2 Bioenergy: Sustainable Renewable Energy

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Abstract

Bioenergy is one of the major renewable sources of energy, originating from sunlight and produced via photosynthesis. It is one of the many different resources available to human beings for meeting their energy requirements. Bioenergy is one among different renewable sources of energy. It is derived from living organic materials known as biomass. Looking at the increasing energy demand in the country, bioenergy is a significant energy source for meeting future energy requirements. At the same time, it is an efficient and green source of energy, thereby helping curb the greenhouse gas emissions. Bioenergy can be utilized in a number of ways namely heat, electricity, or as biofuels, and can be obtained from varied sources ranging from agricultural crops to animal, human, and industrial wastes. Similarly, there are different technological options for producing bioenergy, depending on the type and source of biomass. This chapter will throw light on the benefits, challenges, and need of bioenergy as a source of sustainable renewable energy. Further, it will discuss the various technologies for biomass conversion like combustion, gasification, pyrolysis, and anaerobic digestion. Various possible uses of biofuels as sustainable renewable energy will also be thrown light on.

Keywords

Bioenergy · Sustainable energy · Biomass conversion technologies · Sustainable energy

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2.1 Introduction: Bio Energy—A Sustainable Energy Source

Energy is critical for the growth and development of countries. This is especially true for a country like India given its fast pace of development and a huge population base. Most of the world's energy requirements (approximately 80%), however, are fulfilled by fossil fuels, which are the leading causes of greenhouse gas (GHG) emissions. The challenge therefore today for most nations, especially the developing nations, is to improve energy availability and access to modern and clean energy sources for all its citizens. These clean energy sources have to be financially affordable and sustainable, should address energy security, and minimize GHG emissions.

The United Nations Framework Convention on Climate Change (UNFCCC) signed the Paris Agreement in 2016 to bring the nations together to reduce their GHG emissions by setting individual targets. The aim of this agreement was to limit the rise in global temperature to below 2 °C at the earliest. However, only a handful of nations are likely to achieve their NDCs (Nationally Determined Contributions) owing to lack of commitment on the one hand and lack of sustainable alternatives to fossil fuels on the other. This need for sustainable alternatives has lead to the discovery and production of bioenergy.

Bioenergy is produced from biomass or the organic matter derived from plants and animals. The primary source of bioenergy is sunlight, which is a major driver for photosynthesis. Bioenergy is classified as a renewable energy source. The technologies used for production of bioenergy range from as simple as burning of wood to generating thermal energy for heating and cooking, to as complex as advanced generators for production of liquid biofuels. Bioenergy is one of the primary sources for world energy supplies and is the most widely used renewable energy globally.

The energy derived from biomass can be further converted into heat, electricity, or biofuels like bioethanol. Biofuel is a green source of energy that comes from organic matter or biomass or wastes. It is a safe alternative that not only emits less carbon dioxide (CO_2) but is also an advantage to the struggling economy by creating an industry and providing more jobs. It is a sustainable fuel that reduces the dependence on petrol, diesel, or other fossil fuels.

To make biofuels, several materials may be used, including maize, sugarcane, wood waste, grasses, algae, animal waste, wastewater sludge, or other plant matter that would be unusable otherwise. Today, most biofuels are made from crops and are referred to as conventional biofuels. Newer technologies for creation of fuels from waste, inedible crops, and forest products are called second-generation biofuels or advanced biofuels and are considered to be more sustainable as compared to the former. Two biofuels namely bioethanol and biodiesel are already being used commercially in the transportation sector.

Biogas can potentially be used for electricity generation and also as an alternative to compressed natural gas (CNG) which is a fossil fuel based energy source. In 2018, the global production of biogas and biomethane production has been estimated to be approximately 35 Mt. Overall, the use of biofuel for transport has been increasing gradually with figures showing an increase of 6% on yearly basis in 2019.

Although biofuels are a positive move toward sustainable energy, the contemporary economic conditions do not favor the biofuels industry. The production of bioenergy at large scale has been found to be expensive and thus, researches are underway to bring down the costs. As per estimates, it was forecasted that by the year 2024, the production of biofuel will increase by 25%; however, the global COVID-19 pandemic decreased the fuel demand, in turn suppressed the crude oil prices. Biodiesel manufacturers, however, did not witness much impact of the pandemic due to increased e-commerce activities which required transportation. In the foreseeable future, clean and green energy sources are bound to play a key role in reducing global warming, halting climate change, and reducing dependence on fossil fuels which are fast depleting.

2.2 Biomass

Biomass is any living or recently dead matter from animals and/or plants, excluding fossilized fragments of organisms. Thus, all the living matter comprises of biomass. Biomass energy includes those products which can be used for energy generation in place of fossil fuels. Biomass utilizes carbon dioxide for photosynthesis and gives it back when it is used for generating energy. The process leads to a carbon-neutral cycle preventing the increase in GHG concentration.

