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Biorefinery of Alternative Resources: Targeting Green Fuels and Platform Chemicals

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Preface

The production and overwhelming usage of fossil fuels and petrochemicals have resulted in several environmental concerns such as increased greenhouse gas emissions, global warming and pollution. Moreover, the production and consumption of fossil fuels and their derivatives are prodigiously increasing due to rapid urbanization, industrialization, population growth and improvements in day-to-day lifestyle. Due to the many adverse effects of fuels and chemicals derived from fossil resources on the environment and ecosystems, it has become highly imperative to find alternatives that are not only environmentally friendly but also fully or partially biodegradable, cost-effective, feasible. Moreover, these green alternatives, usually referred to biofuels, biochemical and biomaterials should be promising to make a paradigm shift in the consumer market to replace the fossil fuels and petrochemicals.

Renewability, carbon neutrality, abundancy, reasonably priced as well as non-competency to food, fodder and arable lands are other attributes of a potential bioresource to generate biofuels and biochemicals. Some of such potential bioresources include lignocellulosic biomass (e.g., agricultural crop residues, forestry residues and energy crops), microalgae, municipal solid wastes, industrial effluents, cattle manure and other organic refuse. This book is a compilation of twenty chapters, which discusses the potential of such bioresources to produce biofuels, platform chemicals and other bio-based products. Several thermochemical and biological conversion technologies are described in terms of their conversion pathways to biofuels and biochemical through biomass-to-liquid (e.g., pyrolysis, liquefaction, fermentation and mechanical extraction), biomass-to-gas (gasification and anaerobic digestion) and gas-to-liquid (Fischer-Tropsch catalysis). This book provides the up-to-date information on the production and utilization of biofuels and biochemical, biomass conversion routes (thermochemical, hydrothermal, biological, mechanical and physicochemical), reforming technologies as well as techno-economic and life-cycle assessment studies.

Chapter 1 by Arun and Dalai gives an overview of the opportunities, prospects and challenges in the biofuel sector in the current market scenario. A detailed analysis on the risk factors association with technological innovation in the biofuels sector is the main objective of this chapter.

Chapter 2 by Pasin et al. describes the bioconversion potential of lignocellulosic biomass to bioethanol. The composition of cellulose, hemicellulose and lignin as well as their biosynthesis in different agricultural crop residues and hydrolysis are provided.

The pretreatment procedures, enzymatic hydrolysis and microbial fermentation of biomass to second-generation bioethanol are described.

Chapter 3 by Rana and Parikh highlights the catalytic conversion of ethanol to several value-added chemicals such as acetaldehyde, acetic acid, acetone, ethylene, butanol, 1,3-butadiene and ethyl acetate. The role of catalysts, catalyst supports, metal-support interactions, oxygen storage capacity, acidity and basicity of catalyst in the conversion of ethanol to platform chemicals are described.

Chapter 4 by Phung and Busca summarizes the reaction pathways in bioethanol conversion such as dehydration, oxidation, steam reforming, dehydrogenation and Guerbet reaction to base chemicals and fuel derivatives. A highlight on different catalysts, catalytic reactions and ethanol-derived products are made.

Chapter 5 by Nanda et al. throws light on butanol and propanol as the next-generation biofuels. The fuel chemistry, production technologies from petrochemicals and biomass as well as biotechnological developments in the fermentation of lignocellulosic biomass to produce butanol and propanol are provided.

Chapter 6 by Sarangi et al. makes a review of the industrial applications and production pathways of biomethanol as a biofuel and biochemical. The industrial applications, technical challenges, future perspectives and several production pathways of biomethanol are summarized.

Chapter 7 by Naira et al. analyses various thermochemical and biological conversion routes of lignocellulosic and algal feedstocks to produce biofuels and biochemicals for use in energy, food, pharmaceutical, cosmetic and textile industries. The co-production technologies of biofuels and biochemicals from sugars (pentose and hexose) and lignin as well as the generation of bioactive components such as lipids, carbohydrates and proteins from algae have been described.

Chapter 8 by Koshin et al. discusses the main biorefining approaches and concepts in the thermochemical and biological conversion of rice husk and nutshells into valuable gaseous, liquid and solid biofuel products. The physicochemical properties and geographical distribution of rice husk and nutshells as well as their industrial relevance of their fuel and chemical products are highlighted.

Chapter 9 by Singh et al. reviews the thermochemical (e.g., pyrolysis, liquefaction, torrefaction and gasification) and biological (enzymatic saccharification and fermentation) conversion technologies of *Miscanthus* as an energy crop to biofuels. The value-added applications of *Miscanthus*, especially in pulp and papermaking, biocomposites and biochemical production are also discussed. The physicochemical properties of bio-oil and biochar generated from *Miscanthus* are also described for fuel and material applications.

Chapter 10 by Suryawanshi et al. reviews the challenges, opportunities, recent developments and techno-economic feasibility of hydrothermal liquefaction and pyrolysis of lignocellulosic biomass for bio-crude oil production. The scope of the chapter also extends to bio-oil upgrading technologies, value-added chemical production and application of novel catalysts in hydrothermal liquefaction and pyrolysis of waste biomass.

Chapter 11 by Masoumi et al. described the production of biocrude oil via hydrothermal liquefaction of microalgae. Special attention is also given to the effects of process parameters on hydrothermal liquefaction to improve the bio-oil yield. Several bio-oil upgrading techniques are explored to remove the heteroatoms using various heterogeneous acid catalysts.

