An Overview of Techno-economic Analysis and Life-Cycle Assessment of Thermochemical Conversion of Lignocellulosic Biomass

15

Ranjeet Kumar Mishra and Kaustubha Mohanty

Abstract

Energy derived from biomass provides a promising alternative source that reduces dependence on fossil fuels along with the emission of greenhouse gases (GHG). The production of heat, electricity, power, fuels, and various chemicals from the biomass can be achieved via thermochemical conversion technologies. This chapter summarizes the techno-economic analysis and life-cycle assessment of lignocellulosic biomass via thermochemical conversion routes such as combustion, pyrolysis, gasification, liquefaction, (hydrothermal). and co-firing. Specific indicators such as production costs, techno-economic analysis, functional units, and environmental impacts in a life-cycle analysis for different techniques were compared. Finally, the research lacunae and possible future trends in biomass conversion via thermochemical conversion techniques have been discussed, which may positively impact the future of research related to techno-economic and environmental benefits of bioenergy.

Keywords

Biomass · Thermochemical techniques · Techno-economic analysis · Life cycle assesments

---

R. K. Mishra · K. Mohanty (✉)
Department of Chemical Engineering, Indian Institute of Technology Guwahati, Guwahati, Assam, India
e-mail: kmohanty@iitg.ernet.in

P. K. Sarangi et al. (eds.), *Recent Advancements in Biofuels and Bioenergy Utilization*, https://doi.org/10.1007/978-981-13-1307-3_15

Abbreviations

AAS	Acid-acid synthesis
BCB	Bubbling circulating bed
CHP	Catalytic fast pyrolysis and hydroprocessing
COE	Cost of electricity
COS	Carbonyl sulfide
DME	Dimethyl ether
FTS	Fischer-Tropsch synthesis
GHG	Greenhouse gas emissions
HCN	Hydrogen cyanide
HPH	Hydropyrolysis and hydroprocessing
IGCC	Integrated gasification combined cycle
kWh	Kilowatt hour
LCA	Life-cycle assessment
MAG	Methanol-to-gasoline
MAS	Mixed alcohol synthesis
MJ	Megajoule
MTE	Methanol-to-ethanol
MW	Megawatt
MWe	Megawatt electric
MWh	Megawatt hour
ORC	Organic Rankine cycle
PC	Pulverized coal-fired
RFS2	Revised renewable fuel standard
RME	Rapeseed methyl ester
S2D	Syngas-to-distillates
SF	Syngas fermentation
SNG	Synthetic natural gas
TEA	Techno-economic analysis

15.1 Introduction

Biomass has garnered considerable attention as a viable resource for the production of fuel, value-added chemicals, power, and electricity. In addition, the biomass-derived fuels have a definite advantage over fossil fuel in terms of emission such as CO, CO_2, SO_x, and NO_x gases. Currently, fossil fuels are the principal sources of energy for the entire world. However, the use of fossil fuel emits a high amount of greenhouse gases (GHG) and particulate matter in the environment, which adversely impact the environment. Additionally, the rapid depletion of fossil fuel resources has forced researchers to develop new technologies and strategies. Energy from the renewable sources is the best alternative to fossil fuel. In 2007, the US Congress set new revised renewable fuel standard (RFS2) in which biofuel was used as an alternative fuel to reduce the consumption of petroleum fuel from domestic uses (Brown 2015). The RSF2 issued an official order to increase the blending volume of biofuel with petroleum fuels such as diesel and gasoline for retail use (Brown 2015).

Among all the renewable energy sources such as solar, geothermal, wind, hydrogen and fuel cell, hydrothermal, tidal, biomass, etc., biomass has the potential to produce energy as well as different types of value-added products. The thermochemical conversion technology is the best route to convert biomass into end products in solid, liquid, and gaseous forms. Further, the efficiency of thermochemical technology depends on the types of biomass to produce different kinds of value-added products (Demirbas 2001).

There are many thermochemical conversion technologies, which produce various value-added products and energy such as combustion, pyrolysis, gasification, liquefaction (hydrothermal), carbonization, and co-firing. Among all the available thermochemical conversion technologies, pyrolysis can convert biomass into solid, liquid, and gas without consuming oxygen. Liquid fuel and gaseous products are the two major products of thermochemical technology which can be further upgraded into the various valuable forms of energy such as transportation fuel, electricity, and value-added chemicals. The significant advantage of lignocellulosic biomass over other feedstocks is that they can be sourced from the nonedible parts of food crops. Thus, their production does not deplete resources meant for food crops nor do they cause a food crisis. However, the crops specifically cultivated for energy production may compete with conventional crops for the use of land (area for cultivation), particularly when the former get subsidies for cultivating the energy crops (Rathmann et al. 2010), although in some cases, energy crops are grown in marginal lands (Liu et al. 2011) and do not compete with other conventional crops for land. The use of biomass for the production of power and energy has been around since the nineteenth century; it was the widespread adoption of thermochemical technology in 2012 that made it a significant player in the energy sector. Thus, when the USA sets up a commercial-scale biorefinery plant, the catalytic fast pyrolysis and hydroprocessing (CHP) yielded 10 million gallons/year of bio-based gasoline and diesel, produced from the yellow pine feedstock (Lane 2013).

Though the viability of setting up more such biorefineries is dependent on the techno-economic analysis (TEA) and life-cycle assessment (LCA) of lignocellulosic biomass, there is a clear paucity of available data. Bridgwater et al. (2002) reported a comparative study of techno-economical assessment of biomass pyrolysis, combustion, and gasification for production of electricity. The same source reported that combining a diesel engine with fast pyrolysis is a significant option for electricity production, with the promise of long-term profits. The report of Gnansounou and Dauriat (2010) on techno-economic analysis of lignocellulosic biomass singled out the high cost of biomass feedstock, as the main factor that must be brought down, to reduce the overall production cost of lignocellulosic bioethanol. The production of biofuel (second generation) from the lignocellulosic biomass by using thermochemical process (fast pyrolysis) was reported by Damartzis and Zabaniotou

(2011). They also focused the possible opportunity and future challenges in process integration applications. Muench and Guenther (2013) have carried out life-cycle assessment on conversion of biomass into heat and electricity, through thermochemical technologies. Menten et al. (2013) reviewed the generation of greenhouse gas (GHG) emission via the thermochemical processes by using meta-regression analysis model.

This present study is focused on the techno-economic analysis and life-cycle assessment of lignocellulosic biomass using thermochemical conversion technology. Life-cycle analysis is an important tool to estimate the potential of environmental impact on end products through various processes in the complete life cycle. Life-cycle analysis is a systemic tool used to evaluate the materials and inputs and output parameters where the generation of emission and subsequent environmental impact of the products is estimated during biomass life cycle. Life-cycle analysis has been done using the ISO series 14040, but the calculation is less proficient by this method because this method was based on data-intensive process. The ISO series 14040 stated that life-cycle assessment has been categorized into four stages. The first stage deals with the selection of the goals, scopes, and boundary definitions. The second stage is characterized by life-cycle inventory analysis. The third stage is distinguished by life-cycle impact and assessment, and the fourth stage is earmarked for result interpretation (Schenck 2009). Four major and cardinal parameters, the feedstocks, system boundaries, functional unit, and environmental impact, determine the life-cycle assessment analysis. By evaluating the techno-economic analysis of different kinds of thermochemical conversion technologies, the most economical route can be identified.

15.2 Biomass to Energy Conversion Technologies

Biomass feedstocks, environment, and economic considerations are the three major parameters which are known to directly influence conversion of biomass into fuel and energy. Conversion of biomass to energy products can be achieved via three main processes such as biochemical process, thermochemical process, and mechanical extraction. Thermochemical and biochemical technologies are widely adopted, whereas mechanical extraction is used for the production of fuel from biomass from sources like rapeseed methyl ester (RME). However, mechanical extraction is not used extensively because of lower yield. Biochemical technology is associated with aerobic and anaerobic digestion, whereas thermochemical process includes combustion, gasification, pyrolysis, and liquefaction (Demirbas 2007). The detailed schemes of conversion of biomass are presented in Fig. 15.1.

15.2.1 Biochemical Conversion of Biomass

Conversion of biomass into value-added products through the biochemical process is an ancient technology. For example, India and China were using this technology for

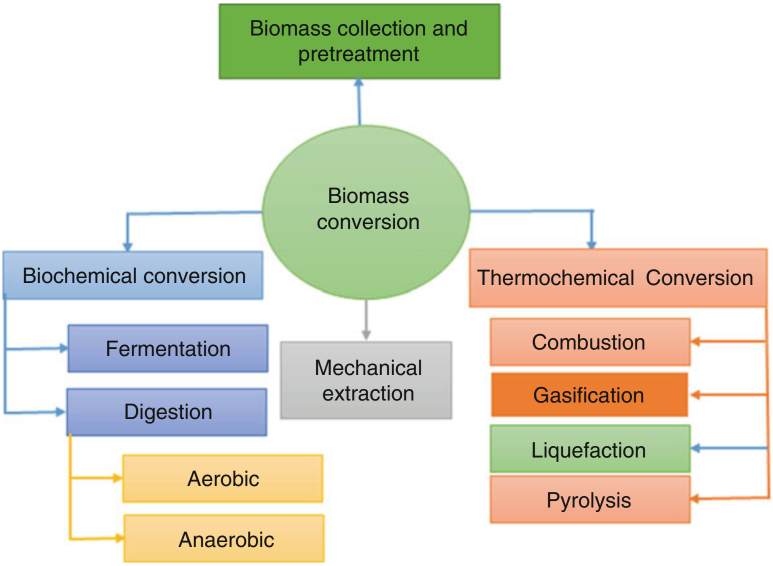

Fig. 15.1 General schemes of biomass to energy conversion routes

a long time for the production of methane gas via anaerobic microbial digestion using animal waste as raw material. Recently, biochemical techniques have been used for the production of automotive fuel (ethanol) through the fermentation process. During biochemical conversion of biomass, higher molecular weight compounds break down into smaller molecular weight compounds by the use of bacteria or enzyme. Among the available technologies, the biochemical conversion method stands out for its significantly low energy requirement; it is handicapped by the long incubation period required for conversion of materials into products. The major routes of the biochemical process are digestion (aerobic and anaerobic), fermentation, and enzymatic or acid hydrolysis.

Anaerobic digestion is a process in which microorganisms break down biodegradable materials in the absence of oxygen. Methane and carbon dioxide are the final products of anaerobic digestion along with some solid residue. Bacteria consume the carbon present within the biomass and break down into smaller compounds. The aerobic process uses oxygen from the outside of the biomass to break down the biomass into smaller compounds. The fermentation process is a biochemical process in which biomass is converted into sugars by use of acid or enzyme. Furthermore, sugar is converted into ethanol or other various value-added chemicals. Lignin is left as residue due to its higher thermal stability. However, production of ethanol from starch- and sugar-based feedstocks via fermentation process has been commercialized. Lignocellulosic biomass requires acid, enzymatic, or hydrothermal treatment to break down the cellulose and hemicellulose into simple sugars, which in turn are carried out by bacteria, yeast, and enzymes.

15.2.2 Thermochemical Conversion of Biomass

In the thermochemical process, heat is supplied for breaking higher molecular weight compounds into smaller molecular weight compounds. During thermochemical conversion, biomass is converted into gases which are later synthesized into desired products or used directly in engine and boilers. Synthesis of syngas into liquid fuel via Fischer-Tropsch is the best example of thermochemical conversion. Energy from the biomass can be extracted by six routes such as combustion, pyrolysis, gasification, liquefaction, carbonization, and co-firing.

15.2.2.1 Combustion

Burning of biomass in the existence of air or O_2 is known as combustion. It is the simplest of all thermochemical techniques. This process includes homogeneous and heterogeneous reactions. The stored chemical energy in biomass is converted into heat energy, power, electricity mechanical energy, and several other products by using the different types of devices such as furnaces, stoves, steam turbines, boilers, etc., during combustion. Further, the advantage of combustion over other process is that it has the potential to burn any biomass, but in practice, biomass having less than 50% moisture is more efficient unless biomass is pre-dried. If biomass contains more than 50% moisture, then the biological process is more proficient (Sharma et al. 1999). However, it was reported that hydrothermal liquefaction is a cost-effective thermochemical technique which can handle biomass with any level of moisture content (Akhtar and Amin 2011). There are several applications of combustion such as domestic heating, cooking, and large-scale industries (100–1300 MW power production). To increase the combustion efficiency, co-combustion (biomass with coal) is an attractive option/route. Total conversion efficiencies achieved were 22–40% through biomass combustion. Meanwhile, higher combustion efficiency can be reached via co-combustion or when the plant is more than 100 MWe (Kumar et al. 2015). Stirling cycle is used for combustion to deliver shaft power directly, but it is limited only to small outputs. Due to the higher emission of NO_x, carbon dioxide, particulate matter, and formation of higher ash content make this process unfeasible (Kumar et al. 2003a).