Burning of biomass along with fossil fuels can be used as an economically cheaper method for mitigating GHGs. About 80% of potential energy from biomass can be efficiently tapped by combined heat and power (CHP) operations. In these systems, the waste heat from bio power production operation is tapped and used for heating or cooling purposes. Biomass is also helpful in producing transportation fuels for reducing the usage of petroleum products and decreasing GHG emissions. Presently two most prominently used biofuels are ethanol and biodiesel. Further, researches are under way to create a number of advanced second-generation biofuels made from non-food biomass feedstock, such as municipal organic waste, wood shavings, and algae. These fuels are composed of cellulosic ethanol, biobutanol, methanol, and synthetic gasoline/diesel equivalents. Thus, biofuels are a significant source for clean transportation fuel.

2.2.1 Biomass Feedstock

As discussed earlier, biomass is derived from plants and animals and thus, wherever these two are present, biomass can be produced. Agricultural crops, animal and plant wastes, and other organic wastes are all sources of biomass. The type of biomass regulates the kind and amount of bioenergy that can be produced from it as well as the technology that should be used for the generation process. For instance, the agricultural crops like corn and canola are suitable for producing liquid biofuels such as ethanol and biodiesel, whereas moist biomass are more appropriate to produce biogas through anaerobic digestion. This biogas can further be combusted to generate power and heat or upgraded into a transport fuel namely biomethane.

Every geographical region has its own biomass feedstock from agriculture and forest, agro industries, and urban sources. Besides, most of the biomass feedstock thus generated has the potential utility for making liquid fuels, heat and electric power along with other bio-based products. Thus, biomass is a flexible and extensively available source that can be used to generate energy to meet local needs and purposes. Some of the most common (and/or most promising) biomass feedstock are:

- grain crops like wheat and corn; starch crops like sugar cane, and sweet potatoes;
- agricultural waste in the form of rice and wheat straw;
- food waste from food processing industries, from catering units, restaurants, etc.;
- forestry waste in the form of forest thinning, stump wood, branches, crests, residues, etc.;
- animal byproducts like animal remains, fish oil, wastes, and manure;
- energy crops like soybean, rapeseed, sunflower, and cotton seed;
- urban waste products such as municipal solid wastes (MSW), sludge, wood wastes, and waste cooking oil.

2.3 Biomass and Land Use

Biomass is a significant renewable energy resource like wind and solar, and has a favorable effect on our atmosphere. It declines our reliance on climate change-causing fossil fuels. Biomass energy, however, is unique and differs from other renewable sources of energy as its production is related to the organic waste from farms, forests, and other ecologies from which the raw material namely biomass is obtained. The use of biomass for biofuels has both environmental and social impacts. They affect water resources, soil system, biodiversity, and local communities both positively and negatively. These impacts, however, differ depending on the types of biomass being used, as well as the time and method of their procurement. Therefore, it is essential that biomass is produced and harvested as sustainably as possible. Here, sustainability implies selecting those management practices which curtail negative impacts and help in achieving local land-management objectives like soil preservation, sustainable forest stewardship, sustainable food production, and wildlife management.

One of the debates regarding land use and biomass is the “food-vs-fuel” debate. This issue often arises as a result of conflict between food production and bioenergy, as a number of conventional food crops like sugar and corn are also most commonly used bioenergy feedstock. A number of times, agricultural lands are used for producing dedicated energy crops, which has certainly contributed to increased prices for many of these supplies. To reduce the problems arising from agricultural lands being used for biomass, other alternatives can be used like increased use of agricultural and forestry wastes, food wastes, and use of marginal lands for growing bioenergy crops.

Another problem largely linked with biomass production is the emission of GHGs especially CO_2, CH_4, and N_2O, emerging from land management and land use change. These emissions can be divided into direct and indirect sources. Direct emissions emerge from clearing of land, use of fertilizers, practices undertaken while growing or harvesting a biomass crop, etc. On the other hand, indirect emissions emerge as a result of market-driven land use changes like clearing of forests, grasslands, or other ecosystems for growing crops or other commodities (Environmental and Energy Study Institute 2020).

With favorable government policies and efficient implementation, these fuels can become an effective alternative in future. Demand for sustainable fuels today is driven by rising fuel prices, need for energy security, and higher pollution levels. Fuels such as bioethanol and biodiesel have already been commercialized in many countries. Bioethanol is mainly produced from corn, sugarcane, and sweet sorghum, while biodiesel is produced from rapeseed and palm oil (first-generation feedstock). However, the cultivation of feedstock results in the depletion of grasslands and rainforests, negatively impacting the ecosystem. Utilization of food crops for fuel also creates food versus fuel concerns due to the increased strain on the food supply chain. Furthermore, while these fuels are considered carbon-neutral, as the carbon dioxide (CO_2) produced will be reutilized by plants, the fuel consumed for biomass transportation as well as the energy and water required in the production process adversely affects the environment. Researchers are working on developing solutions that will make these fuels more sustainable. The biofuel industry is still in nascent stages owing to quite a few challenges that it faces in upscaling processes. Latest researches in biofuel production are exploring ways to reduce the costs along with deploying artificial intelligence (AI) to bring in efficiency in process development and maintenance.