Chapter 12 by Mahari et al. makes a review of the recent advancements in co-pyrolysis as a next-generation conversion technology for energy and material recovery from biomass. The chapter also includes a discussion on the impact of process parameters on co-pyrolysis, technical challenges, opportunities, application and combustion performance of the resulting synthetic liquid fuel products.

Chapter 13 by Volli et al. deals with the conversion of biomass and organic residues to bio-oil through thermochemical technologies. The technical developments towards improving the bio-oil yields, fuel properties, influence of process parameters and reactor configurations are discussed in details.

Chapter 14 by Trinh et al. reviews the pros and cons of biomass pyrolysis technology along with opportunities for environmental benefits and circular economy. The integration of molecular modeling with actual experiments has been highlighted as a new paradigm for mechanistic studies to design hybrid catalysts and enhance the bio-oil yield and upgrading processes. The chapter also introduces the novel sonochemical technique in biomass treatment and conversion.

Chapter 15 by Samart et al. describes novel approaches in the conversion of hydroxymethylfurfural using heterogeneous catalysts to advanced fuels and chemicals. The chapter also discusses the synthesis of hydroxymethylfurfural from sugars along with its conversion through oxidation, photocatalytic and electrochemical, hydrogenation, Oxidative amidation and reductive amination and polycondensation reactions.

Chapter 16 by Devi and Dalai provides the information about different pathways available for the conversion of glycerol into specialty chemicals. Various approaches and strategies have been discussed to investigate the effects of reaction parameters, i.e., temperature, pressure, catalyst type, reaction time, type of solvent on glycerol conversion and product selectivity.

Chapter 17 by Siang et al. summarizes the recent advances in catalytic steam reforming of glycerol to produce syngas. The yield in terms of catalytic design using various catalysts, supports and promoters, operating conditions are described. The mechanistic pathways and kinetic models are provided to describe glycerol reaction rates.

Chapter 18 by Minh et al. describes the thermodynamic aspect of biogas reforming under different conditions. Some significant works related to catalyst design, kinetic and mechanistic studies of biogas reforming processes are described.

Chapter 19 by Nayak et al. displays an extensive report on the opportunities and challenges in biodiesel production and its compatibility in present diesel engines without any engine modification. The experimental data quantifying the performance, emissions and combustion analysis of biodiesel are also summarizes.

Chapter 20 by Bhatia et al. describes the progress in microbial fuel cells in terms of structural modification, substrates utilization, modes of operation, supplementation of different microbial communities, challenges and opportunities.

This chapter provides insights on the technological advancements and utilities of the microbial fuel cells.

The editors are grateful to all the authors for contributing their scholarly materials to develop this book. Our sincere thanks to Springer Nature for the editorial assistance in preparing this book.

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Growth of Biofuels Sector: Opportunities, Challenges, and Outlook

1

Naveenji Arun and Ajay K. Dalai

Abstract

The demand for biofuels is increasing due to the uncertainties in the supply of fossil fuels, increased pollution hazards, rural economic growth, and the necessity to control carbon emissions. It is important to seek an alternate fuel resource to curb the carbon emissions. The transition from fossil fuel refineries to sustainable biorefinery can be clearly noticed in the present era. The dependency on food-based crops, which leads to the food versus fuel issue, has been addressed with the search for alternative and sustainable nonfood feedstocks such as lignocellulosic biomass. Until date, the methodology to unlock the full potential of lignocellulosic biomass is still in infancy. The migration from food-based biofuel feedstocks to lignocellulosic feedstocks and other organic wastes needs technological innovation and policies that could provide financial support. The detailed analysis on the risk factors associated with technological innovation in the biofuels sector is relatively less, which is the main objective of this chapter.

Keywords

Biofuels · Lignocellulosic biomass · Biorefining

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1.1 Introduction

Globally, the consumption of renewable and low-carbon biofuels is on rise owing to the international policies that focus on decreasing the greenhouse gas (GHG) emissions. Biofuels derived from lignocellulosic biomass, oil seeds, microalgae, and other organic wastes such as municipal solid wastes, cattle manure, industrial effluents, and sewage sludge have tremendous potentials to meet the future clean energy demands of the world (Nanda et al. 2015). Biofuels can be derived through the thermochemical conversion (e.g., pyrolysis, liquefaction, and gasification) and biochemical conversion (e.g., anaerobic digestion and fermentation) of organic wastes (Nanda et al. 2014, 2017b). The usable forms of biofuels are mostly in the form of liquid (e.g., bio-oil, biodiesel, microalgal oil, bioethanol, and biobutanol) and gaseous (e.g., syngas, producer gas, biohydrogen, and biomethane) forms (Nanda et al. 2016a). However, the bio-oils derived from the pyrolysis of biomass and organic wastes require catalytic upgrading (hydrotreating) to be transformed into synthetic transportation fuels (Arun et al. 2015, 2017).

