual transportation gasoline in the USA (Wu et al. 2010).

The process of conversion of cellulosic biomass into liquid or gaseous fuel is a very meandering phenomenon. The route for conversion of cellulosic biomass into the biofuel has about 45–50% conversion energy efficiency (Fajardy et al. 2019). Consumption of the products from these routes releases only about 25–30% of the carbon dioxide to the atmosphere which is relatively very low to that of fossil fuel consumption. In the USA, according to the 2018 data produced by EPA, 75.4% of the total carbon dioxide emission in the atmosphere was from the combustion of fossil fuels (Hockstad and Hanel 2018). As of today, the thermochemical and the biochemical are the two prominent conversion routes exploited for the processing of cellulosic biomass. Each of them has its own merits, demerits, and the technological pathway. Biochemical conversion is preferred for high efficiency during conversion as well as high selectivity whereas, the major advantage of thermochemical conversion is the ability to accept wide range of feedstocks and robust technology while conversion. The pyrolysis, and gasification/liquefaction incorporate in the latter approach, where the fermentation, hydrolysis, and anaerobic digestion are the former approach.

The economic aspects, environmental standards, type and amount of the biomass feedstock, its size and shape distribution, and the required form of energy are some of the fundamental aspects that play an important role while selection for the suitable cellulosic biomass conversion approach (Kenney et al. 2013). The infancy of the current understanding of the mechanistic and biochemistry attributes of commercial enzymes, its costly nature and the slow specific enzymatic hydrolysis are the major impediments for large scale biofuel production.

Thermo-chemical routes, also referred to as biomass to liquids (i.e. BTL), are basically the incorporation of heat energy and chemical catalysts for the breakdown of cellulosic biomass into its intermediate components. The thermochemical conversion route encompasses combustion, pyrolysis, and gasification; yielding intermediates (i.e. bio-oils by pyrolysis and syngas by gasification). To the contrary, in bio-chemical conversion route, several enzymes and micro-organisms are

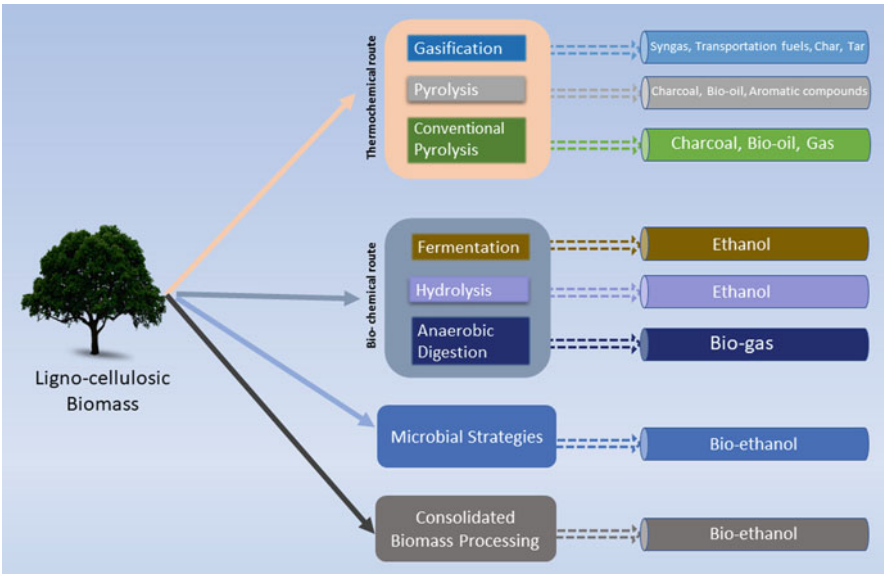


**Fig. 5.2** Types of lignocellulosic biomass conversion routes and their final products

employed for the breakdown of biomass into desirable products (i.e. ethanol). Bio-chemical route is sub-categorized into anaerobic digestion and fermentation. Here, we examine challenges and opportunities of both the thermo-chemical and bio-chemical pathways for the biomass conversion. A brief description of the diverse routes in the lignocellulosic biomass conversion and its end products is manifested in Fig. 5.2.