2.4 Technologies for Biomass Conversion

There are a number of technologies which can be used for producing bioenergy depending on the type of biomass used, type of bioenergy intended to be produced, environmental regulations, economic factors, etc. There are three primary conversion technologies for biomass, namely biochemical, thermochemical, and physiochemical. The three conversion technologies further have different processes as follows (Adams et al. 2018; Balat 2006; Mokraoui 2015; Dornburg and Faaij 2001; Kar et al. 2018; Nanda et al. 2014; Sharma et al. 2014; Srirangan et al. 2012; Tursi 2019):

- Biochemical conversion: anaerobic digestion and fermentation;
- Thermochemical conversion: pyrolysis, gasification, combustion, and hydrothermal processing; and

- Physiochemical conversion: consists principally of extraction (with esterification).

Let us discuss the conversion technologies in detail.

2.4.1 Biochemical Conversion

As the name suggests, biochemical conversion of biomass uses microorganisms and enzymes for conversion of the biomass into fuels—gaseous such as biogas or liquid such as bioethanol. Anaerobic digestion and fermentation are the two most commonly used biochemical conversion technologies, as illustrated in Fig. 2.1 (Chen and Wang 2016; Zafar 2020a, b).

2.4.1.1 Anaerobic Digestion

Anaerobic digestion is carried out in anaerobic environment, to convert the organic waste into biofertilizer and biogas. The technology is most commonly used for conversion of biodegradable industrial, domestic wastes, or sewage sludge or special-grown crops for production of fuel. Moist organic waste is biochemically broken down in highly controlled, anaerobic environment, producing biogas. The biogas thus produced can be further used for electricity and heat generation (Arif et al. 2018; Batstone and Virdis 2014; Braber 1995; Náthia-Neves et al. 2018; Zafar 2020a, b). The process of anaerobic digestion has been illustrated in Fig. 2.2.

Acetic-acid-forming bacteria and methane-forming archaea are some of the microorganisms effecting anaerobic digestion. They act as catalysts in the production of biogas through a number of chemical reactions (Evans et al. 2009). The process is carried out in physical containment, excluding gaseous oxygen from the reactions (Beychok 1967). There are four phases in anaerobic digestion, namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis. As part of the process, anaerobic microorganisms biochemically convert the organic material into carbon dioxide (CO_2) and methane (CH_4), as depicted in Eq. (2.1).

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4 \tag{2.1}$$

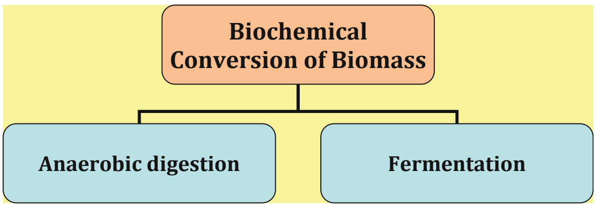

Fig. 2.1 Biochemical conversion of biomass

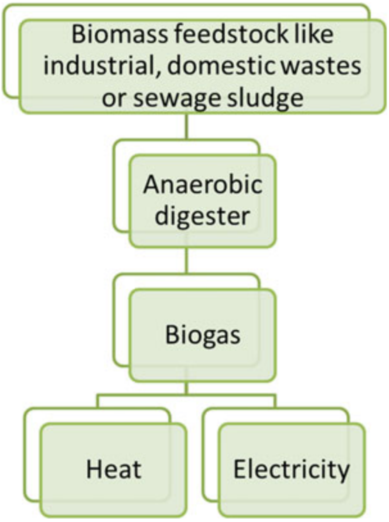

Fig. 2.2 Anaerobic digestion of Biomass

Hydrolysis

Biomass is composed of large polymers which are organic in nature. Anaerobic digestion process involves breaking down large polymers into monomers through bacterial action. Once decomposed, they become freely available to acidogenic bacteria. This process is termed as hydrolysis, wherein, smaller molecules are dissolved into solution (Sleat and Mah 1987). During this stage, simple sugars, fatty acids, and amino acids are generated. In the process, extracellular enzymes are involved, which are secreted by hydrolytic bacteria (Li et al. 2011). The process of hydrolysis takes place under the action of organisms like bacteria, fungi, and protists. It is further significant to understand that certain substrates, like lignin and cellulose have complex structures which make it difficult to break them down, and hence, enzymes are often used to augment their hydrolysis process (Lin et al. 2010).

Acidogenesis

The second stage is acidogenesis which further leads to breakdown of the monomeric products by acidogenic (fermentative) bacteria, leading to the production of Volatile Fatty Acids (VFAs). Additionally, ammonia, carbon dioxide, and hydrogen sulfide are also produced in the process (Alexiou and Panter 2004; Bergman 1990). The concentration of VFAs thus produced varies in terms of the class of organic acids (Bergman 1990). This stage is the fastest among all the other stages of anaerobic digestion (Deublein and Steinhauser 2008).