The most commonly used classification of biofuels is presented in Fig. 1.1 (Raud et al. 2019). Based on the production process, biofuels can be classified as primary biofuels (from biomass in natural form) and secondary biofuels (from biomass in processed form). The first-generation biofuels involve the usage of edible feedstocks, which create the “food versus fuel” argument worldwide (Nanda et al. 2018). The second-generation biofuels addressed this issue as they are mostly produced from nonedible biomass through thermochemical and biochemical processes. Algae and other aquatic biomass are classified as third-generation biofuels and offer advantages such as low land usage, high lipid content, and high atmospheric CO_2 uptake capabilities (Correa et al. 2019). Genetic modification of third-generation biofuels can lead to the forecasted fourth-generation biofuels, which are mostly under research and developmental phase. Table 1.1 gives the examples of different generations and categories of biofuels. The advantages of different generations of biofuels are summarized in Table 1.2.

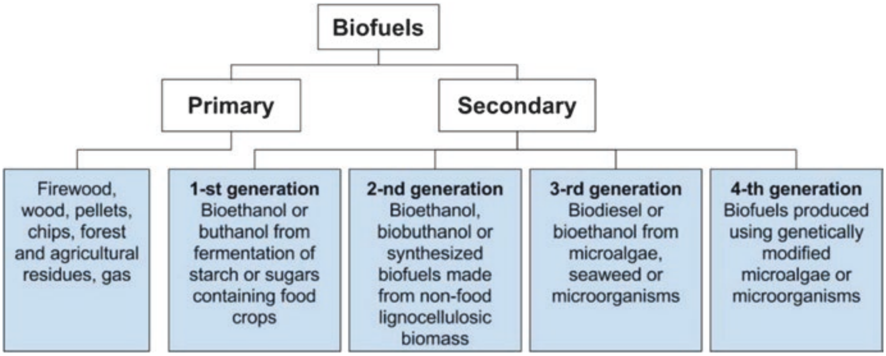

Fig. 1.1 Classification of biofuels according to processing technology and biomass type (Reproduced with permission from Raud et al. 2019)

The sustainable biorefining of biomass can also result in the production of a broad spectrum of marketable products such as biofuels, biochemicals, biomaterials, bioadditives for food and feed, as well as heat and power (Hassan et al. 2019; Arun and Dalai 2019). During the Paris climate conference (COP21) in 2015, nearly 200 countries decided to limit global warming below 2 °C (Chen et al. 2016). Many studies have reported about the "food versus fuel" debate, and a transition toward cellulosic alcohols has gained equal attention as cellulosic ethanol has the potential to lower the GHG emission by 90% in comparison to gasoline.

At the current population growth rate, it is estimated that the earth's population in 2030 will be around 8.5 billion people (Hassan et al. 2019). In 2016, the annual GHG emission was measured at 51.9 gigatons of CO_2 equivalent ($GtCO_2e$), while the target is to reduce the emissions by 11–13.5 $GtCO_2e$ per year by 2030. To control the catastrophic damages caused by anthropogenic activities, the United Nations agreed on 17 sustainable development goals for 2030 (Hassan et al. 2019). Several criteria considered for evaluating the socioeconomic and environmental benefits of biofuel production systems are shown in Fig. 1.2.

According to the Food and Agriculture Organization (FAO), the total world consumption of agricultural products will be 60% higher in 2050 in comparison to the consumption in 2005. Another estimation by FAO indicates that by 2050, additional 70 million hectares of cultivated land will be required to meet the food demands of the future generation. Hence, there is a clear indication of competition between urbanization and agriculture. The urban expansion can potentially result in loss of agricultural lands and it is estimated that the global loss of agricultural lands will be 1.8–2.4% by 2030.

The European Bioeconomy Strategy was launched by the European Commission in 2012, which was themed on "Innovating for sustainable growth: A bioeconomy for Europe" (European Environment Agency 2019). After assessment by the European Union Commission in 2017, the scope of the current action plan was found to be inadequate for the sustainable development of the biorefinery sector in

Table 1.1 Different generation and categories of biofuels (Reproduced from Kamani et al. 2019 with permission from The Royal Society of Chemistry)

Generation	Source/substrate	Product
Primary	Firewood, wood chips, pellets, animal waste, forest, and crop residues	Used in unprocessed form, mainly for heating, cooking, and electricity purposes
Secondary	Seeds, grain, and sugars	Bioethanol/biobutanol (by the fermentation of starchy or sugar-rich crops), biodiesel (by the transesterification of plant oils)
Secondary	Lignocellulosic biomass	Bioethanol/biobutanol (using enzymatic hydrolysis), methanol, mixed alcohol, green diesel (by thermochemical processes) and biomethane (by anaerobic digestion)
Tertiary	Algae and seaweed	Biodiesel and bioethanol from algae and seaweeds, hydrogen from microorganisms and green algae

Table 1.2 Advantages and disadvantages of different generations of biofuels (Reproduced with permission from Abdullah et al. 2019)