## 5.2 Thermo-Chemical Conversion Routes

### 5.2.1 Gasification

Gasification is the thermochemical conversion process of biomass into a combustible gaseous mixture such as syngas. It primarily involves the use of high temperature (800–900 °C) and a controlled environment for the conversion of biomass into a combustible gas mixture such as producer gas or syngas. The producer gas or syngas is a mixture of hydrogen, carbon monoxide, methane, carbon dioxide, and nitrogen (Demirbas 2004; Naik et al. 2010; Piemsinlapakunchon and Paul 2019; Yu et al. 2019). The oxidizing agents also known as gasifying agent such as air, steam, $CO_2$, $O_2$, and $N_2$ play an utmost prominent role in the decomposition of large polymeric molecules of biomass into lighter molecules and ultimately to permanent gases, ash, tar, char, and other minor contaminants. The incomplete conversion of biomass lead to the production of char and tar (Kumar et al. 2009).

The production of syngas is possible through two different pathways, namely catalytic (requires high temperature for operation as high as 1300 °C) and non-catalytic (involves low temperature comparatively) (Naik et al. 2010; Carvalho et al. 2017). The syngas can be upgraded to liquid hydrocarbons such as diesel and gasoline through Fischer–Tropsch (FT) synthesis (Alonso et al. 2010). Sasol South Africa is an example that incorporates FT synthetic facilities to produce liquid fuels, chemicals, and electricity. Carbon monoxide and hydrogen, the major components of syngas, are the building blocks of essential products such as chemical-fertilizers and fuels; thereby, syngas is primarily used to make a range of power transportation fuels, fertilizers, chemical intermediates, and substitute natural gas (Naik et al. 2010).

Biomass gasification is a promising biomass conversion process and has significant potential due to its flexibility to use irrespective of feedstock nature and to convert into energy, and broad range of transportation fuels and chemicals (methanol, urea). In addition, gasification process aids in reducing methane emissions from landfills and production of ethanol from non-food sources. The use of syngas from gasification coupled with the gas turbines and fuel cells is being used to enhance the efficiency and cut off the investment costs of electricity generation through biomass (Demirbaş 2001; Kumar et al. 2009). On the contrary, the amount of water in the biomass and cleaning the impurities in the product gas from various contaminants such as alkali compounds, and tar are the technical bottlenecks in the commercialization of fuels and chemical production.

The operation of gasification reactors encompass four steps, namely drying, volatilization, reduction, and combustion (Damartzis and Zabaniotou 2011). In a nutshell, the biomass gasification despite the fact being a prominent technology in the production of second generation automotive biofuel, it is still in its infancy in terms of commercialization.

### 5.2.2 Pyrolysis

Pyrolysis, the precursor of combustion and gasification of biomass, is the conversion phenomenon of biomass into a fuel source in the absence of oxygen. It comprehends the thermal anaerobic destruction of biomass into a carbon rich solid residue (charcoal), an oil-like liquid (bio-oil or crude oil) and a hydrocarbon rich gaseous products, acetic acid, acetone, and methanol by heating the biomass to about 700–800 K (Demirbaş 2003). The thermal environment and the temperature have a significant effect on the pyrolysis yield. Bio-char is the by-product of pyrolysis at longer reaction times (i.e. temperature around 450 °C), whereas gaseous compounds are produced at high temperatures around or greater than 800 °C. An intermediate temperature is optimum for the production of bio-oil (Alonso et al. 2010). Thus produced bio-crude is considered not only to be used in engines and turbines, but also has been regarded to be efficient as feedstocks refineries (McKendry 2002). The conversion of biomass into its subsequent products yield around 20–30% aromatic compounds in the presence of H-ZSM-5 (Carlson et al. 2009).