15.2.2.2 Gasification

Gasification is the thermochemical process where biomass is converted into a mixture of gases with the presence of oxygen, steam, or air at the higher temperature (>700 °C). Pyrolysis and gasification are known as an extension of combustion in which gaseous products are enhanced as compared with solid (biochar). However, the gaseous products are further being condensed and liquid fuel formed. Further, using oxygen gas as the gasifying agent rather than air improved the calorific value of product gas and removed nitrogen. There are many controlling parameters such as rate of heating, the design of the reactor, and post-processing of gases which produced a clean and high quality of gas through gasification. Gas with lower calorific value can be achieved through direct burning which can be used as a fuel for the gas engine and gas turbine. On the other side, production of methanol from these gases is the best example of gasification (Ganesh and Banerjee 2001). Biomass integrated gasification is one of the promising routes where gaseous fuel is converted into electricity through higher efficiency turbines. Biomass integrated gasification process has various advantages over the other processes, attributed to its lower equipment cost and production of clean gas. About 40–50% net conversion efficiencies can be achieved by gasification for 30–60 MW plant capacity (Kumar et al. 2015). The produced syngas from the gasification was used for the production of potential fuels such as methanol and hydrogen, which are used in transport vehicles. It was observed that indirect gasification or blown oxygen is preferred for the production of methanol.

Over the time, various gasification routes have been developed for the production of syngas. These processes are used for the conversion of biomass into fuel such as ethanol- and hydrocarbon-based fuel by catalytic treatment. Among all the developed routes, acid-acid synthesis (AAS), Fischer-Tropsch synthesis (FTS), mixed alcohol synthesis (MAS), methanol-to-gasoline (MAG), methanol-to-ethanol (MTE), syngas-to-distillates (S2D), and syngas fermentation (SF) are the popular routes. All the gasification routes, which are used for upgradation of syngas, employ different kinds of catalysts. These catalysts may have certain negative impacts such as the presence of contaminants in the raw syngas such as H_2S, carbonyl sulfide (COS), NH_3, hydrogen cyanide (HCN), HCl, tar, and different types of particulate matter. Therefore, the syngas requires cleaning before upgradation (Woolcock and Brown 2013). The catalysts such as ZnO and CuO are used for the production of methanol via acid-acid synthesis (AAS) technology. However, iodide- and iridium-based catalysts were used for the production of acetic acid from methanol (Zhu and Jones 2009). Furthermore, the produced acetic acid was upgraded with hydrogenation process and produced a mixture of ethanol and water. After separation of water from the mixture, fuel grade ethanol was produced. Methanol-to-ethanol, methanol-to-gasoline synthesis, and syngas-to-distillates pathways also produced methanol by converting syngas at the initial stages. All the pathways reacted with methanol over dehydration catalysts and produced dimethyl ether (DME) in the methanol-to-ethanol (MTE) pathway.

Dimethyl ether (DME) is converted into methyl acetate through heterogeneous catalytic carbonylation. Further methyl acetate is again hydrogenated to produce methanol. However, in case of MTG pathway, dimethyl ether (DME) reacts with the zeolite catalyst and yields alkenes and a blend of aromatics, which have the boiling points equivalent to gasoline (Phillips et al. 2011). The methanol dehydration and hydrocarbon synthesis phases are combined with syngas-to-distillates (S2D) pathways by the reaction of methanol with appropriate catalysts in a single reactor. The syngas is then compressed before combining with methanol and reacting over as metal sulfide catalysts to produce mixed alcohol stream during methanol-to-gasoline (MAS) route. The mixed stream is then separated into individual components such as ethanol, methanol, and alcohols. Further, the produced methanol is recycled, while ethanol is upgraded by distillation process to produce a high-quality fuel. During Fischer-Tropsch synthesis (FTS), the syngas reacts with metal catalysts such as cobalt, iron, and ruthenium catalysts to produce alkanes and hydrocarbons waxes.

Syngas fermentation (SF) routes ferment the cleaned syngas (not cleaned with catalysts) with *Clostridium* bacterium (Abubackar et al. 2011). The use of biocatalyst combines the carbon dioxide and hydrogen gas in the syngas to yield ethanol. Upgradation of syngas through biochemical routes has several advantages over catalytic synthesis process such as high selectivity, consolidation of process steps, and lower operational pressure and reduced the sensitivity of biocatalysts to sulfur and nitrogen contaminants in syngas compared with the metal catalyst. However, lower mass transfer between gaseous feedstock and the microorganism is the major disadvantage (Koroneos et al. 2008).

15.2.2.3 Pyrolysis

The cracking of biomass or organic materials in the absence or partial presence of oxygen at moderate temperature (400–700 °C) is known as pyrolysis. Brown (2015) reported that thermal decomposition of biomass at temperature range 300–700 °C to produce solid, liquid, and gases is known as pyrolysis. Among all the thermochemical techniques, pyrolysis can produce solid, liquid, and gas products. The production of liquid fuel is a major consideration through pyrolysis which can be further upgraded for extraction of various value-added chemicals. However, recently pyrolysis is used for the production of biochar which can be used as an excellent biochar for various applications such as adsorption of toxic gases, soil abetments and fertilizers, and water and wastewater (Mohan et al. 2014).Various process parameters such as heating rate, temperature, particle size, feed composition, types of reactor, sweeping gas flow rate, and composition of biomass affected pyrolysis. Temperature, heating rate, and residence time are the major parameters that influenced pyrolysis. Further, particle size also affected pyrolysis product yields (Graham et al. 1984).

Based on the process conditions, pyrolysis is grouped into six subcategories and presented in Table 15.1. However, based on the application of pyrolytic liquid as a transportation fuel, pyrolysis is divided into four major categories. The slow pyrolysis and upgrading of syngas are considered as the first type; fast pyrolysis and hydroprocessing (FPH) is the second type; catalytic pyrolysis and hydroprocessing (CPH) is the third, while hydropyrolysis and hydroprocessing (HPH) are considered as forth type of pyrolysis. Slow pyrolysis has the lower temperature and lower residence time (5–45 min). Hence, decomposition occurred over the long period. Slow pyrolysis is operated at lower temperature <400 °C (mostly), which yields a higher amount of char along with lower yield of liquid, which is the complex mixture of acids (acetic acids, formic acids, carboxylic acid) and water.

Slow pyrolysis is used for a long time for cooking purposes, but recently it has been used for the production of potential fuel such as methanol and for fertilizer production (Shabangu et al. 2014). During fast pyrolysis, biomass is decomposed at a much higher temperature (500 °C) and higher heating rate, which converts biomass into fuel and chemicals within a few seconds. During fast pyrolysis, the liquid yield is higher compared with biochar and syngas. Biochar and syngas are low value-added products that are used for combustion for getting heat and power. In fast

Table 15.1 The summary of a few biomass thermochemical technologies

Conversion technology	Process condition	Reactor types	Product yield	References
Fast pyrolysis	Smaller particle size (<3 mm); short residence time (0.5–2 s); moderate temperature (400–600 °C) in the absence of oxygen; atmospheric pressure	Fixed bed reactor, tubular reactor, bubbling fluidized bed reactor, auger reactor, rotating cone reactor, ablative pyrolyzer, cyclone reactor, Py-GC/MS	Liquid: 65–75 wt% Gas: 13–25 wt% Solid: 12–19 wt%	Isahak et al. (2012), Carlson et al. (2009), Jones et al. (2009), Xianwen et al. (2000), Thangalazhy-Gopakumar et al. (2010), and Lu et al. (2011)
Slow pyrolysis	Slow heating rate; moderate temperature (350–750 °C); atmospheric pressure or desired pressure; long residence time; presence of nitrogen and absence of oxygen gas	Batch reactor, semi-batch reactor, static batch reactor	Liquid: 30–50 wt% Gas: 15–30 wt% Solid: 30–60 wt%	Williams and Besler (1993, 1996), Shadangi and Singh (2012), Sınağ et al. (2004), and Shadangi and Mohanty (2014a, b)
Intermediate pyrolysis	Moderate temperature (<500 °C); moderate vapor residence time (4–10 s); atmospheric pressure	–	Liquid: 45–55 wt% Gas: 25–35 wt% Solid: 15–25 wt%	Kebelmann et al. (2013)
Flash pyrolysis	Rapid heating (<0.5 s); smaller particle sizes (<0.5 mm); higher temperature (400–1000 °C)	–	Liquid: 60–70 wt% Gas: 10–15 wt% Solid: 15–25 wt%	Scott et al. (1985), Scott and Piskorz (1984), Liden et al. (1988), and Samolada and Vasalos (1991)
Vacuum pyrolysis	Moderate temperature (300–600 °C); pressure: <50 kPa	–	Liquid: 45–60 wt% Gas: 17–27 wt% Solid: 19–27 wt%	Xu et al. (2009), Patel et al. (2011), and Boucher et al. (2000)
Ablative pyrolysis	Moderate temperature (450–600 °C); atmospheric pressure; particle size: 1.4–3.5 mm;	–	Liquid: 60–80 wt% Gas: 6–10 wt% Solid: 12–20 wt%	Peacocke (1994) and Lédé (2003)

(continued)

Table 15.1 (continued)

Conversion technology	Process condition	Reactor types	Product yield	References
	slightly higher residence time			
Hydrothermal gasification	High temperature (600–1200 °C); presence/absence of catalyst; small particle size; gasifying agents	Fixed bed, moving bed, fluidized bed, and entrained flow gasifier	Gas: 1–2.6 m^3/kg	Parthasarathy and Narayanan (2014), Zhou et al. (2009), and Alauddin et al. (2010)
Combustion	High temperature, 740–1300 °C; air mass flow, 0.1–0.5 $kg/m^2.s$	Fixed bed, fluidized bed, circulating bed, and entrained flow bed combustor, drop tube furnace	Power and heat	Arce et al. (2013), Nussbaumer (2003), and Wang et al. (2014)
Co-combustion	Higher temperature: 700–1100 °C	Boiler	Power and heat	Hein and Bemtgen (1998), Spliethoff and Hein (1998), and Nussbaumer (2003)
Hydrothermal/ thermochemical liquefaction	Moderate to high temperature, 250–550 °C; pressure, 5–25 MPa; heating rate, 5–140 °C/ min; solvent required	Parr high-pressure reactor	Liquid: 60–75 wt%	Zhang et al. (2009)
			Gas: 15–20 wt%	
			Solid: 8–20 wt%	
Carbonization	Low to high temperature, 400–1200 °C; heating rate, 4–5 °C/min	Stainless steel container inside a furnace, hydrothermal carbonization	Solid: 20–35 wt%	Kumar et al. (1992)
Hydrothermal carbonization	Temperature, 250 °C; pressure, 4 MPa; particle size, 1–10 μm	–	Biochar: 40–60 wt.%	Sevilla et al. (2011) and Reza et al. (2014)
Co-firing	Biomass: 5–20 wt%	Boiler	Power and heat	Sebastián et al. (2011), Savolainen (2003), and Zuwala and Sciazko (2010)

pyrolysis, smaller particle size (<1.0 mm), moderate temperature (500–700 °C), and lower residence time (2–5 s) were used for enhancing liquid yield (Bridgwater et al. 1999).

Liquid fuel obtained from pyrolysis is associated with several disadvantages such as higher oxygen content, which is further upgraded by hydroprocessing process and results in hydrocarbons and aromatics. The hydroprocessing process is divided into two types: the first type is known as hydrotreating, while the second type is known as hydrocracking. The treatment of organic compounds in the presence of pressurized hydrogen is known as hydrotreating in which oxygen is removed along with nitrogen, sulfur, and chorine (heteroatoms). However, hydrotreating is a carbon-efficient process because water is used for removal of oxygen, but it requires a large amount of hydrogen (Brown and Brown 2013). During hydrocracking, hydrogen is reacted under more complex conditions to fragment higher modules into fuel range molecules. Further removal of oxygen can be done by catalytic pyrolysis or hydroprocessing (CHP) technology. Zeolite catalysts are usually used and homogeneously mixed with the biomass, which is placed at the downstream of the reactor to remove the CO and CO_2 in the absence of H_2. Hydropyrolysis and hydroprocessing (HPH) are carried out with pressurized hydrogen and catalysts, and the resultant product could be used as fuel because the high amount of oxygen content is removed. It was also observed that HPH process is more carbon efficient than CHP process. The HPH process produced fine grade fuel without any separate hydrocracking units.