Topic	First-generation biofuel	Second-generation biofuel	Third-generation biofuel	Fourth-generation biofuel
Competition with food crops	Made from edible oil and starch feedstock	No food-energy conflict	No food-energy conflict	No food-energy conflict
Land footprint	Requires arable land	Require arable land or forests	Non-arable land can be used for cultivation	Non-arable land can be used for cultivation
Conversion to biofuels	Easy conversion	Need sophisticated downstream processing technologies due to high contents of hemicelluloses and lignin	Easy conversion due to increased hydrolysis and/or fermentation efficiency	Easy conversion due to increased hydrolysis and/or fermentation efficiency
Water footprint	Potable water is required for cultivation	Potable water is required for cultivation	Waste, saline, and non-potable water also can be used	Waste, saline, and non-potable water also can be used
Environment friendliness	Using pesticides and fertilizers are of the main concerns	No expenditure on fertilizer or pesticides. Deforestation is a concern	CO_2 fixation, wastewater treatment, and no expenditure on fertilizer are benefits. Ecological concerns such as marine eutrophication are a disadvantage	CO_2 fixation and wastewater treatment are the benefits, but release of genetically modified organisms is a main concern
Commercialization	Commercially produced	Commercially produced	Insufficient biomass production for commercialization	Insufficient biomass production for commercialization
Sustainability	Use of natural resources such as water and land is not conservative	Does not preserve ecology due to deforestation concerns	Does not have favorable economics	There are concerns about the release of genetically modified organisms to the environment and ecological risks
Nutrient requirements	Using pesticides and fertilizers is of the main concern	Does not require any fertilizer treatment	Large carbon and nitrogen sources are required. Solar energy is only available during daytime. Nutrients can be recycled in the process	Large carbon and nitrogen sources are required. Solar energy is only available during daytime. Nutrients can be recycled in the process

Harvesting	Harvesting is done by hand or machine picking	Harvesting is done by hand or machine picking	Harvesting of microalgae is expensive and complicated	Harvesting of microalgae is expensive and complicated
Regulation	The regulations are fairly clear	The regulations are fairly clear	No regulation is available for marine cultivation	No regulation is available for marine cultivation. Furthermore, strict regulation is for the intended release of GM algae
Financial input	The capital cost is fairly low	The capital cost is fairly low	The initial cost for large-scale cultivation is too high	The initial cost for large-scale cultivation is too high
Environmental condition	Parameters such as temperature and humidity must be within a suitable range	Parameters such as temperature and humidity must be within a suitable range	Can be cultivated in harsh environmental conditions such high pH, salinity, and high light intensities	Can be cultivated in harsh environmental conditions such high pH, salinity, and high light intensities

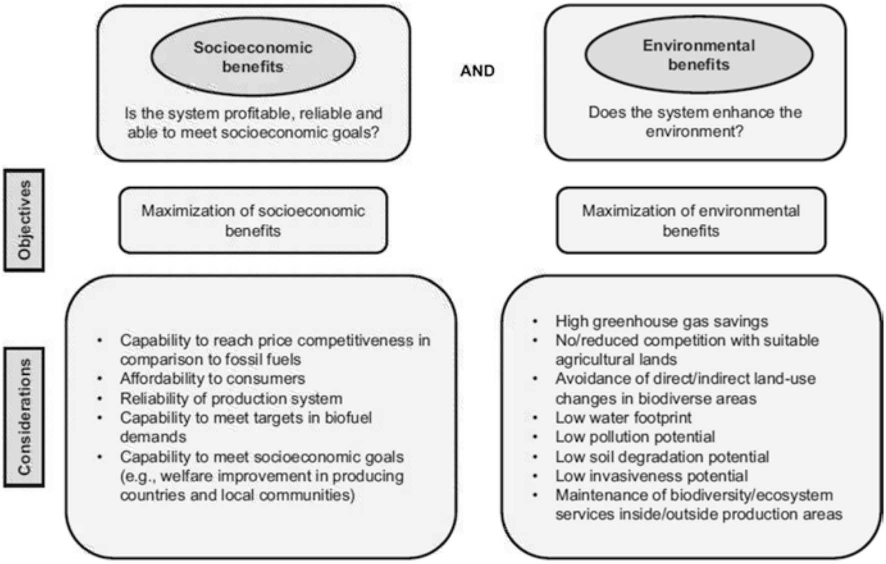

Fig. 1.2 Criteria to be considered when evaluating the socioeconomic and environmental benefits of biofuel production systems (Reproduced with permission from Correa et al. 2019)

the Europe. More recently, Brazil, the USA, Canada, the European Union, and many Asian countries have started posing strict legal mandates for the usage of biofuels on commercial scale.

According to International Energy Outlook (2016), the world's energy consumption is expected to increase by approximately 48% between 2012 and 2040. The production of conventional biodiesel involves the usage of fertilizers, mechanical equipments (which uses fossil fuels), and arable land. According to the Innovation Outlook, Advanced Biofuels-IRENA, the basic energy input to produce conventional biodiesel comes from fossil fuels. Therefore, the production cost for conventional biodiesel is US $1.6 per liter in comparison to US $1.2 per liter for diesel. In European Union, the annual turnover of current biofuel economy is €2.3 trillion and 18.5 million people are employed in the biofuel sector (Hassan et al. 2019). The S2Biom project supported by the European Commission indicates that the bio-based products will have a market worth of €40 million by 2020 and are projected to have a 4% annual growth rate. Many biofuel policies struggle to address the integrations between company's perspective and policy development. The success of biofuel policies has been primarily based on climate change and community support. It is estimated that nearly 67 biorefineries based on lignocellulosic biomass are in current operation globally. Tables 1.3 and 1.4 illustrate the main products that can be obtained by the hydrothermal conversion of lignocellulosic and non-lignocellulosic biomasses, respectively.