## 5.3 Conventional Pyrolysis

Conventional pyrolysis is a slow and irreversible process for the disintegration of organic matters in biomass into various pyrolysis products. This traditional technique has been used mainly for the production of charcoal (Yaman 2004). In developing nations, charcoal is used as a domestic fuel source because its energy density content is relatively higher and is smokeless (Demirbaş 2001). On the contrary, fast pyrolysis (thermolysis) or flash pyrolysis also known as ultra-pyrolysis is considered an innovative design with promising characteristic as an alternative for efficient pyrolysis of biomass feedstock that includes seaweed and algae (Shuttleworth et al. 2012). As suggested by name, fast pyrolysis is a rapidly occurring thermochemical conversion of biomass with 60–70% bio-oil yield and 20% bio-char and syngas simultaneously; depending upon the nature of feedstock (Naik et al. 2010). Hayes (2009) has reported 60–70% bio-oil yield and obtain increased yield of bio-crude products. Here, the expedition decomposition of biomass induces the production of vapors, aerosols, and gaseous products. Flash pyrolysis is a thermochemical biomass conversion route performed in the range of 1000–1300 K in order to change the small fraction of dried biomass into bio-crude.

Biomass pyrolysis is at utmost prominent attention as an alternative for a thorough exploitation of cellulosic biomass due to its inherent attributes such as significant economic benefits over other existing thermal conversion processes in addition to the notable logistical aspects. However, the major impediment for direct bio-oil use are the poor thermal stability, high acidity, low energy, density, and corrosive nature that perils equipment lifetime once used in existing engines (Demirbaş 2003; Alonso et al. 2010).

### 5.3.1 Bio-Chemical Conversion Routes

In spite of the fact that the thermochemical conversion is employed for biomass conversion, the use of promiscuous biological enzymes has gained a significant attention in industrial setting due to its efficient and selective nature in the biochemical reaction (Jaeger et al. 1999). Nevertheless, the factors such as poor stability, increased cost, low activity of the currently available enzymes trigger the uncertainty in the feasibility of biomass conversion for sustainable fuel production. On this account, the need for the development of novel enzymes is of prime significance for bio-economy (Barnard et al. 2010). The biochemical conversion technology assists the conversion of cellulosic biomass into different intermediates through the aid of bio-catalysts, novel enzymes or microbes. At present, the exploitation of biochemical pathway inherited into the native micro-organisms can be often touted route for the proper biomass utilization and its conversion in industrial processes (Alper and Stephanopoulos 2009). So far, the two divergent microorganisms, namely *Escherichia coli* and *Saccharomyces cerevisiae* have produced a promising organisms of choice for biotechnological applications in biofuel industry.

Fermentation and anaerobic digestion are the two major processes in bio-chemical conversion pathways.

#### 5.3.1.1 Fermentation

Basically, this process is used in commercial scale for the large scale production of ethanol from different crops such as sugarcane, sugar beet, corn, and wheat (McKendry 2002). Mostly, yeast is used for converting sugars into ethanol. The batch processes, semi-continuous processes, and continuous processes are the three different fermentation processes deployed for ethanol production (Saxena et al. 2009). The use of transgenic micro-organisms can enhance the efficiency of fermentation process. The insertion of genes into a micro-organism possess the ability to ferment both 5-carbon sugar (pentose) and 6-carbon sugar (hexose) (Ingram et al. 1991). Nevertheless, it is of prime importance for the lignocellulosic biomass to undergo hydrolysis due to its recalcitrant nature.

#### 5.3.1.2 Hydrolysis

The hydrolysis comprises of acid treatment and enzymatic hydrolysis of biomass. The acid treatment incorporates both concentrated as well as the dilute acid hydrolysis process. The concentrated hydrolysis mainly de-crystallize cellulose with concentrated acid, followed by the dilute acid hydrolysis into sugars (Kyoung Heon Kim and Nguyen 2002). The later hydrolysis process more efficient for ethanol production from biomass, where 0.7% sulfuric acid is used at 190 °C to hydrolyze the hemicellulos present in the plant biomass at a first stage. In addition, the second stage yields cellulose fraction by using 0.4% sulfuric acid at 215 °C (Brennan et al. 1986).