15.2.2.4 Liquefaction

Liquefaction is the process in which water plays a significant role in thermochemical conversion. The water is used as a catalyst and reactant at a higher temperature, which results in separating all the organic material into individual compounds. Liquefaction is advantageous over gasification and pyrolysis because it does not require dry biomass (Zhang et al. 2009) and it reduced the number of unit operation required for conversion of biomass into liquid fuel. In this process, biomass is directly converted into fuel and chemicals.

15.2.2.5 Carbonization

Carbonization is known as an extension of pyrolysis, which is operated at a slower heating rate and produces a higher yield of solid products compared with liquid and gas. The production of solid biochar via carbonization is dependent on the operating temperature (generally lower temperature) (Strezov et al. 2007). Carbonization was used to produce biochar, which is also used for combustion and cooking purposes.

15.2.2.6 Co-firing

Co-firing is the clean and low-cost technology in which biomass is converted into electricity efficiently by adding biomass as a partial substitute for fuel in the boiler (Agbor et al. 2014). Co-firing is also used for improving combustion of fuel with low energy content. Biomass co-firing varied between 5 and 20 wt.% depending on boiler capacities and efficiencies (Sebastián et al. 2011). Co-firing technology has a

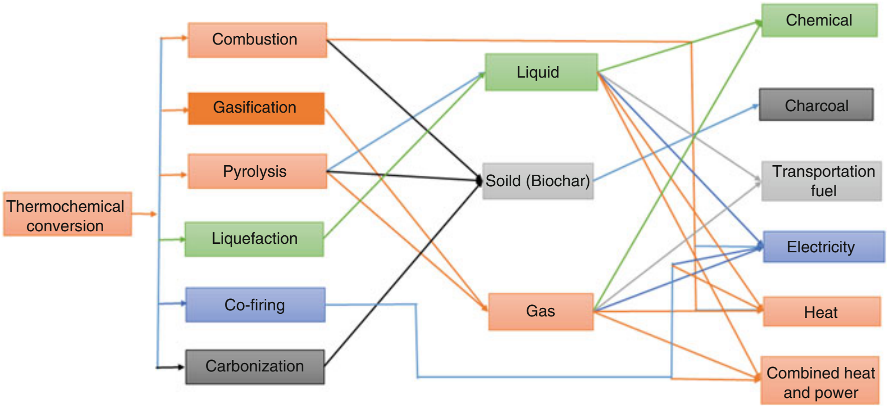

Fig. 15.2 End products produced from thermochemical conversion. (Redrawn based on Patel et al. 2016)

positive impact on the environment by reducing the consumption of fossil fuels. Co-firing of coal or biomass with natural gas improves heat content of the fuel, combustion efficiencies, and equipment performances.

15.2.2.7 Process End Products

The primary products such as solid, liquid, and gas obtained from the six thermochemical conversion technologies are presented in Fig. 15.2. The produced liquid fuel from pyrolysis can be used as alternative fuel after suitable upgradation and directly in the boiler and turbine for power generation. Hydroprocessing unit is mostly used for the upgradation of the pyrolytic liquid. Hydroprocessing process provides upgraded fuel with the presence of catalysts and hydrogen. Various value-added chemicals can be reformed from the liquid fuel. On the other hand, product gas can be used directly into boiler or turbine for the production of heat and electricity. It is also interesting that a range of chemicals can be extracted from product gas (Patel et al. 2016). During gasification, product gases are associated with the higher calorific value. Therefore, they can be converted into transportation fuel and power generation (Parthasarathy and Narayanan 2014). Furthermore, the solid biochar produced through carbonization and slow pyrolysis is used as soil conditioner, insulation, catalysts, beauty products, and fertilizers, besides having the potential to reduce global warming emission.

15.3 Techno-economic Assessment

Biomass is considered as carbon neutral source due to complete recycling of carbon. The quality of biomass has made it more attractive for production of power and energy in recent years. The fossil fuel has more potential as compared to biomass-derived fuel and energy, but biomass seemed more cost competitive compared with fossil fuel worldwide due to its inherent advantages. Therefore, techno-economic analysis of biomass and biomass-derived fuel through thermochemical process becomes essential for improved efficiency and commercialization. Also, prediction of cost for producing fuels and chemicals is the major outcome of the techno-economic analysis.

Bridgwater et al. (2002) studied techno-economic analysis of thermochemical conversion technologies such as combustion, pyrolysis, and gasification for power generation. In addition, they derived standard equations for calculation of capital and operating costs for each of these technologies. For assessing economic assessment of specific processes, these equations provide useful information. Various products such as biofuel, energy, biochemicals, and electricity can be derived from biomass through thermochemical conversion. Economic analyses of thermochemical conversion products were derived, which helped in evaluating the production cost of each product. The production cost of the various biomass-derived products such as biofuel, power, electricity, and biochemical depends on the thermochemical process adopted. The data reported in this chapter was adopted based on 2014 US $ value, and 2% inflation was used. The comparisons of the production cost of different biofuels are shown in Tables 15.2 and 15.3.

15.3.1 Gasification

Gasification is used to convert carbonaceous products into liquid transportation fuel at a commercial scale. The process helps to overcome prevailing shortage of petroleum products that resulted in turning coal into diesel for jet fuel application through the gasification pathway by using Fischer-Tropsch synthesis. Over the time, the gasification process was upgraded and employed for generation of various products. Acetic acid synthesis (AAS), which is used for generation of ethanol from cellulose through gasification (Zhu and Jones 2009), methanol-to-ethanol (MTE) also used for ethanol production, methanol-to-gasoline synthesis (MTG), mixed alcohol synthesis (MAS), syngas-to-distillates (S2D), and syngas fermentation (SF) are the main products. During gasification, materials decomposed at the high temperature (1500 °C) and formed the mixture of gases such as CO, CH_4 H_2, CO_2, and light hydrocarbons. The products obtained from the gasification is known as syngas, which was further converted into generation of power and electricity through either combustion or upgrading via catalysts into transportation fuel such as ethanol (Zhu and Jones 2009), methanol (Phillips et al. 2011), gasoline (Swanson et al. 2010), diesel, and jet fuel (Zhu et al. 2012). In addition, a novel *Clostridium* bacterium has the potential to convert switch grass-based syngas into ethanol via syngas fermentation (Piccolo and Bezzo 2009), thereby combining thermochemical and biochemical processes to yield cellulose biofuel. Syngas is the product output from gasification, which can yield high-quality fuel directly or in combination with catalysts. Furthermore, gasification-derived syngas can be used for the production of power by using advanced turbines.

Table 15.2 Comparison of the production cost of fuel and chemical from different biomass thermochemical conversion technologies

Bio-product	Feedstock	Location	Technology	Capacity (dry tonnes/day)	Base year	Production cost (2014 USD)	References
Methanol	Forest residue	Western Canada	Atmospheric pressure gasification + upgrading	2000	2008	$0.33/kg $0.26/L $16.31/GJ	Sarkar et al. (2011)
	Forest residue	Western Canada	Pressurized gasification + upgrading	2000	2008	$0.51/kg $0.41/L $25.53/GJ	Sarkar et al. (2011)
	Forest residue	Western Canada	Atmospheric pressure gasification + upgrading	3000	2008	$0.32/kg	Sarkar et al. (2011)
	Maize residue	South Africa	Gasification + methanol synthesis using super converter	10–2000 MW (thermal)	2008	$34.24–94.26/GJ	Amigun et al. (2010)
	Pine	Ithaca, USA	Gasification at 800 °C + methanol synthesis	500–9600	2012	$15.61–33.29/GJ	Shabangu et al. (2014)
	Pine	Ithaca, USA	Pyrolysis at 450 °C + methanol synthesis	500–9600	2012	$26.01–49.94/GJ	Shabangu et al. (2014)
	Pine	Ithaca, USA	Pyrolysis at 300 °C + methanol synthesis	500–9600	2012	$57.22–109.24/GJ	Shabangu et al. (2014)
Ethanol	Agricultural biomass	Almeria, Spain	Steam–air indirect circulating fluidized bed gasification + upgrading	2140	2010	$1.03/kg	Valle et al. (2013)
	Agricultural biomass	Karlsruhe, Germany	Fast pyrolysis + gasification + upgrading	600	2008	$16.22/GJ	Trippe et al. (2010)
	Natural gas	Karlsruhe, Germany		–	2008	$10.20/GJ	Trippe et al. (2010)
	Coal	Karlsruhe, Germany		–	2008	$6.96/GJ	Trippe et al. (2010)

Dimethyl ether	Forest residue	Western Canada	Atmospheric pressure gasification + upgrading	2000	2008	$0.53/kg $0.35/L $18.40/GJ	Sarkar et al. (2011)
	Forest residue	Western Canada	Pressurized gasification + upgrading	2000	2008	$0.78/kg $0.51/L $26.70/GJ	Sarkar et al. (2011)
	Forest residue	Western Canada	Atmospheric pressure gasification + upgrading	3500	2008	$0.50/kg	Sarkar et al. (2011)
Ethylene	Lignocellulosic biomass	Karlsruhe, Germany	Gasification syngas-DME-ethylene	–	2010	$2.24–2.30/kg	Haro et al. (2013)
Propylene	Lignocellulosic biomass	Karlsruhe, Germany	Gasification syngas-DME-propylene	–	2010	$2.20–2.26/kg	Haro et al. (2013)
Ammonia	Forest residue	Western Canada	Atmospheric pressure gasification + upgrading	2000	2008	$2.35/kg $1.60/L $124.73/GJ	Sarkar et al. (2011)
	Forest residue	Western Canada	Pressurized gasification + upgrading	2000	2008	$3.06/kg $2.09/L $111.01/GJ	Sarkar et al. (2011)
	Forest residue	Western Canada	Atmospheric pressure gasification + upgrading	3000	2008	$2.32/kg	Sarkar et al. (2011)
Bio-oil	Energy crops	UK	Fast pyrolysis	100–800	2009	$13.18–28.56/GJ	Rogers and Brammer (2012)
Biochar	Pine	Ithaca, USA	Slow pyrolysis	–	2012	$0.23–0.29/kg	Shabangu et al. (2014)

(continued)

Table 15.2 (continued)

Bio-product	Feedstock	Location	Technology	Capacity (dry tonnes/day)	Base year	Production cost (2014 USD)	References
Fischer-Tropsch fuel	Forest residue	Western Canada	Atmospheric pressure gasification + upgrading	2000	2008	$1.09/kg $0.88/L $24.54/GJ	Sarkar et al. (2011)
	Forest residue	Western Canada	Pressurized gasification + upgrading	2000	2008	$1.72/kg $1.37/L $38.38/GJ	Sarkar et al. (2011)
	Forest residue	Western Canada	Atmospheric pressure gasification + upgrading	4000	2008	$1.06/kg	Sarkar et al. (2011)
Hydrogen	Forest residue	Western Canada	Battelle Columbus Laboratory (BCL) gasifier	2000	2008	$1.32/kg $10.98/GJ	Sarkar and Kumar (2010a)
	Straw	Western Canada	Battelle Columbus Laboratory (BCL) gasifier	2000	2008	$1.45/kg $12.11/GJ	Sarkar and Kumar (2010a)
	Forest residue	Western Canada	Gas Technology Institute (GTI) gasifier	2000	2008	$1.46/kg $12.30/GJ	Sarkar and Kumar (2010a)
	Straw	Western Canada	Gas Technology Institute (GTI) gasifier	2000	2008	$1.50/kg $12.43/GJ	Sarkar and Kumar (2010a)
	Whole tree	Western Canada	Gas Technology Institute (GTI) gasifier	2000	2008	$1.49/kg $12.39/GJ	Sarkar and Kumar (2010b)
	Whole tree	Western Canada	Fast pyrolysis + steam reforming	2000	2008	$2.70/kg $22.52/GJ	Sarkar and Kumar (2010b)
	Forest residue	Western Canada	Fast pyrolysis + steam reforming	2000	2008	$3.38/kg $28.15/GJ	Sarkar and Kumar (2010b)