The commercialization of biofuels sector involves high capital expenditure (CAPEX), and it is important to integrate the biochemical processes with the existing

Table 1.3 Summary of main structures and major compounds of lignocellulosic biomass (Reproduced from Usman et al. 2019 with permission from The Royal Society of Chemistry)

Lignocellulosic biomass	Percentages of main structures			Major compounds into hydrothermal conversion aqueous products
	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	
Crop straw and husk	29.2–46.0	18.2–36.4	15.0–28.2	Volatile fatty acids, capronic acid, lactic acid, furfurals, sugars, alcohols, and cyclopentenone
Newspaper	44.2	17.8	26.8	Volatile fatty acids, furfurals, sugars, alcohols, and phenols
Orange pomace	14.3	6.3	3.3	Acetic acid, 5-hydroxymethylfurfural, furfurals, ethanol, acetone, butanone, and alkyl derivatives
Recycled paper	60.8	14.2	8.4	Volatile fatty acids, furfurals, sugars, alcohols, and cyclopentenone
Spent grain	18.5	26.5	19.1	Cyclopentenones, carboxylic acids, pyrazines, and ketones
Sugarcane bagasse	56.0	4.6	36.4	Volatile fatty acids, phenols, furfurals, sugars, alcohols, and cyclopentenone
Switchgrass	32.8	23.7	18.2	Volatile fatty acids, phenols, furfurals, sugars, alcohols, and cyclopentenone
Woody biomass	38.6–63.6	7.7–20.2	17.6–32.7	Phenols, furfurals, glycolic acid, acetic acid, alcohols, and cyclopentenone

Table 1.4 Summary of main structures and major compounds of non-cellulosic biomass (Reproduced from Usman et al. 2019 with permission from The Royal Society of Chemistry)

Non-lignocellulosic biomass	Percentages of main structures			Major compounds into hydrothermal conversion aqueous products
	Protein (wt%)	Carbohydrates (wt%)	Lipids (wt%)	
Dried distillers' grains	42.2	35.0	22.4	Cyclopentenones, carboxylic acids, pyrazines, ketones, and oxygenated aromatics
Food waste	15.0–25.2	41.3–62.1	13.4–30.2	Volatile fatty acids, 5-hydroxymetgylfurfural, furfural, ethanol, ketones, alkyl derivatives of 2-cyclopenten-1-one
Macroalgae	12.2–30.9	54.3–83.6	0.9–6.2	Nitrogenous compounds, long-chain fatty acids, glycerol, alcohols, and acetone
Microalgae	8.1–71.4	4.2–57.1	2.4–40.1	Volatile fatty acids, phenols, pyrazines, benzenes, alkanes, and fatty acids
Mixed cultural algae	27.2	17.9	5.7	Short-/long-chain organic acids, amino acids, phenols, urea, N-heterocyclic compounds, acetamide, and ketones
Sewage sludge	27.6–33.4	3.3–4.0	6.6–13.8	Volatile fatty acids, benzene, acetic acid, carbonic acid, alkenes, phenolic, and aromatic compounds