Acetogenesis

Acetate produced in the previous stage renders a part of the original substrate into the one suitable for acetoclastic methanogenesis (Fournier and Gogarten 2008). In this stage, acetate is formed, and hydrogen and carbon dioxide are also released (Hansen and Cheong 2013). This stage is closely interrelated with the subsequent stage namely methanogenesis in terms of providing substrates for methanogens (Hedderich and Whitman 2006; Liu and Whitman 2008).

Methanogenesis

Methanogenesis is the final stage of anaerobic digestion. In this stage accessible intermediary products from the preceding stages are changed to methane, carbon dioxide, and water by methanogens, also called as methanogenic microorganisms (Ferry 2010). These methanogenic microorganisms are sensitive to oxygen and need a higher pH level as compared to earlier stages (Wolfe 2011). According to researches, Methanosarcina spp., unlike other sensitive microbes, tend to be comparatively vigorous and can tolerate ammonia, sodium, and acetate concentrations. They can also withstand pH levels which are otherwise damaging to other methanogenic microbes (De Vrieze et al. 2012). The culmination of this stage is determined by the end of biogas production (Verma 2002).

Anaerobic digestion is thus a four-stage process, including continuous breakdown of wastes by anaerobic microorganisms and converting it into methane, carbon dioxide, and trace gases, known as biogas (Zhang et al. 2016). Each stage has its own set of microorganisms with their distinct features and environmental requirements (Deublein and Steinhauser 2008). Environmental concerns and waste menace have catalyzed anaerobic digestion as a promising technology for biomass conversion having a wide range of applications (Meegoda et al. 2018). Table 2.1 summarizes the different phases of anaerobic digestion.

2.4.1.2 Fermentation

Fermentation is an anaerobic technology which decomposes the glucose component of the biomass. The process is composed of biochemical reactions wherein simple sugars are converted into ethanol, CO_2, glycerol, and carboxylic acids. The process is carried out under anaerobic conditions by microorganisms mainly yeasts (Lin and Tanaka 2006; Strezov 2014). Microalgae species like Chlamydomonas, Scenedesmus, Chlorella, Spirulina, and Dunaliella have been found to gather large amounts of glycogen, cellulose, and starch (Günerken et al. 2015; Holtzapple 1993a, b, c). The process of fermentation is depicted in Eq. (2.2) (Strezov 2014).

Table 2.1 Phases of anaerobic digestion

Phase	Type of microorganism	Output
Hydrolysis	Acidogenic bacteria	Simple sugars, amino acids, and fatty acids
Acidogenesis	Acidogenic (fermentative) bacteria	Volatile fatty acids (VFAs), ammonia, carbon dioxide, and hydrogen sulfide
Acetogenesis	Methanogenic microorganisms	Acetate, hydrogen and carbon dioxide
Methanogenesis	Methanogens or methanogenic microorganisms	Methane, carbon dioxide, and water

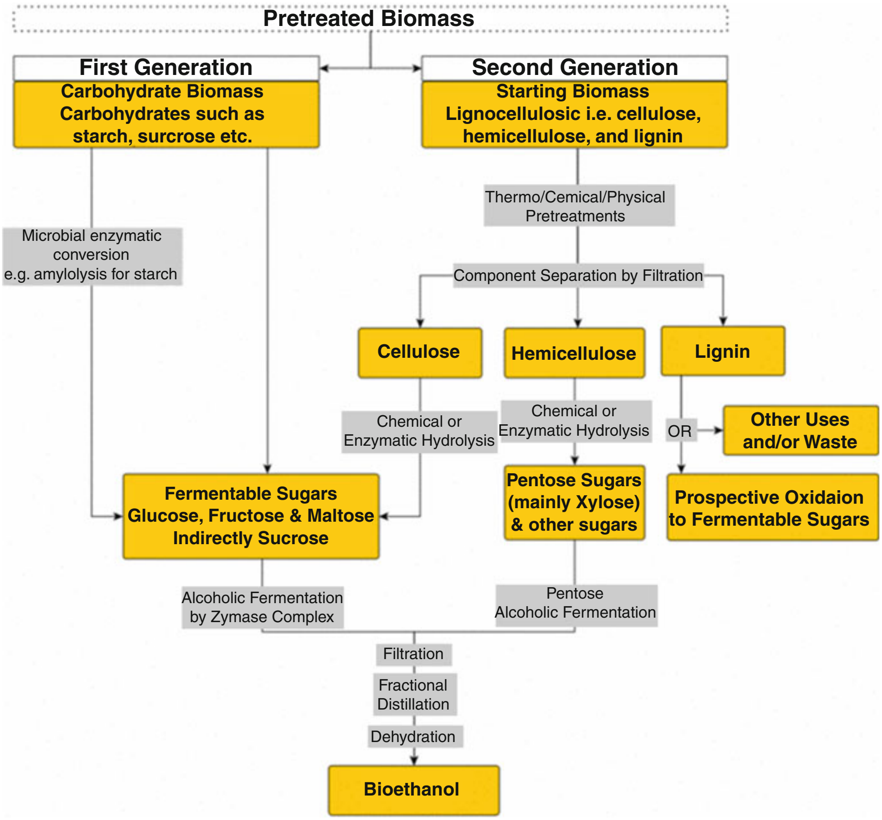

Fig. 2.3 Fermentation of biomass for ethanol production (Zammit 2013)

$$\text{Sugars} \rightarrow \text{Ethanol} + CO_2 + \text{byproducts} \tag{2.2}$$

Bioethanol production requires complex polysaccharides as raw materials. However, microbes are not able to metabolize the polysaccharides and therefore, hydrolysis is required to break them down to simple sugars before they can be used (Günerken et al. 2015). Crude alcohol generated ought to go through a concentration phase by distillation (Bibi et al. 2017). The remaining solid matter can further undergo processes such as gasification and liquefaction (John et al. 2011). Figure 2.3 depicts the process of fermentation of biomass for ethanol production.