	Straw	Western Canada	Fast pyrolysis + steam reforming	2000	2008	\$5.12/kg \$42.79/GJ	Sarkar and Kumar (2010b)
Gasoline	Lignocellulosic biomass	Karlsruhe, Germany	Gasification syngas-DME-gasoline	–	2010	\$1.57–1.62/L \$57.18–58.05/GJ	Trippe et al. (2013)
	Coal	Karlsruhe, Germany	Gasification syngas-DME-gasoline	–	2010	\$1.05/L	Trippe et al. (2013)
	Lignocellulosic biomass	Karlsruhe, Germany	Gasification syngas-FT synthesis-gasoline	–	2010	\$1.72–1.77/L	Trippe et al. (2013)
	Coal	Karlsruhe, Germany	Gasification syngas-FT synthesis-gasoline	–	2010	\$1.13/L	Trippe et al. (2013)
	Woody biomass	Golden, USA	Gasification syngas-methanol-gasoline	2000	2007	\$0.60/L \$18.07/GJ	Phillips et al. (2011)
Liquefied petroleum gas (LPG)	Woody biomass	Golden, USA	Gasification syngas-methanol-LPG	2000	2007	\$0.46/L \$18.07/GJ	Phillips et al. (2011)
Diesel	Lignocellulosic biomass	Karlsruhe, Germany	Gasification syngas-FT synthesis-diesel	–	2010	\$1.72–1.77/L	Trippe et al. (2013)
	Coal	Karlsruhe, Germany	Gasification syngas-FT synthesis-diesel		2010	\$1.09/L	Trippe et al. (2013)

(continued)

Table 15.2 (continued)

Bio-product	Feedstock	Location	Technology	Capacity (dry tonnes/day)	Base year	Production cost (2014 USD)	References
Gasoline and diesel	Woody biomass	Ames, USA	Mild catalyst pyrolysis	2000	2011	$1.03/L	Thilakaratne et al. (2014)
	Woody biomass	Ames, USA	Mild catalyst pyrolysis with cogeneration of electricity and hydrogen	2000	2011	$0.85/L	Thilakaratne et al. (2014)
	Stover	Ames, USA	Fast pyrolysis + hydroprocessing	2000	2011	$0.72/L	Brown et al. (2013)
	Corn Stover	Ames, USA	Gasification + Fischer-Tropsch synthesis and hydroprocessing	2000	2007	$1.22–1.52/L	Swanson et al. (2010)
Naphtha and diesel	Corn Stover	Ames, USA	Fast pyrolysis + upgrading, with hydrogen generation on-site	2000	2007	$0.94/L	Wright et al. (2010)
	Corn Stover	Ames, USA	Fast pyrolysis + upgrading, with merchant hydrogen	2000	2007	$0.64/L	Wright et al. (2010)

Source: Adapted from Patel et al. (2016)

Table 15.3 Comparison of the production cost of electricity from different biomass thermochemical conversion technologies

Feedstock	Location	Technology	Power output (MW)	Base year	Production cost ($/MWh in 2014 USD)	References
Energy crop	UK	Organic Rankine cycle based CHP system	0.15	2013	48–60.2	Huang et al. (2013)
Energy crop	UK	Biomass gasification (downdraft gasifier) based CHP system	0.15	2013	104.04–116.30	Huang et al. (2013)
Woody biomass + coal	The Netherlands	Supercritical pulverized coal-fired (PC) boiler	500	2011	86.91–133.30	Domenichini et al. (2011)
Woody biomass + coal	The Netherlands	Supercritical circulating fluidized bed (CFB) boiler	500	2011	89.77–146.34	Domenichini et al. (2011)
Woody biomass	The Netherlands	Subcritical CFB boiler	250	2011	173.82–318.68	Domenichini et al. (2011)
Woody biomass	The Netherlands	Subcritical bubbling circulating bed (BFB) boiler	75	2011	246.20–434.56	Domenichini et al. (2011)
Torrefied biomass	The Netherlands	IGCC without CO_2 capture	–	2008	99.78–144.26	Meerman et al. (2013)
Torrefied biomass	The Netherlands	IGCC with CO_2 capture	–	2008	141.89–197.19	Meerman et al. (2013)
Coal	The Netherlands	IGCC without CO_2 capture	–	2008	93.8	Meerman et al. (2013)
Coal	The Netherlands	IGCC with CO_2 capture	–	2008	129.84	Meerman et al. (2013)
Biomass	UK	Fast pyrolysis, diesel engine	1–20	2002	88.78–177.56	Bridgwater et al. (2002)
Biomass + natural gas	Brazil	Indirect co-firing of biomass-derived gas with natural gas	150	2003	73.36	Rodrigues et al. (2003)
Biomass	Brazil	Biomass sole plant	24	2003	166.87	Rodrigues et al. (2003)

Adapted from Patel et al. (2016)

Fischer and Pigneri (2011) estimated the techno-economics study of power generation from gasification pathway in Vanuatu and reported that small-scale gasifiers with readily available raw material supply could be more economical, than similar-sized diesel engine for power generation. Generally, gasifiers are operated at higher pressure or sometimes at normal atmospheric pressures as well. The production cost of the various products such as methanol fuel, ethanol fuel, Fischer-Tropsch fuel, and NH_3 has been presented in Table 15.2, which is derived from pressurized or atmospheric gasifiers. From Table 15.2, it can be concluded that the atmospheric-based gasifier plant is more economical than the high pressurized gasifier-based plant (Sarkar et al. 2011). The production costs of methanol operated at atmospheric and pressurized gasifiers are $0.29/kg and $0.45/kg, respectively, with a 2000 dry tonnes per day capacity. It was also observed that production cost of dimethyl ether (DME), NH_3, and Fischer-Tropsch fuel displayed the similar trend. The capital costs of pressurized equipment are much higher than atmospheric equipment and are one of the possible reasons for the higher price.

According to Bridgwater (1995), the pressurized systems are four times higher than atmospheric systems for a power plant with a capacity of 20 MW. The capital cost of the atmospheric gasifier is much lower than pressurized gasifiers which may be one of the possible reasons for the higher price. The pressurized systems are fourth times higher than atmospheric systems for 20 MW capacities of power plants (Bridgwater 1995). Due to the complex feeding section, higher feeding cost is another possible reason for the higher production cost of pressurized systems. At higher capacities of plants, the atmospheric system is more prominent than pressurized systems.

The lignocellulosic biomass such as agricultural residue, forest waste, woody biomass, and various energy crops are the major feedstocks for gasification. Therefore, the economics related to gasification are associated with the types of biomass. Thus the production of hydrogen fuel from agricultural residue has the higher production cost of about $1.29–1.33 per kg, while forestry biomass has a lower production cost of about $1.17–1.13 per kg, showing a direct correlation with biomass feedstocks used. Huang and Mcllveen-Wright (2006) reported that mixing of biomass with coal (co-gasification) seems a most promising approach because the volatile content of biomass enables the autothermal gasification. Cormos (2013) studied on co-gasification (biomass and solid waste with coal) in a polygenerated-based integrated gasification combined cycle (IGCC) with carbon capture and concluded that the product produced from IGCC contains H_2, synthetic natural gas (SNG), and liquid fuel. By increasing co-production cost with power directly affected the plant payback period. Further, the payback period can be controlled by producing a higher yield of SNG and Fischer-Tropsch fuel with power.

15.3.2 Combustion

Different types of the boiler can be used for generation of power from biomass through combustion. Supplying biomass as feedstock in pulverized coal-fired (PC) boiler provides the lower electricity cost compared with fluidized bed boilers

(Table 15.3). Comparison of different fluidized bed boilers indicates that circulating fluidized bed boilers produce electricity at a lower cost than the bubbling circulating bed (BCB) boilers. Moreover, cost of electricity (COE) produced from subcritical boilers is more costly than that from supercritical boilers (PC and CFB). The comparison with various fluidized bed boilers and circulating fluidized bed boilers produced the electricity or power at a reduced cost than bubbling fluidized bed boilers. The higher cost of biomass transportation results in increased cost of electricity produced from solely biomass-based power plants. Since coal transportation is comparatively cheaper, the co-firing of biomass with coal could reduce the production cost of electricity (Table 15.3). Due to higher installation cost of the conventional power generation plant, the biomass has higher breakeven electricity selling price than the cogeneration plant. Production of power and heat by cogeneration gives the more economical solution. An analysis of biomass-based combined heat and power (CHP) showed that higher cost of electricity could be adjusted by a production of heat (Huang et al. 2013). The production cost of organic Rankine cycle (ORC)-based combined heat power plant has the higher initial capital cost compared with gasification-based combined heat and power plant (Patel et al. 2016). However, organic Rankine cycle (ORC)-based combined heat power (CHP) plant agrees with economic profits such as lower electricity price compared with gasification-based combined heat and power unit. The higher amount of production of heat from organic Rankine cycle (ORC)-based combined heat power (CHP) plant is the possible reason which helps improving economic performance significantly (Huang et al. 2013).

15.3.3 Pyrolysis

Fast pyrolysis produced several types of products and by-products from the biomass such as pyrolytic liquid, which can be further synthesized into transportation fuels or several other value-added chemicals. In addition, fast pyrolysis is used for power generation with the combined diesel engine (Patel et al. 2016). Rogers and Brammer (2012) evaluated production cost of bio-oil from the energy crop such as *Miscanthus* and willow through fast pyrolysis and found to be \$12–26/GJ with variable feedstock and plant size. Consumption of electricity and surplus char selling are the two major factors that strongly affected production cost of pyrolytic liquid from pyrolysis. All the processing and handling of biomass is carried out by using electricity which increases the production cost. It was studied that the produced pyrolytic liquid can be used in a diesel engine for power production in the plant, which in turn reduced the dependence on fossil fuel. The study also confirmed that about 18% of produced pyrolytic liquid would be consumed (Patel et al. 2016). The selling of solid residue (biochar) is the best possible solution to reduce the overall production cost up to 18%, but the selling price of the biochar is market dependent.

The product output obtained from the fast pyrolysis (pyrolytic liquid) and hydroprocessing (upgraded fuel such as transportation fuel) has been studied by several researchers. These studies were based on the initial production cost of pyrolytic liquid derived from biomass, through pyrolysis and improvement in cost of pyrolytic liquid for upgraded fuel, such as transportation fuel by adding hydrogen and catalysts. Wright et al. (2010) evaluated production cost of naphtha and diesel fuel produced from the pyrolytic liquid and reported that the production cost of upgraded fuel would be \$0.56–0.82 per liter, with 2000 dry tonnes per day plant capacity (Table 15.2). However, the alteration in production cost depends on hydrogen price and cost of catalysts. The production cost of hydrogen from outside the system is much cheaper than that produced from the process itself. The production cost of transportation fuel is critically affected by two main factors, i.e., price of biomass and rate of conversion yield. Brown et al. (2013) studied that production cost of upgraded fuel (gasoline and diesel produced from fast pyrolysis and hydroprocessing) was \$0.68 per liter with 2000 dry tonnes per day of plant capacity. This also falls within the range proposed by Anex et al. (2010). It was found that production of electricity for the fast pyrolysis and diesel engines seemed to be a realistic option. The electricity production costs of a fast pyrolysis and diesel engine system range from around \$0.14/kW h (base year 2002) at 1 MWe to around \$0.07/kW h (base year 2002) at 20 MWe (Bridgwater et al. 2002). However, this is higher than in an established combustion system and lower than any other novel biomass power generation system (Bridgwater et al. 2002). The fast pyrolysis process and diesel system are not sufficient and capable of production in higher capacities. The lower rate of conversion of feedstock into liquid fuel which results in higher electricity production cost and grinding of biomass which results in higher consumption of electricity are two main reasons for the lower efficiencies.

However, disposable products obtained from process, produced heat, several other by-products, selling of solid residue (biochar, coal), produced water, or cogeneration of various value-added chemicals along with power are the other potential solutions which can improve the economy of generation of power from biomass fast pyrolysis and diesel engines (Gnansounou and Dauriat 2010). In addition, system decoupling (more than one engine added in series) is another potential possible solution for improving the economy of the power generation from biomass fast pyrolysis and diesel engine. The production cost of electricity through decoupling system is more proficient than traditional closed coupled systems because of economic benefits of pyrolysis plant (Gnansounou and Dauriat 2010). On the other hand, the decoupling system has the potential to fulfil the requirements of power load at all times because both processes are operated independently.