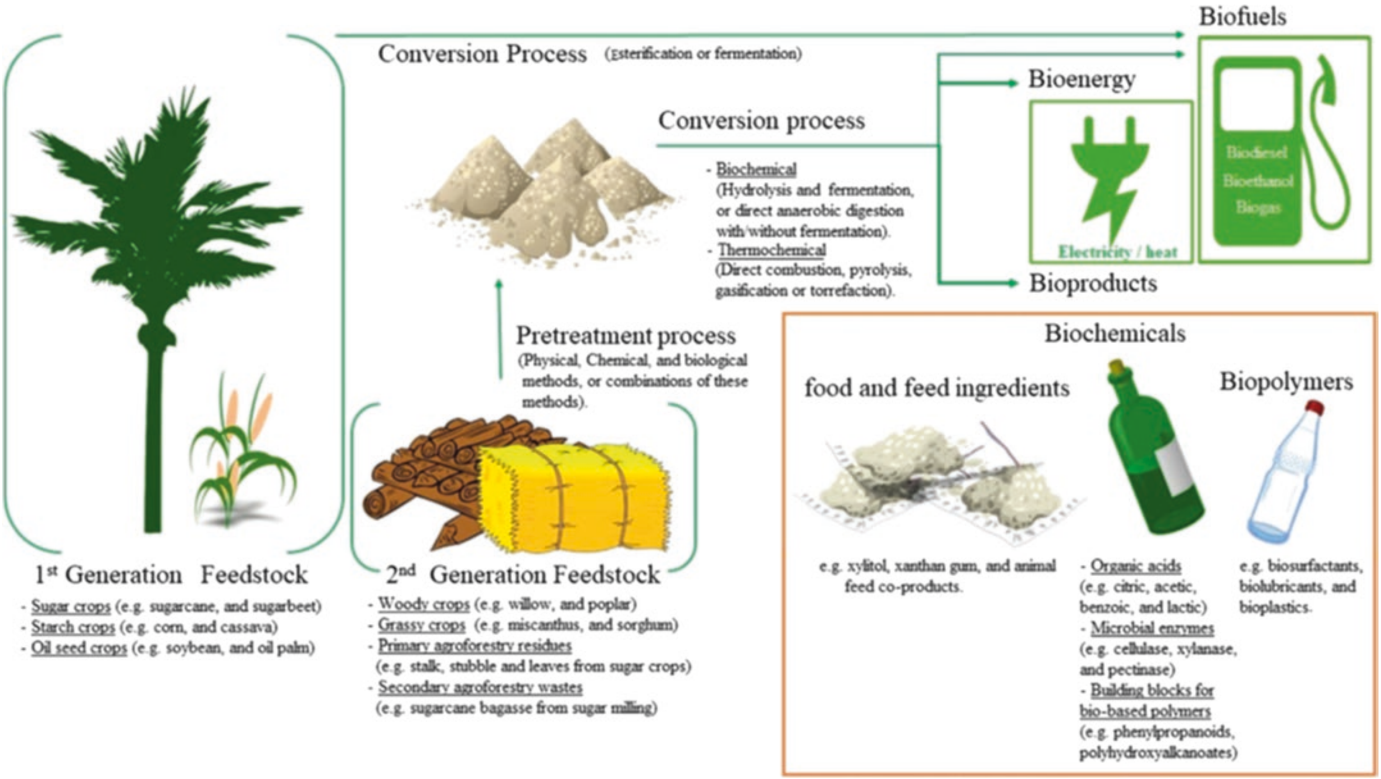

Fig. 1.3 Schematic diagram showing differences between first- and second-generation lignocellulosic feedstocks, valorization processes, and end products (Reproduced with permission from Hassan et al. 2019)

refinery setup to produce biofuel products with minimum operational cost (Fig. 1.3). In the future, it is imperative to consider the energy efficiency of biofuel blends and the influence of carbon taxation policy, and they needed to be included in the analysis. The policy makers should consider and analyze the risks involved in the commercialization of technologies that produce advanced biofuels. The identified potential risks are related to the management processes, market conditions, and profitability. The developed policies should find a balance between the translation of technology and business perspective. Most of the green energy innovation policies have attempted to address the optimal balance between technological push and supply-demand pull in green technologies. This chapter provides insights into the present state of energy demand, search for novel feedstocks, and potential risks associated in the commercialization of novel biofuels production technologies.

1.2 Biofuel Scenario in Canada and the World

After agreeing to the 2015 Paris Climate Conference (COP21), the Government of Canada has taken initiatives to curb the greenhouse gas (GHG) emissions (Nanda et al. 2016b). To achieve the Clean Fuel Standard and achieve the climate change objectives, discussions with provincial and federal governments and indigenous peoples and rural communities are in swift progress. According to the International Energy Agency (IEA), to meet the Paris commitment of keeping the global warming below 2 °C, the consumption level of biofuels should triple by 2030. On an average, about 140–150 patents are filed annually and this clearly indicates a worldwide hunger for advanced biofuel systems.

Owing to Canada's extensive forestry and agricultural resources, the prospects for advanced biofuels seem to be promising. In Canada, the Renewables Fuels Regulations Act was enacted in August 2010. According to this act, the gasoline pool must contain 5% by volume of renewable fuel, and in the diesel pool, the renewable fuel content should be 2% by volume. With the depression of oil prices in 2015 in Canada, the energy sector continued to account for 20% and 18% of the gross domestic product of Alberta and Saskatchewan, respectively (Mondou et al. 2018). According to Dragojlovic and Einsiedel (2015), biofuels generated from nonfood crops are recently gaining societal acceptance in the USA compared to corn-based ethanol. Moreover, the communal perception on the climate change and its associated risks and threat are the key predictor of the defiance toward biofuels in the USA.

In Canada, the annual consumption of biodiesel has increased by 100% in comparison to 2010 (123 million liters). The Federal Renewable Fuels Regulations also mandates the minimal blending of renewable fuels to decline the average lifecycle carbon intensity (CI) of fuels over time. The energy density of ethanol is about 33% lower than gasoline and it means that consumers must purchase more of ethanol to meet the energy requirements. This also indicates greater distribution cost and higher tax rates. It must be noted that blending ethanol (5–10 vol%) can increase the energy efficiency of the vehicle by 1%. In addition, blending with ethanol also permits refineries to produce gasoline blend stock with lower octane number, which can potentially reduce the greenhouse gas intensity. In future, it is imperative to consider the energy efficiency of biofuel blends and the influence of carbon taxation policy and they needed to be included in the analysis.

Biomass from lignocellulosic materials (e.g., agricultural crop residues and woody biomass), algae, and oilseed crops can be converted to biofuels through applicable thermochemical and biochemical conversion routes. The oil extraction from oilseed crops and algae undergoes transesterification to produce biodiesel. The de-oiled algal biomass can undergo supercritical water gasification due to its high moisture content to produce syngas (Reddy et al. 2014; Okolie et al. 2019; Yadav et al. 2019). The syngas is further converted to refined fuels such as green diesel, green kerosene, and other hydrocarbons through Fischer-Tropsch catalysis. Fermentation of syngas using acidogenic bacteria can produce bioethanol. Lignocellulosic biomass and de-oiled algae can also undergo pyrolysis to produce bio-oil, biochar, and producer gas. The sugars in lignocellulosic biomass can be recovered using enzymatic hydrolysis and fermentation to produce alcohols, e.g., bioethanol and biobutanol (Fig. 1.4), or through gasification and Fischer-Tropsch catalysis to produce alcohols and hydrocarbon (Fig. 1.5) (Nanda et al. 2014, 2017a).