Unlike acid hydrolysis, during enzymatic hydrolysis, the synergistic actions of multifunctional cellulolytic enzymes screened from the various micro-organisms are of fundamental significance for the microbial degradation of cellulosic biomass and its downstream applications. The cellulase enzymes are considered as the most prominent among them so far (Saxena et al. 2009). The microbes deploy their extracellular cellulases to hydrolyze and metabolize the recalcitrant nature of plant carbohydrates into sugars which is then fermented by bacteria, yeast or other micro-organisms to produce ethanol (Ando et al. 1986; Lynd et al. 1999, 2016; Thapa et al. 2020).

#### 5.3.1.3 Anaerobic Digestion

Anaerobic digestion is the natural biological conversion of organic wastes into bio-fertilizers or bio-gas by the use of bacteria in anaerobic condition. Thus, produced bio-gas encompasses an energy content of about 20–40% of the lower heating value of feedstock and can be used in gas turbines, and as a natural gas substitute. This is a reliable commercial technology for the organic waste and cellulosic feedstock treatment. The energy produced through anaerobic digestion can be used for both electricity and heating purposes.

## 5.4 Microbial Strategies for Lignocellulosic Degradation

The different cellulolytic and xylanolytic enzymes derived from various cellulolytic and xylanolytic bacteria, fungi can be exploited for the biomass conversion to feedstock chemicals. A study done by Benedict C. Okeke stated the strain of *P. janthinellum* FS22A and *T. virens* FS5A proved to be promising for the co-production of cellulolytic and xylanolytic enzymes in a research lab scale; yet further investigations are required to enhance their enzyme production (Okeke et al. 2015). The holistic approach in engineering the microbial enzymes, their proper isolation, identification, expression, characterization, and final assay can aid further to achieve tailor-made cellulases and xylanases for various industrial applications.

The bacterial species present in soil, marine, herbivore guts possess multi-functional novel enzymes that can efficiently hydrolyze the plant cell wall constituents (Medie et al. 2012). The bacterial glycosidase hydrolases enzymes enhance functions and synergistic effects and hence are often multi-modular (www.cazy.org). Sigoillot et al. (2012) stated that Basidiomycota and Ascomycota fungi demonstrated effective ability to produce wide range of lignocellulolytic enzymes to deconstruct lignocellulosic materials. Soft-rot fungi degrade plant polysaccharides; brown-rot fungi such as *Gloeophyllum trabeum*, *Coniophora puteana,* and *Postia placenta* degrade cellulose and hemi-cellulose; white-rot fungi are efficient in the degradation of wood components (Daniel et al. 2007; Irbe et al. 2011; Sigoillot et al. 2012). Hyperthermophiles archaea domain and thermophilic bacteria like *Thermotoga* and *Aquifex* have the ability to grow on crystalline cellulose and unprocessed plant biomasses (Yang et al. 2009).

The enzymatic hydrolysis of plant cell wall takes place through the combined action of three different glycol-hydrolyze (GH) enzymes, namely endoglucanase (EC 3.2.1.4), exo-glucanase also known as cellobiohydrolases (EC 3.2.1.91) and β-glucosidases (EC 3.2.1.21). All these enzymes hydrolyze the β-1, 4 covalent bonds where the glucose units are connected in the cellulose fiber. Endoglucanase belong to families GH5, GH6, GH7, GH9, GH12, GH45, and GH74. β-glucosidases belong to families GH1 and GH3. The two important synergistic action endo-exo between endoglucanases and cellobiohydrolases and the exo-exo between two cellobiohydrolases are of phenomenal importance during the hydrolysis of cellulose. Hemicellulose hydrolysis also requires the intervention of several functional enzymes along with the complementary activities at various levels. GH and carbohydrate esterase (CH) are involved in the hemi-cellulose hydrolysis by cleaving ester bonds between the acetyl groups and hemi-cellulose chains (Shallom and Shoham 2003).

The production of better competitive enzymes cocktails through the exploration of fungal bio-diversity with their Secretomes is one of the new approach in isolating the multi-functional enzymes to increase the saccharification efficiently in biomass conversion. In addition, the library of new microbial genome sequencing, the proteomic and transcriptomic analysis and thorough studies of various bacterial, fungal and other microbes thriving in harsh habitats and enzymes isolated therein,

can definitely be the kernel of hope to open new avenues for lignocellulolytic/xylanolytic discovery.