Slow pyrolysis of biomass results in the solid residue (charcoal) and liquid (methanol) (Shabangu et al. 2014). Production of solid residue from slow pyrolysis is dependent on the temperature. However, lower temperature reduced the production cost. Furthermore, biochar production cost affected the cogeneration plants' profits at the lower temperature due to higher char yield. Shabangu et al. (2014) estimated that selling of biochar provided 70% of the plant revenue, while 30% revenue came from methanol at the lower temperature (300 °C). However, in case of 450 °C, it was the opposite. Gasification of biomass is another possible solution for cogeneration of biochar. Price of char does not affect the revenue in gasification process because char yield is lower than slow pyrolysis.

15.3.4 Liquefaction

Conversion of biomass into fuel and energy can be done through thermochemical means such as pyrolysis, combustion, liquefaction, and gasification. Pyrolysis is being used along with hydroprocessing (for upgradation of fuel), while gasification is being used with Fischer-Tropsch synthesis and hydroprocessing. The biochemical process is being used with various types of bacteria and enzymes. Anex et al. (2010) estimated that production cost of liquid fuel ranged from $0.53/L to $1.45/L of gasoline (based on 2007) with 2000 dry tonnes per day capacity plant, while it was assumed that price of biomass feedstock is $82.7 tonnes per day. Some specific process parameter such as temperature, heating rates, oxygen feed flow rate, and types of gasification system does not seriously affect the production cost through different pathways. In addition, implementation of different pathways significantly affected the production cost of various products. Due to lower initial capital investment, direct liquefaction has the lower cost ($0.56–0.975/L) compared to gasification and biochemical pathways. Production of liquid fuel from bio-oil through direct liquefaction via fast pyrolysis by adding hydrogen showed lower production cost as compared to direct production of hydrogen by pyrolysis. However, upgradation of bio-oil to transportation fuel produced from pyrolysis is not well defined; therefore, it is relatively less popular and less used. However, it has potential to replace the fossil fuel completely or partially if used properly such as blending with fossil fuel. Hence, before large-scale implementation, this process requires further development. Upgradation of liquid fuel produced from gasification increases production cost ($0.53–1.64 per liter compared with pyrolysis).

Trippe et al. (2013) studied straw biomass for production of gasoline by dimethyl ether (DME) synthesis and production of diesel by Fischer-Tropsch synthesis. Based on the techno-economic analysis, they concluded that 38% and 39% of total energy efficiencies were required for biomass to the final product. The production cost of gasoline produced from DME synthesis is $0.82/L, while diesel and gasoline through Fischer-Tropsch synthesis are $0.88/L. The capital cost of the liquefaction through pyrolysis and biochemical routes is more economical than gasification route at the lower and the higher temperature situations. Furthermore, the production cost of liquid fuel via biochemical route is relatively higher than gasification route, which offers lower operating cost.

Swanson et al. (2010) have compared the production cost of transportation fuel with two gasification situations with equal syngas synthesis process. The low temperature was being used as the first scenario in the fluidized bed gasifier, and the higher temperature was being used in an entrained flow gasifier. Based on the product yield of products, it was concluded that high-temperature route has the lower production cost compared with lower temperature route; however, capital cost is more at higher temperature condition. The conversion of lignocellulosic biomass through liquefaction pathways yet needs to be commercialized. It is important to mention that the production cost of a pioneer plant is 60–90% higher than those of nth plant, while capital cost of a nth plant is much lower (double of nth plant) than pioneer plant (Swanson et al. 2010). Biosyncrude is another intermediate for conversion of biomass into biofuel or pyrolytic liquid; however, it is still under research (Patel et al. 2016). It will take some time to compete with existing literature. Biosyncrude is a mixture of liquid and biochar (solid residue) produced from fast pyrolysis. In Germany, they investigated the first-time production of biosyncrude at an estimated production cost of $14.4/GJ with 600 tonnes per day capacity plant. However, the production cost of biosyncrude in Germany is higher than other fuels such as natural gas ($9.06/GJ) and conventional fuel such as coal ($6.18/GJ) (Patel et al. 2016).

15.3.5 Co-firing

Due to environmental benefits, co-firing of biomass with coal or natural gas could be one of the interesting thermochemical technologies compared with the combustion of only coal (Agbor et al. 2014). Co-firing of coal with biomass or plastic waste in fluidized bed technology can be a good route due to fuel flexibility nature. The effect of blending (biomass or plastic waste) up to 20% in a co-firing system (circulating fluidized bed reactor) is found to be negligible for the performance of the co-firing system when blending of biomass or plastic equated with systems fueled by coal (McIlveen-Wright et al. 2006).The techno-economic analysis of biomass-based co-firing plants with coal-fired plants confirms that the capital cost and operating cost are the two major factors to be considered while co-firing biomass with coal or plastic waste. De and Assadi (2009) evaluated economic analysis of biomass co-firing with various parameters like biomass-to-waste ratio, the price of feedstocks, total plant capacity, and distribution of biomass density around the plant. They reported that when the cost of biomass is higher than coal, co-firing cost will increase due to increase in the rate of co-firing; therefore, electricity cost also increases.

15.4 Comparison of the Economics of Different Technologies

The economy of biomass-based fuels is attributed to the end products, which are produced by using different conversion pathways. Production of hydrogen via pyrolysis and gasification followed by steam reforming is one of the best examples. The production cost of gasified hydrogen is more economical than the hydrogen produced from pyrolysis and steam reforming. The comparative study confirmed that power generation from fast pyrolysis with diesel engines is more economical than electricity and power produced through the gasification process. Various researchers have compared the production cost of hydrogen through gasification and steam reforming process. It was confirmed that pyrolytic liquid or bio-oil gasification process is not as economical as the bio-oil reforming processes (Zhang et al. 2013). The bio-oil gasification capital cost is higher than reforming pathways due to the higher cost of the gasifier (entrained flow). However, the lower capital cost is observed between reformers and air separation. Furthermore, cleaning of gases become more complicated in gasification when compared with the reforming system (Zhang et al. 2013). McIlveen-Wright et al. (2006) studied the techno-economic analysis of generation of electricity from the supercritical boiler by combustion and gasification. They reported that supercritical gasification boiler is more economical (46.5%) compared to the supercritical combustion system. Supercritical boiler gasification system required lower investment cost of production of electricity than combustion system. Supercritical boiler combustion has the investment of $2150–2400 per kW, and supercritical boiler gasification system has $1350–1450 per kW. Electricity production cost from combustion system is reported to be $68–78/MWh, while for gasification system $49–54/MWh (McIlveen-Wright et al. 2006).

The gasification technology combined with fermentation process was compared with conventional enzymatic hydrolysis – combined with fermentation process for the production of high-grade fuel (ethanol). It was noticed that gasification with combined fermentation technology required higher ethanol production cost than ethanol produced from enzymatic hydrolysis with fermentation process (Piccolo and Bezzo 2009). Higher capital cost, high energy recovery expense, and moderate ethanol yield are the major issues responsible for the higher cost. However, there is a much better application for the broad range of production of ethanol via gasification and fermentation technologies.

15.5 Life-Cycle Assessment (LCA)

Biomass-derived end product produced from the thermochemical process has the potential to mitigate generation of greenhouse gas emission which comes from various sources such as transportation and industries. LCA is a useful tool to explain various impacts which are categorized quantitatively and qualitatively throughout the life cycle of the end products. There are three significant global system boundaries for conversion of biomass into fuel or power via thermochemical process biomass into useful products (end product), which are:

1. Phase 1: Planting of biomass, harvesting, and transportation
2. Phase 2: Plant site operation and upgradation of fuel if required
3. Phase 3: Demolition of plant and recycling of the plant

Based on the availability of data, Phase 1 and Phase 2 have been studied extensively by the various researchers. Life-cycle assessment of fast pyrolysis, gasification, combustion, and co-firing process is extensively available. However, there is lack of literature on liquefaction and carbonization. A number of the analytical tool such as greenhouse gases, regulated emissions, and energy use in transportation

(GREET), SigmaPro, GHGenius, Tools for Environmental Analysis and Management (TEAM), etc. were used by various researchers for collection of data (Mann and Spath 2001; Hsu 2012; Roberts et al. 2009). Two software, Eco-indicator 95/99 and CML (Centre for Environmental Studies, Leiden University, Netherlands), are widely used to evaluate the environmental impacts of various feedstocks based on the system boundary (Faix et al. 2010). In this study, the life-cycle analysis was done on conversion of lignocellulosic biomass into end products via thermochemical technologies. Among all the existing thermochemical technology, life-cycle analysis on pyrolysis was done by several authors. During the life-cycle assessment of biomass, three significant parameters such as system boundary, functional units, and environmental impact are considered.

15.5.1 Feedstocks

Type of feedstock is an important parameter during conversion of biomass via thermochemical technology. Biomass comprises mainly of hemicellulose, cellulose, and lignin; however, based on the type of feedstocks, their concentrations of these components vary. The higher percentage of cellulose in biomass and the lower percentage of lignin are suitable for this process. There are many reported works, where the potential of some of the popular biomass such as energy crops, forest residues, and agricultural residues was carried out to find out their efficiency of conversion. Furthermore, depending on the cultivation and collection methods, a specific feedstock has the specific environmental impact.

Energy crops are classified under third-generation biomass and are developed in such a way to produce useful and lower energy supply source. The advantage of these crops is that these can be genetically modified to increase their property which can result in higher fuel yield (López-Bellido et al. 2014). However, the use of various herbicides and pesticides are the major drawbacks of these types of agriculture crops which could result in resistant weeds and insects that may be more unsafe for nongenetically modified agriculture crops (Maggi and Delmon 1994). Forest residue is another important source for thermochemical conversion of biomass which is produced from harvesting of timber extraction operations, wood waste from lumber mills, or from dead wood. Concerning heating value and moisture content, forest residue is equivalent to wood, though they differ in their ash content.

Agriculture residue is the third lignocellulosic biomass which comes from the unused portions of wheat, corn, rice, bagasse, etc. after they are harvested. Some biomass such as corn stover, wheat straw, and rice husk have been in use for a long time due to their lower moisture and higher heating value. Due to the seasonal availability of the biomass, their cost increases because some of the crop residues are used for cattle fodder and composting. By addition of certain portions of these wastes into soil, level of groundwater and quality of the soil were improved (Nguyen et al. 2013). Thus, life-cycle analyses of these biomass feedstocks become essential for the production of fuel and chemicals.

15.5.2 Phase Involved in the System Boundary

The numbers of phases that are involved with system boundaries are based on the end products. Conversion of lignocellulosic biomass via thermochemical process has three major phases. The requirement of input and output feedstock of biomass is shown in Fig. 15.3. Life-cycle analyses of Phase 1 and Phase 2 are the major interests of several researchers. However, some researchers reported from the cradle to the grave at all phases in the system boundary. The first phase of system boundary involves collection or cultivation of biomass flowed by transportation of biomass to the plant site. Change in use of land, application of fertilizers and pesticides, carbon sequestration, removal of biomass residue from the soil, and transportation distance from the storage site to plant site are the major aspects. Change in land use has greater effects (direct and indirect) on the environment. Direct change in land use comprises conversion of forest or grassland into cropland for biofuel or power production, while the indirect use of change in land comprised when non-croplands were converted into cropland because existing cropland was used for power and biofuel production (Lange 2011). Most of the studies on life-cycle analysis do not include land change, which results in the change in carbon content in the changed land (cultivated area) for the feedstock.

Kimming et al. (2011) proposed the use of set-aside land for harvesting purpose for energy crops as maintaining carbon stocks on soil is not good due to legislative and practical reasons. Conventional crops have lower greenhouse gas emission compared with energy crops due to the application of fertilizer and pesticides.