2.4.2 Thermochemical Conversion

The second type of biomass conversion technology is thermochemical biomass conversion which includes controlled heating or oxidation of biomass (Demirbas 2004; Goyal et al. 2008). This technology of biomass conversion is centuries-old and

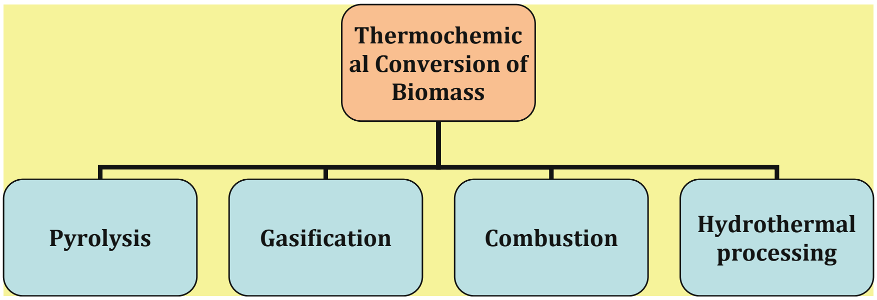

Fig. 2.4 Thermochemical conversion of biomass

has been used in different forms and settings (Park et al. 2018). Thermochemical conversion further constitutes different methods to produce biofuels using biomass, namely pyrolysis, gasification, combustion, and hydrothermal processing, as illustrated in Fig. 2.4 (Demirbas 2009; Ong et al. 2019).

2.4.2.1 Pyrolysis

Pyrolysis is an advanced thermochemical technology to produce synthetic gas from biomass in anaerobic conditions, at temperatures around 1000 °C. It is usually the prime step in combustion and gasification routes (Bridgwater 2003; Yang et al. 2001). Pyrolysis involves thermal breakdown of the biological matter to get solid, liquid, and gaseous produce (Yaman 2004). Due to anaerobic conditions, the volume of gas released through pyrolysis is much lower than gasification; however, it has comparatively higher calorific value (Lupa et al. 2012; Mohan et al. 2006a, b; Neves et al. 2011).

Pyrolysis has a number of advantages which are both economic and environmental in nature. Some of the advantages are listed below (Dutton 2020):

1. It provides a carbon-neutral route for utilization of renewable resources.
2. Waste products like agricultural residues can be fruitfully utilized.
3. The process is helpful in producing liquid fuels having high energy density.

Temperature is an important factor to be considered in pyrolysis. As the temperature goes up, the production of charcoal goes down. To capitalize on the generation from pyrolysis, following factors need to be considered (Abella et al. 2007; Balat et al. 2009; Mohan et al. 2006a, b; Uddin et al. 2018):

1. Production of charcoal requires low temperature and low heating rate process.
2. Further, low temperature, higher rate of heating, and short gas residence time, are good for liquid fuels.
3. Lastly, a high temperature, low heating rate, and a long gas residence time favor the production of gaseous fuel.

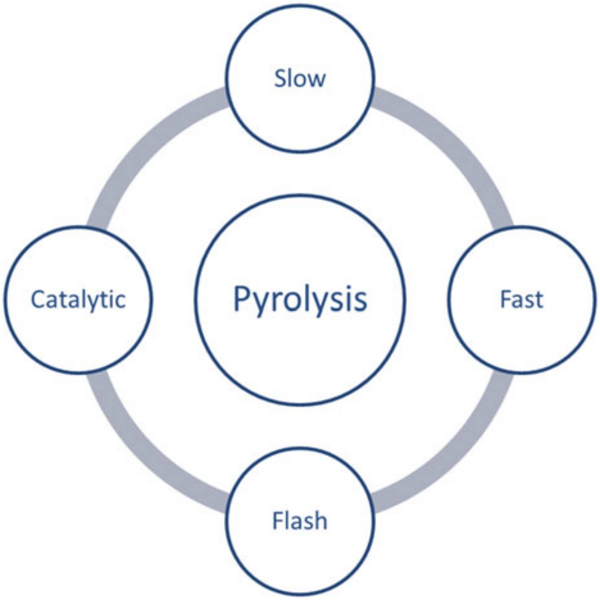

Fig. 2.5 Types of pyrolysis

Table 2.2 Pyrolysis methods and their operating conditions

Type of pyrolysis	Temperature (°C)	Residence time	Heating rate (°C/s)	Major output
Slow	400–500	Long (5–30 min)	Low (10)	Gases, char, bio-oil
Fast	400–650	Short (0.5–2 s)	High (100)	Bio-oil, gases, char
Flash	700–1000	Very short (<0.5 s)	Very high (>500)	Gases, bio-oil

Source: Boyt (2003)

Pyrolysis process has different types namely into slow, fast, flash, and catalytic (Fig. 2.5).