Algae-based biofuels seem to have the potential to offer a sustainable pathway for bioenergy and bioproducts (Yadav et al. 2019). Alga is an energy density biological source and can accumulate lipids up to 50% of dry cell weight (U.S. DOE 2010). As a part of advanced biofuel systems, algal biofuels have gained attention. The catalytic cracking process for the biofuels production from algal oil is energy intensive and it is important to analyze the energy return on investment (EROI). In chemical and enzymatic processes, reusability of catalyst is an important factor and various studies have been done to develop a cost-effective catalyst for chemical and enzymatic conversion. Algal biofuel production process possesses high productivity (per acre) because it is not based on food resources and can be cultivated on open ponds and wastewater. It is imperative to cultivate the specific type and strain of algae (e.g., microalgae, macroalgae, and cyanobacteria) for the successful algae-based biofuels production process. Although algal biofuels industry seems promising, it is limited by several factors such as biomass cultivation, availability of advanced processing facilities, technical challenges, and logistic issues (Chen et al. 2016). There are many uncertainties in the availability and commercial usage of fossil fuels after 2040. In the last two decades, the oil price had an average volatility of 30% per year. According to the UK Production Capacity Outlook to 2030, the design and development of cost-effective catalysts for fuel upgrading technologies such as Fischer-Tropsch process, hydrotreating, or transesterification seem to be a primary challenge in process commercialization.

As discussed earlier, biofuel feedstocks can be categorized into three categories such as (a) biomass produced on marginal lands, (b) agricultural crop residues and forestry biomass, and (c) cattle manure and organic wastes (Junginger et al. 2006). It is globally estimated that these waste and biomass categories can supply bioenergy accounting up to 200 EJ, 100 EJ, and 100 EJ, respectively. However, an access to complete integrated biofuels process assessment is unavailable. The estimation

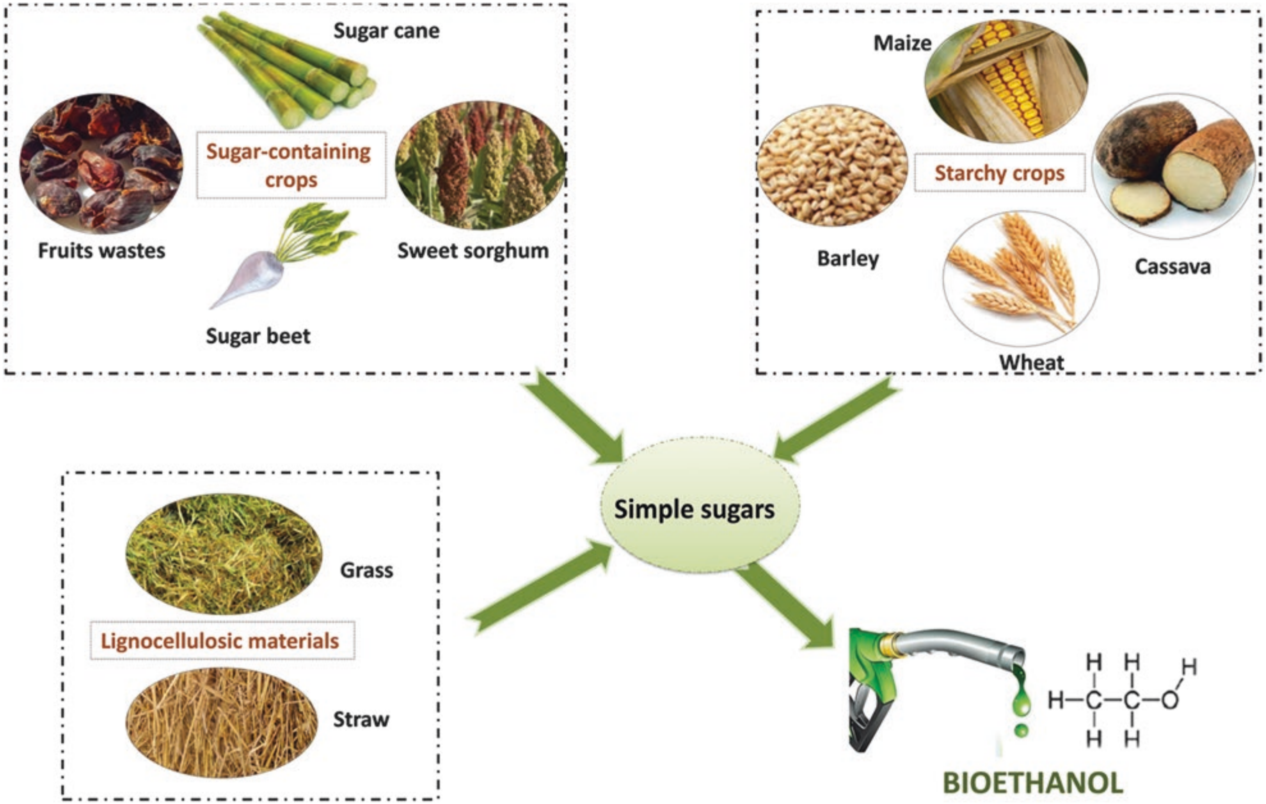

Fig. 1.4 The agricultural residues used for the production of bioethanol (Reproduced from Kamani et al. 2019 with permission from The Royal Society of Chemistry)