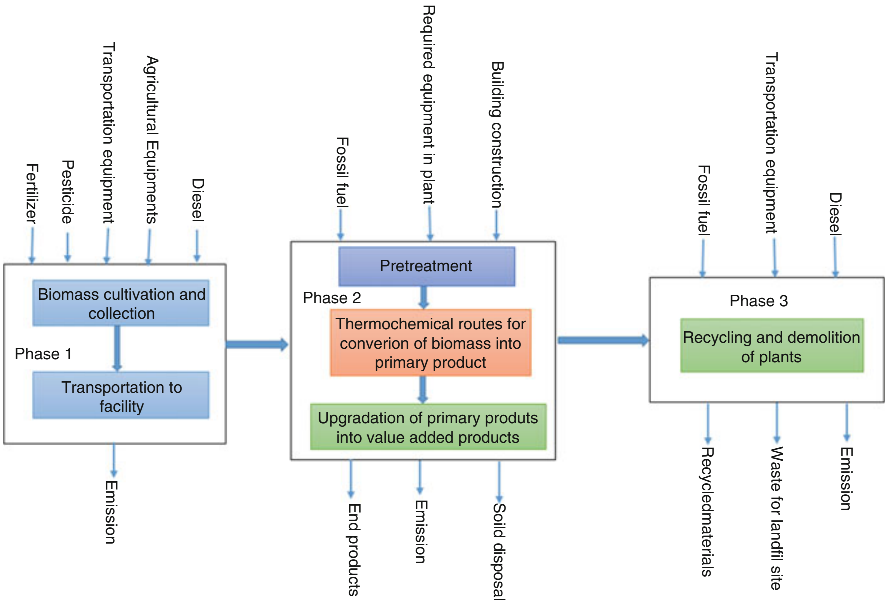

Fig. 15.3 General layout schemes of the system boundary (Redrawn based on Patel et al. 2016)

Skowrońska and Filipek (2014) suggested that production of 1 kg of NPK (nitrogen, phosphorus, and potassium) required 9.91 MJ of energy. However, most of the energy is required for nitrogen production. The production of fertilizer facility leads to the formation of nitrogen oxide, methane, and carbon dioxide emissions which put an extra burden on the environment (Skowrońska and Filipek 2014). To overcome the issues of food scarcity, use of agrochemical (chemicals and fertilizers) increases the production rate of crops within the same land. The use of frequent fertilizer and chemicals degrades the quality of the soil as well as atmosphere. Skowrońska and Filipek (2014) again suggested that replacement of chemical fertilizers with organic fertilizers such as compost is an excellent alternative.

Extraction of the biomass residue from the soil leads various types of pollution and also degrades the quality of the soil. The biomass residues contain lots of mineral matter and nutrients which have the positive effect on the quality of the soil. Gabrielle and Gagnaire (2008) reported that significant extraction of biomass residue (agricultural residue or energy crops) from agriculture soil reduces the ability of volatilization of NH_3 due to significant drops of immobilization of mineral fertilizer. Hence, straw management is essential for the production of fuel, chemicals, and power; therefore, the life-cycle analysis of biomass straw is essential (Gabrielle and Gagnaire 2008). The transportation of biomass from husbandry site or forestry site to plant site is an important characteristic of system boundary. In most of the cases, it was assumed to be carried out near the plant which reduced transportation cost and environmental impacts. About 30–200 km distance was considered in this study. Mostly distance depends on the biomass size facility. Therefore, it is essential to estimate overall life-cycle assessment of greenhouse gas emission of a conversion pathway.

The second phase of system boundary comprises biomass pre-treatment such as crushing, chipping, grinding, and drying. However pre-treatment process varies from process to process. The distribution of particle size of biomass and water molecules depends on the type of thermochemical conversion process. Thus, type of conversion technology also has an adverse effect on the overall variation of environmental impacts. Combustion, gasification, pyrolysis, and co-firing technologies are preferred majorly due to the availability of data. In addition construction materials used for equipments depend on various process conditions such as temperature, pressure, the rate of heating, etc. For example, highly viscous, corrosive, and polar nature of bio-oil makes it mandatory to store it in the stainless steel vessel. The extraction of iron ore and manufacture process of these types of vessels results in the higher emission of greenhouses gases (Martínez et al. 2009). Thus, reduction of greenhouse gas emission of this phase become essentially challenging.

15.5.3 The Functional Units

The functional unit is one of the most critical parts of the life-cycle assessment analysis and required clear and exact definition. It does not measure physical products but measures function of end products. The selection of the functional units is very crucial because it works as the locus point of all evaluated environmental impacts. In addition, selection of appropriate functional unit is not direct, and variation in functional unit conceives the problem during the life-cycle inventory. Depending on the scope and aim of the work, various researchers have used different functional units. The calorific value of end product, transportation distance, the weight of the feedstock, and the area used for the cultivation of the feedstock was chosen widely by different researchers. Also, based on the system boundary, authors have chosen functional units. Comparing the various units is a very difficult task, but it is possible if all units can be converted into the same unit and provided the same boundary condition is maintained for all life-cycle analysis (Singh et al. 2010).

15.6 Environmental Impact Assessment

Environmental impact assessment (EIA) is one of the utmost difficult tasks executed after defining all the system boundaries and inventory requirement of products or processes. For the calculation of its multiple impacts on ecosystem, human health, and resource depletion, Eco-indicator 99 and Eco-indicator 95 are usually used. These impacts are further categorized into different types of environmental effects. Global warming potential, acidification and eutrophication, ozone layer depletion, human health into smog and toxic substances (heavy metals, carcinogens, and pesticides), and resource diminution into solid waste and energy consumption are the main subdivided ecosystems. Environmental impacts evaluated by the different researchers are presented in Table 15.4. Global warming potential is one of the major study areas, while human health and resource diminution have less importance when compared with the ecosystem. The potential of global warming is reported pursuantly CO_2 equivalent which includes CH_4, N_2O, and CO_2 emissions. Similarly, acidification and eutrophication are evaluated in kg SO_2 equivalent and kg PO_2 equivalent, respectively. Sebastián et al. (2011) suggested that production of fertilizers has significant greenhouse gas emission compared with biomass planting because at the time of cultivation of biomass, net emission of CO_2 is zero due to photosynthesis.

Pre-treatment of biomass is an energy-intensive process and completely connected with the types of thermochemical pathways. Crushing, grinding, chipping, making of pellet, and drying are the major pre-treatment steps. Agriculture residue contains 10–20 wt. % moisture which is lower than forest residue and whole forest (40–50 wt. %) (Kumar et al. 2003b). Hence, consumption of energy differs with the moisture content of the types of feedstock. Iribarren et al. (2012) reported that pre-treatment of the poplar biomass had the utmost environmental impact compared to other unit operations used in fast pyrolysis system because of direct use of the conventional fuel. Distribution of the particle size varies on the process requirement. In fast pyrolysis lower particle size is preferred due to higher heat and mass transfer, while the use of higher particle size reduced liquid yield and increases biochar yield (Iribarren et al. 2012). Royo et al. (2004) estimated that size reduction of 25 mm to 3 mm biomass required 443 MJ per dry tonne energy consumption,

Table 15.4 Summary of the life-cycle assessment of different thermochemical conversion technologies

Process	Feedstock	End product	Boundary	Functional unit	Environmental impact categories	Comments	References
Co-firing	Rice straw	Power	Phases 1 and 2	1 MWh	Acidification, global warming potential (GWP), eutrophication, human toxicity	Significant reduction in impact categories at 5% biomass co-firing condition	Shafie et al. (2013)
Co-firing	Willow	Electricity	Phases 1 and 2	1 MWh	Net energy ratio and net global warming potential	Net energy ratio increased by 9% and net global warming potential decreased by 7–10% at 10% co-firing.	Heller et al. (2004)
						GWP:910 kg CO_2 eq/MWh	
Co-firing	Wood residue	Electricity	Phases 1, 2, and 3	1 kWh	Global warming potential	GWP: 894.3 g CO_2 eq/kWh at 15% co-firing −1002.9 g CO_2 eq/kWh at 5% co-firing	Mann and Spath (2001)
Co-firing	Energy crop and wheat straw	Electricity	Phases 1, 2, and 3	1TJ	Global warming potential	GWP: 298 tonnes CO_2 eq/TJ 10% direct co-firing	Sebastián et al. (2011)
						GWP: 300 tonnes CO_2 eq/TJ 10% indirect co-firing	
						Coal boiler efficiency and biomass treatment are important parameters	
Fast pyrolysis	Corn Stover	Bio-gasoline	Phases 1 and 2	1 ha	Global warming potential	GWP: 7.65 tonne CO_2 eq/ha	Kauffman et al. (2011)
						Corn stover removal rate is the sensitive parameter that affects the biochar and bio-oil yield	
Fast pyrolysis	Short rotation poplar	Gasoline, diesel, and char	Phases 1 and 2	1 MJ	Cumulative energy demand, global warming, ozone layer depletion, photochemical	GWP:-50.54 kg CO_2 eq/MJ	Iribarren et al. (2012)
						Biomass pretreatment, pyrolysis, and steam	

					oxidant formation, land competition, acidification, eutrophication	reforming are the main contributors in the environmental impact categories	
Fast pyrolysis	Forest residue	Gasoline and diesel	Phases 1 and 2	1 km	Global warming potential and net energy value (NEV)	GWP: 98–117 g CO_2 eq/km NEV: 0.92–1.09 MJ/km GWP and NER are lower than the conventional gasoline and diesel	Hsu (2012)
Fast pyrolysis	Corn Stover	Gasoline	Phases 1 and 2	1 MJ	Global warming potential	During upgrading of biofuel by hydroprocessing: GHG emissions reduction is maximized when hydrogen is produced from bio-oil reforming	Han et al. (2013)
Fast pyrolysis	Logging residue, hybrid poplar, willow, and waste wood	Electricity	Phases 1 and 2	1 kWh	Global warming potential	Depending on the feedstock type, life-cycle GHG savings of 77–99% estimated for power generation from pyrolysis oil to fossil fuel combustion	Fan et al. (2011)
Ablative pyrolysis	Wood chip	Electricity	Phases 1 and 2	1 kWh	Global warming, ozone depletion, photochemical ozone creation potential, acidification, eutrophication	All impact categories are significantly decreased except eutrophication potential due to use of fertilizer during cultivation	Faix et al. (2010)
Slow pyrolysis	Corn stover and switchgrass	Biochar	Phases 1 and 2	1 tonne of dry biomass	Global warming potential	GWP for corn stover: –864 kg CO_2 eq/tonne of dry biomass GWP for switchgrass: +36 kg CO_2 eq/tonne of dry biomass	Roberts et al. (2009)

(continued)

Table 15.4 (continued)

Process	Feedstock	End product	Boundary	Functional unit	Environmental impact categories	Comments	References
Flash pyrolysis	Wood waste	Biofuel and power	Phases 1 and 2		Global warming, ozone layer depletion, photochemical smog, acidification, eutrophication, ecotoxicity, human toxicity	Emission from combustion of bio-oil affects GWP, acidification, human toxicity, and eutrophication	Zhong et al. (2010)
Gasification	Forest residue	Heat and power	Phases 1 and 2	1 MJ	Global warming, ozone layer depletion, photochemical oxidization, acidification, eutrophication, toxicity, abiotic depletion	GWP: 8.8–10.5 g CO_2 eq/MJ environmental impacts are significant for the biomass procurement and plant operation	Guest et al. (2011)
Gasification	Poplar energy crop	Electricity	Phase 1, 2, and 3	1 MWh	Global warming, ozone layer depletion, smog, acidification, eutrophication, solid waste, energy consumption	Most negative environmental effects are caused by the use of chemicals and fertilizer	Rafaschieri et al. (1999)
Gasification	Willow biomass	Heat and power	Phases 1 and 2	1 MWh	Fossil energy requirement, primary energy requirement, land use, global warming potential, acidification	Significant reduction in GHG emissions from willow biomass to the fossil fuel based systems	Kimming et al. (2011)

Gasification	Biomass	Hydrogen	Phases 1, 2 and 3	1 MJ	Global warming, smog, acidification, eutrophication, carcinogenesis, heavy metals, smog	Among life-cycle studies for two pathways of hydrogen production, biomass gasification-steam reforming-PSA route is the energy efficient one, and biomass- gasification-electricity-electrolysis has better environmental performance	Koroneos et al. (2008)
Combustion	Birchwood	Heat	Phases 1 and 2	1 kWh	Global warming, photochemical oxidation, acidification, eutrophication	GWP: 80–110 g CO_2 eq/kWh Comparing the life-cycle analysis of new stove technology to old one, the former has the better environmental impact	Solli et al. (2009)
Combustion	Rice Husk	Electricity	Phases 1 and 2	1 MWh	Global warming, acidification, eutrophication, ecotoxicity	GWP: 217.33 kg CO_2 eq/MWh	Shafie et al. (2012)
Combustion	Forest residue	Power	Phases 1, 2 and 3	1 kWh	Global warming	GWP: 11–14 g CO_2 eq/kWh Emission and energy consumption depends on the moisture content and the heating value of biomass	Thakur et al. (2014)
Combustion	Wood waste	Electricity	Phases 1 and 2	1 MJ	Global warming, respiratory effect, photo-oxidant formation, acidification, eutrophication	Inventory data collection is the major factor for life-cycle analysis	Périlhon et al. (2012)

Adapted from Patel et al. (2016)

while size reduction of 300 mm to 25 mm of biomass required 157.5 MJ per dry tonne energy. Environmental impact assessment is subjected to the types of the operating conditions like temperature, heating rate, feed composition, type of reactor, etc. In addition, a material is used for the plant construction and manufacturing of equipment related to greenhouse gas emission. During co-firing, increase in the percentage of biomass reduced environmental impact. However, it decreases the overall efficiency of the boiler in the production of power and electricity (Sebastián et al. 2011). Rafaschieri et al. (1999) studied poplar energy crops in a pressurized fluid bed gasifier at various gasification conditions and reported that replacing oxygen by air as an oxidizer reduced environmental impacts. This is why consumption of electricity was higher for the separation of oxygen and results in the generation of greenhouse gases.