The differentiating factors are the process environments including residence times, rate of heating, particle size, and temperature (Bakis 2008; Balat et al. 2009; Zhang et al. 2007). Table 2.2 depicts the classification of pyrolysis methods with differences in operating conditions.

Slow Pyrolysis

In this process, slow rates of heating the biomass (5–7 K/min) are used for pyrolysis, which produces more of char and less of liquid and gases (Antal and Grönli 2003; Goyal et al. 2008). In this process, good quality charcoal can be produced using slow pyrolysis at low temperature and heating rates, with gas residence time of about 5–30 min (Bridgwater et al. 2001). Slow pyrolysis produces low quality bio-oil which is further reduced by longer residence time (Demirbas 2005; Tippayawong et al. 2008).

Fast Pyrolysis

Fast pyrolysis is a direct thermochemical technique used to produce liquid bio-oil from solid biomass (Demirbas 2006; Huber and Brown 2016; Pattiya 2018). In this process, feedstock is quickly heated to higher temperatures in anaerobic conditions. The primary produce of fast pyrolysis process is high-grade bio-oil (Goyal et al. 2008). It is a speedy thermal disintegration of carbonaceous matter in anaerobic environment. Usually, fast pyrolysis is carried out in moderate temperatures, rapid rates of heating, and short times of residence of the biomass and pyrolysis vapors (Demirbas 2004, as cited in Mašek 2016). To reach the required high heating rate, biomass content requires intensive heat transfer and thus, small particle sizes prove to be a better choice, owing to poor thermal conductivity of biomas (Mašek 2016). Fast pyrolysis has been used to thermally deconstruct biomass feedstock such as algae and a variety of mixed wastes, manure, and organic byproducts from manufacturing (Bridgwater 2003; Manara and Zabaniotou 2012; Mohan et al. 2006a, b).

Flash Pyrolysis

Flash pyrolysis constitutes a reaction time of only a few seconds or less. This technology is marked by very high thermal rate, biomass residence time of only several seconds and fairly small size biomass particles (as rapid heating is needed). Major glitch in the contemporary reactors for this process is the quality of the produced oil. Flash pyrolysis is further divided into (Gercel 2002; Funino et al. 1999; Lede and Bouton 1999):

1. Flash hydropyrolysis, done in the presence of hydrogen, at a pressure up to 20 Mpa.
2. Solar flash pyrolysis uses concentrated solar radiation.
3. Vacuum flash pyrolysis is conducted in vacuum to enable the elimination of condensable matter from the hot reaction zone.

Flash pyrolysis is a method which involves rapidly heating the organic materials in anaerobic environment, leading to the production of organic vapors, gases and char. The vapors are further condensed to bio-oil. As high as 65–70% of the dry feed can be transformed into bio-oil through flash pyrolysis.

Catalytic Pyrolysis

It has been observed that the liquids obtained from above pyrolysis technologies cannot be used directly and needs upgradation. This is because of high oxygen and moisture content present in them (French and Czernik 2010; Wang et al. 2010). Catalytic pyrolysis is a process to improve the quality of the oil thus produced (Balat et al. 2009; Pattiya et al. 2006, 2008). Catalysts can be incorporated into a fast pyrolysis system as in situ (mixed with biomass feedstock or as heat-transfer medium) or ex situ (close-coupled in the reactor above the bed or as a secondary reactor) (Pattiya 2018). Catalytic cracking is used to improve the quality of bio-oil through a catalytic medium. In the process, oxygen is removed from bio-oil compounds in the form of water and carbon dioxide, involving the chemical reactions of rupturing the C–C bonds via dehydration, decarboxylation, and decarbonylation (French and Czernik 2010; Thangalazhy-Gopakumar et al. 2011, 2012; Wang et al. 2010).

Thus, pyrolysis is a thermochemical treatment, which is suitable for any organic (carbon-based) product. During this process, the material goes through chemical and physical separation on exposure to high temperature, in anaerobic conditions.

2.4.2.2 Gasification

Gasification treatment includes heating the material at temperatures ranging between 800 °C and 1000 °C in a gasifier, with restricted oxygen. In such an environment, a significant portion of the material is converted to “syngas” which constitutes methane, hydrogen, carbon monoxide, carbon dioxide, and nitrogen. It also leads to the production of some amounts of char, as a byproduct of gasification (Molino et al. 2016; Sansaniwal et al. 2017; Victoria State Government 2020).