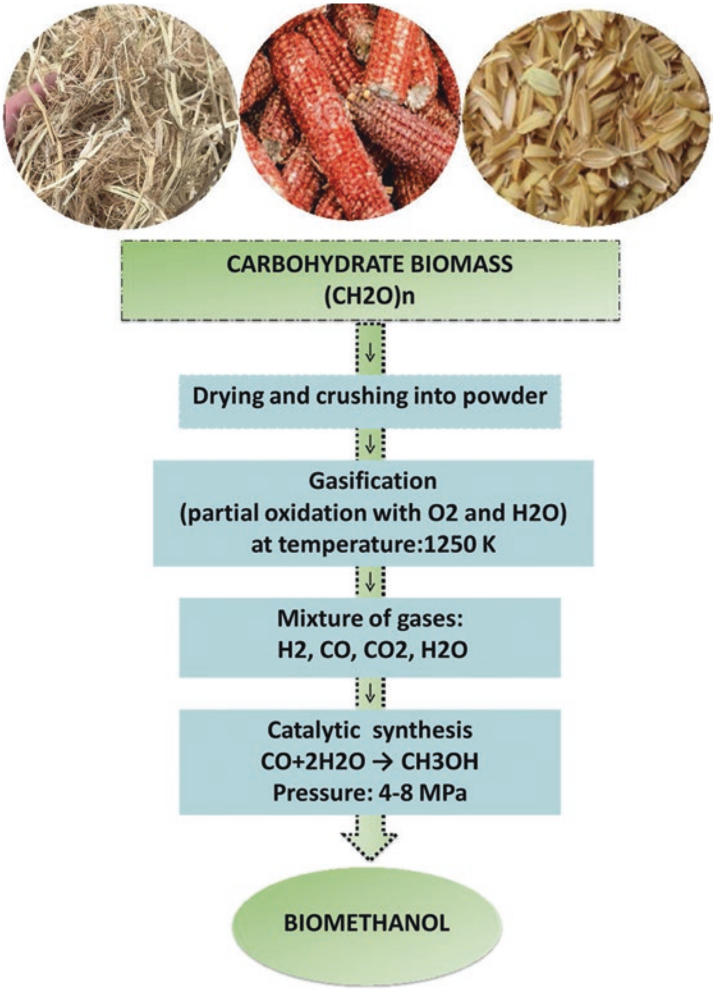

Fig. 1.5 Production of biomethanol from carbohydrate biomass by gasification (Reproduced from Usman et al. 2019 with permission from The Royal Society of Chemistry)

studies done by several international organizations such as USEPA, Stockholm Environmental Institute, and the Intergovernmental Panel on Climate Change (IPCC) provide different conclusions (100–500 EJ per year in 2050) on the reliability of biomass to meet the future energy demands (Junginger et al. 2006). The major difference in the analysis can be attributed to the uncertainty in land availability and yield limits.

1.3 Policies and Their Impacts on the Success of Advanced Biofuels: Scenario in Canada and the World

The governmental commitment to policies and the durability of the policies are of concern for the commercialization of advanced biofuels market. The impact of policy changes is drastic on the venture capital companies in comparison to refineries based on fossil fuels. For the deployment of futuristic biofuels production processes, the uncertainties associated with the government policies need to be reduced. In Canada, many private and federal organizations provide financial support for the commercialization of biofuels sector. The Canadian Foundation for Innovation (CFI) provides financial support for the development of research infrastructure.

The Sustainable Development Technology Canada (SDTC) is a foundation funded by the government of Canada and it provides nonrepayable funds for the development of novel processes and technologies (in the pre-commercial phase) that focus to curb GHG emissions. Through the Next-generation Biofuels Fund (NGBF), about $500 million was sanctioned to private research centers. Recently, Canada’s Networks of Centers of Excellence funded a research initiative called BioFuelNet Canada, which specifically focused on the Agriculture and Agri-Food Canada, Canadian Forest Services, and Transport Canada. Like BioFuelNet Canada, the Cellulosic Biofuel Network was initiated in 2010. The Renewable Industries Canada (RIC) and the Advanced Biofuels Canada (ABC) are the two organizations focusing on the advanced biofuels sector in Canada. The industries that produce conventional biofuels are represented by Renewable Industries Canada, and industries in western Canada (which primarily produce biodiesel) are represented by Advanced Biofuels Canada. Both these organizations have their own unique expertise and policy capabilities. For practical implementation of low-carbon fuel standard (LCFS), skill set development of lifecycle analysis of GHG emissions of fuels is important.

Decision-making step in the commercialization of novel biofuels technologies is strongly dependent on the ability of the government and corporates to take risk without developing aversion considering the challenges in getting higher returns after commercial runs. Tables 1.5 and 1.6 summarize some notable biofuel projects around the world and European Union, respectively. Scientifically, the term risk can refer to challenges, barriers, or constraints and the source of risk can be external (e.g., political, economic, social, and technological) and/or internal (management and operations in an organization). The nontechnical challenges and biases usually hinder the commercial development of bioenergy rather than technical issues (McCormick and Kaberger 2007). The nontechnical risk factors are the factors related to (a) policies; (b) supply, price, and demand of feedstocks; (c) fluctuations in the prices of fossil fuels; (d) food versus fuel debate; and (e) lack of refinery to process advanced feedstocks.

Pries et al. (2016) performed a detailed analysis on the different risks and their influence on the commercialization of advanced biofuels technology. The risks could be classified as political, economic, social, technological, primary, and support activities risks. The primary political risk arises from the support from the