15.7 Conclusions

Since techno-economic analysis of different types of biomass via thermochemical conversion technology has been started recently, most of the study focused on the specific product series for one product. There is a lack of integrated techno-economic analysis for multiple pathways of product cogeneration. Hence, this gap can be filled by studying techno-economic assessment of different types of biomass via thermochemical conversion technology in the near future. However, it is noticed that techno-economic analysis of pyrolysis technology has been studied extensively, but upgradation of pyrolytic liquid for transportation fuels or other purposes still needs more detailed study. The production of fuels through pyrolysis seems the best possible pathway of future research as it has the economic and environmental benefits. The production of power and energy for different types of biomass looked for more advanced techno-economic assessment. There are a large number of studies done for techno-economic analysis of fast pyrolysis, combustion, gasification, and co-firing, but advanced research is still required for economic analysis. It was also found that numerous studies were conducted on co-firing to explain the stoichiometric ratio of biomass along with the plant capacity, but there is a lack of techno-economic analysis on carbonization process.

In the last few years, life-cycle assessment through thermochemical technology on lignocellulosic biomass has been studied; still there is enough scope to carry out more study in this area. Among all pyrolysis technology, fast pyrolysis of lignocellulosic biomass was reported extensively. Furthermore, there is a deficiency of the comparative analysis of diverse pathways based on environmental metrics, which is the major constraint of life-cycle assessment studies. The data availability and life-cycle assessment framework from start to end are the main reasons for varying the system boundaries. A number of programs are available for life-cycle assessment; however, their database varies on location to location, climate, and types of process. Hence, for meaningful life-cycle assessment, a standardized approach is needed. Environmental impact categories (human health, resource depletion and threats to the ecosystem, and global warming potential) are the most emphasized areas of research. Furthermore, direct change of land was studied by very few researchers, but the indirect changes in the land were completely absent in the literature. Thus, more study is needed on the indirect changes in land in the near future. Production of fertilizers and its application are the main contributors to global warming. Therefore, there is a need to develop plant species that require low maintenance and chemicals. Recently, various policies are implemented for use of biofuel in order to reduce environmental pollution in place of fossil fuel. An appropriate and common method is required which provides the comparative analysis of end products and types of the pathways. It was also notable that selection of types of pathways is mainly dependent on the types of feedstocks, ends products, and geographical condition. Therefore, more techno-economic analyses were required to investigate the formation of single products by different types of pathways.

References

Abubackar HN, Veiga MC, Kennes C (2011) Biological conversion of carbon monoxide: rich syngas or waste gases to bioethanol. Biofuels Bioprod Biorefin 5:93–114

Agbor E, Zhang X, Kumar A (2014) A review of biomass co-firing in North America. Renew Sust Energ Rev 40:930–943

Akhtar J, Amin NAS (2011) A review on process conditions for optimum bio-oil yield in hydrothermal liquefaction of biomass. Renew Sust Energ Rev 15(3):1615–1624

Alauddin ZABZ, Lahijani P, Mohammadi M, Mohamed AR (2010) Gasification of lignocellulosic biomass in fluidized beds for renewable energy development: a review. Renew Sust Energ Rev 14:2852–2862

Amigun B, Gorgens J, Knoetze H (2010) Biomethanol production from gasification of non-woody plant in South Africa: optimum scale and economic performance. Energy Policy 38:312–322

Anex RP, Aden A, Kazi FK, Fortman J, Swanson RM, Wright MM, Satrio JA, Brown RC, Daugaard DE, Platon A, Kothandaraman G, Hsu DD, Dutta A (2010) Techno-economic comparison of biomass-to-transportation fuels via pyrolysis, gasification, and biochemical pathways. Fuel 89:S29–S35

Arce ME, Saavedra Á, Míguez JL, Granada E, Cacabelos A (2013) Biomass fuel and combustion conditions selection in a fixed bed combustor. Energies 6(11):5973–5989

Boucher M, Chaala A, Pakdel H, Roy C (2000) Bio-oils obtained by vacuum pyrolysis of softwood bark as a liquid fuel for gas turbines. Part II: stability and ageing of bio-oil and its blends with methanol and a pyrolytic aqueous phase. Biomass Bioenergy 19:351–361

Bridgwater A (1995) The technical and economic feasibility of biomass gasification for power generation. Fuel 74(5):631–653

Bridgwater AV, Meier D, Radlein D (1999) An overview of fast pyrolysis of biomass. Org Geochem 30(12):1479–1493

Bridgwater A, Toft A, Brammer J (2002) A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. Renew Sust Energ Rev 6(3):181–246

Brown TR (2015) A techno-economic review of thermochemical cellulosic biofuel pathways. Bioresour Technol 178:166–176

Brown RC, Brown TR (2013) Biorenewable resources: engineering new products from agriculture. Wiley, Hoboken

Brown TR, Thilakaratne R, Brown RC, Hu G (2013) Techno-economic analysis of biomass to transportation fuels and electricity via fast pyrolysis and hydroprocessing. Fuel 106:463–469

Carlson TR, Tompsett GA, Conner WC, Huber GW (2009) Aromatic production from catalytic fast pyrolysis of biomass-derived feedstocks. Top Catal 52:241–252

Cormos C-C (2013) Assessment of flexible energy vectors poly-generation based on coal and biomass/solid wastes co-gasification with carbon capture. Int J Hydrog Energy 38:7855–7866

Damartzis T, Zabaniotou A (2011) Thermochemical conversion of biomass to second generation biofuels through integrated process design—a review. Renew Sust Energ Rev 15(1):366–378

De S, Assadi M (2009) Impact of cofiring biomass with coal in power plants–a techno-economic assessment. Biomass Bioenergy 33:283–293

Demirbas A (2001) Biomass resource facilities and biomass conversion. Elsevier, Amsterdam

Demirbas A (2007) Producing bio-oil from olive cake by fast pyrolysis. Energ Sources A 30:38–44

Domenichini R, Gasparini F, Cotone P, Santos S (2011) Techno-economic evaluation of biomass fired or co-fired power plants with post combustion CO_2 capture. Energy Proc 4:1851–1860

Faix A, Schweinle J, Schöll S, Becker G, Meier D (2010) (GTI-tcbiomass) life-cycle assessment of the BTO®-process (biomass-to-oil) with combined heat and power generation. Environ Prog Sustain Energy 29:193–202

Fan J, Kalnes TN, Alward M, Klinger J, Sadehvandi A, Shonnard DR (2011) Life cycle assessment of electricity generation using fast pyrolysis bio-oil. Renew Energy 36:632–641

Fischer B, Pigneri A (2011) Potential for electrification from biomass gasification in Vanuatu. Energy 36(3):1640–1651

Gabrielle B, Gagnaire N (2008) Life-cycle assessment of straw use in bio-ethanol production: a case study based on biophysical modelling. Biomass Bioenergy 32:431–441

Ganesh A, Banerjee R (2001) Biomass pyrolysis for power generation—a potential technology. Renew Energy 22:9–14

Gnansounou E, Dauriat A (2010) Techno-economic analysis of lignocellulosic ethanol: a review. Bioresour Technol 101:4980–4991

Graham R, Bergougnou M, Overend R (1984) Fast pyrolysis of biomass. J Anal Appl Pyrolysis 6:95–135

Guest G, Bright RM, Cherubini F, Michelsen O, Strømman AH (2011) Life cycle assessment of biomass-based combined heat and power plants. J Ind Ecol 15:908–921

Han J, Elgowainy A, Dunn JB, Wang MQ (2013) Life cycle analysis of fuel production from fast pyrolysis of biomass. Bioresour Technol 133:421–428

Haro P, Trippe F, Stahl R, Henrich E (2013) Bio-syngas to gasoline and olefins via DME–a comprehensive techno-economic assessment. Appl Energy 108:54–65

Hein K, Bemtgen J (1998) EU clean coal technology—co-combustion of coal and biomass. Fuel Process Technol 54:159–169

Heller MC, Keoleian GA, Mann MK, Volk TA (2004) Life cycle energy and environmental benefits of generating electricity from willow biomass. Renew Energy 29:1023–1042

Hsu DD (2012) Life cycle assessment of gasoline and diesel produced via fast pyrolysis and hydroprocessing. Biomass Bioenergy 45:41–47

Huang Y, Mcllveen-Wright D (2006) Biomass co-firing in a PFBC combined cycle power plant: a techno-environmental assessment based on computational simulations. Fuel Process Technol 87:927–934

Huang Y, McIlveen-Wright D, Rezvani S, Huang M, Wang Y, Roskilly A, Hewitt N (2013) Comparative techno-economic analysis of biomass fuelled combined heat and power for commercial buildings. Appl Energy 112:518–525

Iribarren D, Peters JF, Dufour J (2012) Life cycle assessment of transportation fuels from biomass pyrolysis. Fuel 97:812–821

Isahak WNRW, Hisham MW, Yarmo MA, Hin T-YY (2012) A review on bio-oil production from biomass by using pyrolysis method. Renew Sust Energ Rev 16:5910–5923

Jones SB, Valkenburt C, Walton CW, Elliott DC, Holladay JE, Stevens DJ, Kinchin C, Czernik S (2009) Production of gasoline and diesel from biomass via fast pyrolysis, hydrotreating and hydrocracking: a design case. Pacific Northwest National Laboratory (PNNL), Richland

Kauffman N, Hayes D, Brown R (2011) A life cycle assessment of advanced biofuel production from a hectare of corn. Fuel 90:3306–3314

Kebelmann K, Hornung A, Karsten U, Griffiths G (2013) Intermediate pyrolysis and product identification by TGA and Py-GC/MS of green microalgae and their extracted protein and lipid components. Biomass Bioenergy 49:38–48

Kimming M, Sundberg C, Nordberg Å, Baky A, Bernesson S, Norén O, Hansson P-A (2011) Biomass from agriculture in small-scale combined heat and power plants–a comparative life cycle assessment. Biomass Bioenergy 35:1572–1581

Koroneos C, Dompros A, Roumbas G (2008) Hydrogen production via biomass gasification—a life cycle assessment approach. Chem Eng Process:Process Intens 47:1261–1268

Kumar M, Gupta R, Sharma T (1992) Effects of carbonisation conditions on the yield and chemical composition of Acacia and Eucalyptus wood chars. Biomass Bioenergy 3:411–417

Kumar A, Bhattacharya SC, Pham H-L (2003a) Greenhouse gas mitigation potential of biomass energy technologies in Vietnam using the long range energy alternative planning system model. Energy 28:627–654

Kumar A, Cameron JB, Flynn PC (2003b) Biomass power cost and optimum plant size in western Canada. Biomass Bioenergy 24:445–464

Kumar A, Kumar N, Baredar P, Shukla A (2015) A review on biomass energy resources, potential, conversion and policy in India. Renew Sust Energ Rev 45:530–539

Lane J (2013) Gusher! KiOR starts production of US cellulosic biofuels at scale. Biofuel Digest. http://www.biofuelsdigest.com/bdigest/2012/11/09/gusher-kior-starts-production-of-us-cellulosic-biofuels-at-scale/

Lange M (2011) The GHG balance of biofuels taking into account land use change. Energy Policy 39(5):2373–2385

Lédé J (2003) Comparison of contact and radiant ablative pyrolysis of biomass. J Anal Appl Pyrolysis 70:601–618

Liden A, Berruti F, Scott D (1988) A kinetic model for the production of liquids from the flash pyrolysis of biomass. Chem Eng Commun 65:207–221

Liu T, McConkey B, Ma Z, Liu Z, Li X, Cheng L (2011) Strengths, weakness, opportunities and threats analysis of bioenergy production on marginal land. Energy Proc 5:2378–2386

López-Bellido L, Wery J, López-Bellido RJ (2014) Energy crops: prospects in the context of sustainable agriculture. Eur J Agron 60:1–12