Direct combustion of biomass, the most commonly used conventional process, results in emission of toxic gases, smoke, and dust (Cormier et al. 2006). On the other hand, gasification, as a method of treating biomass can reduce the harmful emissions and provide environmental benefits. The process of producing syngas, involving chemical reactions, is catalyzed by gasification agents (Faaij 2006; Prins and Wagenaar 1997; Santos and Alencar 2020; Sikarwar et al. 2016; Williams and Larson 1996). Syngas can be purified before being combusted, and it has higher efficiency than that of solid biomass used for its production (Farzad et al. 2016). Gasification, as a technology, is more efficient than combustion for generation of electricity. Nonetheless, its requirements for biomass are more stringent like moisture level and size of particle (Hlina et al. 2014; Rutberg et al. 2011).

2.4.2.3 Combustion

Conventionally, combustion has been one of the most commonly used technologies for biomass conversion, constituting 97% of total bioenergy production globally. It comprises of a number of chemical reactions including oxidation of carbon and hydrogen to carbon dioxide and water respectively. The most common uses of biomass fired domestic stoves include heating and cooking in different regions. Nowadays, biomass residues are extensively used for production of electricity wherein biomass undergoes direct combustion leading to the production of steam and in turn, driving a generator to produce electricity (Demirbas 2007; Nussbaumer 2003). Combustion constitutes complex exothermic reactions between oxygen and hydrocarbon present in the biomass (Jenkins et al. 1998; Babu 2008). Incomplete combustion can lead to production of air pollutants like CH4 and CO (Robbins et al. 2012). There are a number of applications of biomass treated through combustion process like cooking, heating, generation of steam in boilers, electricity generation through steam turbine, and so on. Biomass is used either separately or as a supplement to fossil fuels (Basu 2018).

2.4.2.4 Hydrothermal Processing

Hydrothermal processing is a significant process in converting biomass into biofuel. As the name suggests, the process involves water, where the biomass is degraded into smaller fractions. The settings in terms of pressure, time, and temperature during the process depend on the kind of end-product being targeted, i.e., bio-oil, bio-gas, or bio-carbon. The advantage of this technique is that it works with all kinds of biomass, especially because these materials have high moisture contents which do not require pre-drying for this treatment (Kumar et al. 2018; Tekin et al. 2014).

There are two types of hydrothermal process, namely liquefaction and gasification. Hydrothermal carbonization is another method which is comparatively novel (Erlach et al. 2012; Sevilla and Fuertes 2009; Xiao et al. 2012). Hydrothermal treatment is given at temperatures of about 250–374 °C and a pressure of 4–22 MPa (Elliott 2011; Yokoyama and Matsumura 2008). Hydrothermal process might be carried out under either subcritical or supercritical water conditions (Elliott 2011; Karagöz et al. 2005). Most biomass components are soluble in high temperature, also called supercritical water. In supercritical environment, gas is produced by breaking down the macromolecules present in biomass. On the other hand, at lower temperature or subcritical conditions, viscous bio-oil product is produced (Savage et al. 2010).

Using hydrothermal technique, bio-char, oil and gas can be produced from biomass by regulating the variables under which the process is carried out (Yokoyama and Matsumura 2008). Bio-oil can be used in place of petroleum oil and also as a fuel for co-firing with coal. Additionally, the oil can also be transformed into high-quality distillate fuels, such as diesel and gasoline (Savage et al. 2010).

2.4.3 Physiochemical Conversion

The physicochemical technology is aimed at improving the properties of biomass, both chemical and physical. The ignitable constituent of biomass is converted to high-density bio-fuel pellets, having possible applications for steam generation (Zafar 2020a, b).

2.4.3.1 Esterification

A variety of oils and animal fats can be changed to first generation biodiesel using the processes of esterification and/or transesterification, as physiochemical treatments to biomass (Fukuda et al. 2001). Similarly, for second- and third-generation biodiesel, waste oils and microbial oils could be respectively used. It is significant to note that oils primarily comprise of triglycerides, which cannot be used as fuels. Thus, they often lead to issues like incomplete combustion and therefore, crude oils need to be converted through processing. This processing primarily is called transesterification which breaks down the triglyceride molecules into fatty acids and glycerol. Further, through the process of transesterification, the triglycerides are converted into methyl or ethyl esters (biodiesel) using methyl or ethyl alcohol, respectively, as depicted in Eq. (2.3). The process is carried out at temperatures of around 50–70 °C (Leung et al. 2010).

$$\text{Oil} + \text{Short chain alcohol} \rightarrow \text{Biodiesel} + \text{Glycerol} \tag{2.3}$$

The glycerol is subsequently separated from biodiesel, and the excess alcohol is removed. Later, biodiesel is usually purified by water-washing to eliminate any residues before it is finally dried and stored (Canakci and Van Gerpen 1999).

2.5 Examples of Biofuels

2.5.1 Bioethanol

Bioethanol is produced from agricultural wastes such as lignocellulosic biomass which is a second-generation feedstock that is abundantly available. If not disposed of properly this feedstock is often a cause of pollution. Efficient technologies that use microorganisms have been developed to produce bioethanol. Certain microorganisms can utilize second-generation feedstock as they have higher resistance to alcohol during fermentation. Biorefinery is also a feasible option to enhance the sustainability of fuel production. Moreover, revenue can be generated from other valuable products obtained from biomass. Lignin, for instance, is a polymer found abundantly in biomass but hard to extract and thus can be explored for generating other materials. Researchers are now able to treat biomass effectively, and recover lignin and fermentable sugars using enzymes, microorganisms, and different chemical processes.