## 5.5 Consolidated Bio-processing

The economic aspects related with the hydrolysis of cellulosic biomass in producing ethanol is one of the major bottlenecks that needs to be unlocked. Consolidated bio-processing (CBP) reduces the lignocellulosic bioprocessing operation cost with improved cellulosic conversion efficiency through the integration of the enzymatic hydrolysis of cellulose and the subsequent fermentation by the production of single cellulolytic enzyme or microbial consortium.

The efficient operation of CBP requires the engineering of a CBP enabling microbe, which is being made primarily through two different strategies: strategy I incorporates the engineering of a micro-organism that produce cellulase that can ferment sugars; Strategy II is engineering the ethanologenic micro-organisms that exhibit cellulolytic attributes with high product yields and enable cellulose utilization (Amore et al. 2012; Daniel et al. 2012). In regard to CBP strategy I, owing to the high level production of cellulase activity, the filamentous fungi, namely *Trichoderma reesei* is considered as the best potential candidates due to their broad range of tools for genetic manipulation (Xu et al. 2009). Unlike, as far as CBP strategy II is considered, the bacteria like *E. coli* and *Zymomonas mobilis* (Edwards et al. 2011) and fungi *Kluyveromyces marxianus* and *Saccharomyces cerevisiae* are the most interesting candidates (Jung et al. 2013).

Despite being a favorable candidate, both bacteria and yeast are unable to sufficiently produce cellulolytic enzymes in terms of quantity and quality for lignocellulosic biomass degradation. Filamentous fungi are proven to be prolific in production of high amount of cellulolytic enzymes and therefore, the genetic engineering of these fungi is of prime need for enhancing ethanol yield.

## 5.6 Conclusion and Future Perspectives

Biomass is the most ubiquitous renewable carbon source that can be processed in an integrated biorefinery. Hence, the production of various biofuels and other value-added co-products based on lignocellulosic biomass is now a global primacy. Nonetheless, the exploitation of lignocellulosic biomass in the production of biofuels and bio-based chemicals is neither new nor is an historic artefact. The pre-treatment of recalcitrant nature of cellulosic biomass and the expensive biomass conversion technology is a prime bottleneck in its bioprocessing for biofuels and other bio-products. The crucial economic and technological impediment in bio-ethanol production includes but not limited to pretreatment process, enzymatic hydrolysis, fermentation strategy, and distillation process. Even though some of the biomass conversion strategies deliver some apparent advantages, it is considered that none of the technique has become the strategy of choice at this point at least not for all

feedstocks. The bio-chemical complexity, increased oxygen concentration, and elevated stability are some of the pre-eminent factors to be considered during the biomass pre-treatment. Likewise, high processing costs are perceived as the most impediment to commercialization for biomass conversion technologies. The cocktail of biomass pre-treatment technologies could enhance the biomass digestibility while reducing the inhibitory product formation. Similarly, the synergistic action of multi-functional novel cellulolytic/xylanolytic enzymes could improve the biomass conversion efficiency. A coordinated research on the biomass pre-treatment strategies, feedstock digestibility, conversion strategy, enzymatic hydrolysis, and fermentation technology could impart a fundamental understanding in optimizing the robust integrated biorefinery approach in the near future. The successful commercialization of multitude conversion strategy advances necessitates the catalysts synthesis and its optimum performance, kinetic evaluation of the various chemical reaction pathways, comprehensive in situ enzyme characterization as well as theoretical studies comprehending state of the art "omics" approaches.

Despite innumerable challenges, biofuel is the most promising as well as viable energy portfolio not to replace the use of fossil fuels rather complements to meet the world's ever-growing demand of energy. The current and emerging conversion technologies such as pyrolysis, gasification, and cellulosic ethanol production bestow extensive opportunities while improving the biomass conversion efficiency while reducing greenhouse gas emission in the atmosphere, bolstering rural economy, and enhancing the national energy security.

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