Lu Q, Dong C-Q, Zhang X-M, Tian H-Y, Yang Y-P, Zhu X-F (2011) Selective fast pyrolysis of biomass impregnated with $ZnCl_2$ to produce furfural: analytical Py-GC/MS study. J Anal Appl Pyrolysis 90:204–212

Maggi R, Delmon B (1994) Comparison between 'slow' and 'flash' pyrolysis oils from biomass. Fuel 73:671–677

Mann M, Spath P (2001) A life cycle assessment of biomass cofiring in a coal-fired power plant. Clean Technol Environ Pol 3:81–91

Martínez E, Sanz F, Pellegrini S, Jiménez E, Blanco J (2009) Life cycle assessment of a multi-megawatt wind turbine. Renew Energy 34:667–673

McIlveen-Wright D, Pinto F, Armesto L, Caballero M, Aznar M, Cabanillas A, Huang Y, Franco C, Gulyurtlu I, McMullan J (2006) A comparison of circulating fluidised bed combustion and gasification power plant technologies for processing mixtures of coal, biomass and plastic waste. Fuel Process Technol 87:793–801

Meerman J, Knoope M, Ramírez A, Turkenburg W, Faaij A (2013) Technical and economic prospects of coal-and biomass-fired integrated gasification facilities equipped with CCS over time. Int J Greenh Gas Cont 16:311–323

Menten F, Chèze B, Patouillard L, Bouvart F (2013) A review of LCA greenhouse gas emissions results for advanced biofuels: the use of meta-regression analysis. Renew Sust Energ Rev 26:108–134

Mohan D et al (2014) Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent–a critical review. Bioresour Technol 160:191–202

Muench S, Guenther E (2013) A systematic review of bioenergy life cycle assessments. Appl Energy 112:257–273

Nguyen TLT, Hermansen JE, Mogensen L (2013) Environmental performance of crop residues as an energy source for electricity production: the case of wheat straw in Denmark. Appl Energy 104:633–641

Nussbaumer T (2003) Combustion and co-combustion of biomass: fundamentals, technologies, and primary measures for emission reduction. Energy Fuel 17:1510–1521

Parthasarathy P, Narayanan KS (2014) Hydrogen production from steam gasification of biomass: influence of process parameters on hydrogen yield–a review. Renew Energy 66:570–579

Patel RN, Bandyopadhyay S, Ganesh A (2011) Extraction of cardanol and phenol from bio-oils obtained through vacuum pyrolysis of biomass using supercritical fluid extraction. Energy 36:1535–1542

Patel M, Zhang X, Kumar A (2016) Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: a review. Renew Sust Energ Rev 53:1486–1499

Peacocke GV (1994) Ablative pyrolysis of biomass. PhD thesis, Aston University, UK

Périlhon C, Alkadee D, Descombes G, Lacour S (2012) Life cycle assessment applied to electricity generation from renewable biomass. Energ Proc 18:165–176

Phillips SD, Tarud JK, Biddy MJ, Dutta A (2011) Gasoline from woody biomass via thermochemical gasification, methanol synthesis, and methanol-to-gasoline technologies: a technoeconomic analysis. Ind Eng Chem Res 50:11734–11745

Piccolo C, Bezzo F (2009) A techno-economic comparison between two technologies for bioethanol production from lignocellulose. Biomass Bioenergy 33:478–491

Rafaschieri A, Rapaccini M, Manfrida G (1999) Life cycle assessment of electricity production from poplar energy crops compared with conventional fossil fuels. Energ Convers Manag 40:1477–1493

Rathmann R, Szklo A, Schaeffer R (2010) Land use competition for production of food and liquid biofuels: an analysis of the arguments in the current debate. Renew Energy 35:14–22

Reza MT, Andert J, Wirth B, Busch D, Pielert J, Lynam JG, Mumme J (2014) Hydrothermal carbonization of biomass for energy and crop production. Appl Bioenerg 1:11–29

Roberts KG, Gloy BA, Joseph S, Scott NR, Lehmann J (2009) Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. Environ Sci Technol 44:827–833

Rodrigues M, Faaij AP, Walter A (2003) Techno-economic analysis of co-fired biomass integrated gasification/combined cycle systems with inclusion of economies of scale. Energy 28:1229–1258

Rogers J, Brammer JG (2012) Estimation of the production cost of fast pyrolysis bio-oil. Biomass Bioenergy 36:208–217

Royo J, Sebastián F, Canalís P, Rodríguez N (2004) The torsional chamber as an alternative to the technologies usually employed in biomass co-firing. In: Proceedings of power gen Europe

Samolada M, Vasalos I (1991) A kinetic approach to the flash pyrolysis of biomass in a fluidized bed reactor. Fuel 70:883–889

Sarkar S, Kumar A (2010a) Biohydrogen production from forest and agricultural residues for upgrading of bitumen from oil sands. Energy 35:582–591

Sarkar S, Kumar A (2010b) Large-scale biohydrogen production from bio-oil. Bioresour Technol 101:7350–7361

Sarkar S, Kumar A, Sultana A (2011) Biofuels and biochemicals production from forest biomass in Western Canada. Energy 36:6251–6262

Savolainen K (2003) Co-firing of biomass in coal-fired utility boilers. Appl Energy 74:369–381

Schenck R (2009) Introduction to lifecycle assessment scoping & inventory. US EPA Region X, American Center for Lifecycle Assessment, Washington, DC

Scott DS, Piskorz J (1984) The continuous flash pyrolysis of biomass. Can J Chem Eng 62:404–412

Scott DS, Piskorz J, Radlein D (1985) Liquid products from the continuous flash pyrolysis of biomass. Ind Eng Chem Process Des Dev 24:581–588

Sebastián F, Royo J, Gómez M (2011) Cofiring versus biomass-fired power plants: GHG (Greenhouse Gases) emissions savings comparison by means of LCA (Life Cycle Assessment) methodology. Energy 36:2029–2037

Sevilla M, Macia-Agullo JA, Fuertes AB (2011) Hydrothermal carbonization of biomass as a route for the sequestration of CO_2: chemical and structural properties of the carbonized products. Biomass Bioenergy 35:3152–3159

Shabangu S, Woolf D, Fisher EM, Angenent LT, Lehmann J (2014) Techno-economic assessment of biomass slow pyrolysis into different biochar and methanol concepts. Fuel 117:742–748

Shadangi KP, Mohanty K (2014a) Comparison of yield and fuel properties of thermal and catalytic Mahua seed pyrolytic oil. Fuel 117:372–380

Shadangi KP, Mohanty K (2014b) Thermal and catalytic pyrolysis of Karanja seed to produce liquid fuel. Fuel 115:434–442

Shadangi KP, Singh RK (2012) Thermolysis of polanga seed cake to bio-oil using semi batch reactor. Fuel 97:450–456

Shafie S, Mahlia T, Masjuki H, Rismanchi B (2012) Life cycle assessment (LCA) of electricity generation from rice husk in Malaysia. Energy Proc 14:499–504

Shafie S, Mahlia T, Masjuki H (2013) Life cycle assessment of rice straw co-firing with coal power generation in Malaysia. Energy 57:284–294

Sharma A, Unni BG, Singh HD (1999) A novel fed-batch digestion system for biomethanation of plant biomasses. J Biosci Bioeng 87:678–682

Sınağ A, Kruse A, Rathert J (2004) Influence of the heating rate and the type of catalyst on the formation of key intermediates and on the generation of gases during hydropyrolysis of glucose in supercritical water in a batch reactor. Ind Eng Chem Res 43:502–508

Singh A, Pant D, Korres NE, Nizami A-S, Prasad S, Murphy JD (2010) Key issues in life cycle assessment of ethanol production from lignocellulosic biomass: challenges and perspectives. Bioresour Technol 101:5003–5012

Skowrońska M, Filipek T (2014) Life cycle assessment of fertilizers: a review. Int Agrophysics 28:101–110

Solli C, Reenaas M, Strømman AH, Hertwich EG (2009) Life cycle assessment of wood-based heating in Norway. Int J Life Cycle Assess 14:517–528

Spliethoff H, Hein K (1998) Effect of co-combustion of biomass on emissions in pulverized fuel furnaces. Fuel Process Technol 54:189–205

Strezov V, Patterson M, Zymla V, Fisher K, Evans TJ, Nelson PF (2007) Fundamental aspects of biomass carbonisation. J Anal Appl Pyrolysis 79:91–100

Swanson RM, Platon A, Satrio JA, Brown RC (2010) Techno-economic analysis of biomass-to-liquids production based on gasification. Fuel 89:S11–S19

Thakur A, Canter CE, Kumar A (2014) Life-cycle energy and emission analysis of power generation from forest biomass. Appl Energy 128:246–253

Thangalazhy-Gopakumar S, Adhikari S, Ravindran H, Gupta RB, Fasina O, Tu M, Fernando SD (2010) Physiochemical properties of bio-oil produced at various temperatures from pine wood using an auger reactor. Bioresour Technol 101:8389–8395

Thilakaratne R, Brown T, Li Y, Hu G, Brown R (2014) Mild catalytic pyrolysis of biomass for production of transportation fuels: a techno-economic analysis. Green Chem 16:627–636

Trippe F, Fröhling M, Schultmann F, Stahl R, Henrich E (2010) Techno-economic analysis of fast pyrolysis as a process step within biomass-to-liquid fuel production. Waste Biomass Valor 1:415–430

Trippe F, Fröhling M, Schultmann F, Stahl R, Henrich E, Dalai A (2013) Comprehensive techno-economic assessment of dimethyl ether (DME) synthesis and Fischer–Tropsch synthesis as alternative process steps within biomass-to-liquid production. Fuel Process Technol 106:577–586

Valle CR, Perales AV, Vidal-Barrero F, Gómez-Barea A (2013) Techno-economic assessment of biomass-to-ethanol by indirect fluidized bed gasification: impact of reforming technologies and comparison with entrained flow gasification. Appl Energy 109:254–266

Wang G, Silva R, Azevedo J, Martins-Dias S, Costa M (2014) Evaluation of the combustion behaviour and ash characteristics of biomass waste derived fuels, pine and coal in a drop tube furnace. Fuel 117:809–824

Williams PT, Besler S (1993) The pyrolysis of rice husks in a thermogravimetric analyser and static batch reactor. Fuel 72:151–159

Williams PT, Besler S (1996) The influence of temperature and heating rate on the slow pyrolysis of biomass. Renew Energ 7:233–250

Woolcock PJ, Brown RC (2013) A review of cleaning technologies for biomass-derived syngas. Biomass Bioenergy 52:54–84

Wright MM, Daugaard DE, Satrio JA, Brown RC (2010) Techno-economic analysis of biomass fast pyrolysis to transportation fuels. Fuel 89:S2–S10

Xianwen D, Chuangzhi W, Haibin L, Yong C (2000) The fast pyrolysis of biomass in CFB reactor. Energy Fuel 14:552–557

Xu Y, Wang T, Ma L, Zhang Q, Wang L (2009) Upgrading of liquid fuel from the vacuum pyrolysis of biomass over the Mo–Ni/γ-Al_2O_3 catalysts. Biomass Bioenergy 33:1030–1036

Zhang B, von Keitz M, Valentas K (2009) Thermochemical liquefaction of high-diversity grassland perennials. J Anal Appl Pyrolysis 84:18–24

Zhang Y, Brown TR, Hu G, Brown RC (2013) Comparative techno-economic analysis of biohydrogen production via bio-oil gasification and bio-oil reforming. Biomass Bioenergy 51:99–108

Zhong Z, Song B, Zaki M (2010) Life-cycle assessment of flash pyrolysis of wood waste. J Clean Prod 18:1177–1183

Zhou J, Chen Q, Zhao H, Cao X, Mei Q, Luo Z, Cen K (2009) Biomass–oxygen gasification in a high-temperature entrained-flow gasifier. Biotechnol Adv 27:606–611

Zhu Y, Jones SB (2009) Techno-economic analysis for the thermochemical conversion of lignocellulosic biomass to ethanol via acetic acid synthesis. Pacific Northwest National Laboratory (PNNL), Richland

Zhu Y, Jones SB, Biddy MJ, Dagle RA, Palo DR (2012) Single-step syngas-to-distillates (S2D) process based on biomass-derived syngas–a techno-economic analysis. Bioresour Technol 117:341–351

Zuwala J, Sciazko M (2010) Full-scale co-firing trial tests of sawdust and bio-waste in pulverized coal-fired 230t/h steam boiler. Biomass Bioenergy 34:1165–1174