2.5.2 Biodiesel

Biodiesel is largely produced from a variety of oils like rapeseed, palm, soybean, and waste cooking oil. Even though it is an ideal solution the availability of feedstock is a major hindrance. An alternative is to use nonedible oils from plants such as camelina and rubber along with animal fats like beef tallow, and chicken fat. Further genetically modified species of these nonedible oil seed plants like Camelina sativa which have higher oil content have been created. A process for producing synthetic oil using microorganisms has also been developed which significantly reduces dependence on edible oil seed plants. Ecofriendly enzymatic and chemical catalysts with higher oil conversion efficiency are used by industries to simplify separation, thereby speeding up the biodiesel purification process. Using genetically modified microorganisms in biodiesel production reduces the consumption of chemicals. Biodiesel production from microalgae, which is a third-generation feedstock, is another option explored by many companies; however, due to lower yield and complexities associated with the process, very few companies have succeeded in commercializing it. The processes or alternatives mentioned above help in enhancing the sustainability of biodiesel production.

2.5.3 Biogas

Biogas is used to generate electricity or as an alternative to CNG, a fossil fuel used mostly for transportation. Sustainability of biogas production has been enhanced with development of microorganisms producing biogas with higher methane content. CO_2 is a byproduct of the biogas production process. Researchers opine that the CO_2 thus produced can be utilized in the cultivation of microalgae. Moreover, the process to convert this CO_2 into methane has been developed which could help in increasing the methane content in biogas.

2.5.4 Other Sustainable Fuels

Fuel production from carbon emissions using different processes has recently been explored. CO_2 can be converted into liquid fuels like alcohols using the electrochemical and gas fermentation process. Many companies are either developed or developing a commercial process for the production of fuel. Upgraded reactors in terms of design, use of a better catalyst which increased the efficacy of the thermochemical process (gasification); production of different alcohols from renewable feedstock are being researched actively to increase the sustainability of different fuels.

While sustainable fuels cannot replace fossil fuels immediately, they can help in achieving energy security, reducing pollution levels and making the ecosystem healthier when blended with fossil fuels. With favorable government policies and efficient implementation, these fuels can become an effective alternative in future. Overall, continued development in sustainable fuels can lead us to a viable solution for curbing global warming (Joshi 2020).

2.6 Benefits of Biofuels

Biofuels offer a range of social and environmental benefits including energy security, reduced greenhouse gas (GHG) emissions, employment generation and so on. Some of the benefits have been listed below.

2.6.1 Reducing Greenhouse Gas Emissions

One of the primary advantages or benefits of using biofuels is reduction in the GHG emissions. This however, varies depending on factors like the type of biomass used, method of production and procurement, and efficiency of the technology used to produce bioenergy. Usually, GHG emissions reduction from bioenergy systems is maximum when waste feedstock is converted to heat or combined heat and power near the place of waste generation. Bioenergy's GHG reduction potential is higher than those of other renewable sources of energy. For example, stubble, an agricultural waste left after crops are harvested is often burnt in the fields. This stubble can be fruitfully be harvested and combusted in a controlled bioenergy plant. Hence, GHG emissions are reduced at two levels—first by preventing stubble burning in the fields and second by decreasing the use of fossil fuels by producing biofuels.

2.6.2 Generating Heat and Electricity

Biomass can generate both heat and electricity in a combined heat power (CHP) plant unlike most other renewable energy sources. These can then be used for a variety of thermal applications in industry, townships, or neighborhoods.

2.6.3 Better Air Quality

The biomass residues in the form of stubble, other agricultural waste that would otherwise have been openly combusted in the field, are fruitfully combusted under controlled conditions to make bioenergy. This greatly reduces the emissions of GHGs and hence helps in mitigation of climate change.

2.6.4 Biofuels Are Biodegradable

Biofuels such as ethanol and biodiesel are biodegradable unlike fossil fuels which are detrimental to the environment and are one of the major pollutants of surface and ground water.

2.6.5 Local Economic Development

Bioenergy production creates new revenue generation opportunities for the local communities and encourages regional economic development and employment. More market options open up for agronomists for their conventional harvests and for the use of agricultural waste. Requirement of biomass also presents novel openings to farmers to indulge in growing new varieties, especially areas with poor rainfall. Subsidiary activities like growing and harvesting biomass, transportation, construction, operation, and maintenance of bioenergy plants all provide new opportunities for employment.

2.6.6 Providing Support to Agricultural and Food-Processing Industries

Biomass utilization helps building resilience in supporting industries like agriculture and food-processing industries. All the wastes generated through these industries find fruitful outlet in bioenergy production. Such a practice reduces their energy costs as well as supplements their income as they are able to sell the energy derived from biomass to the grid.

2.6.7 Cost Savings

Bioenergy is very useful for remote and difficult terrain areas which are not connected to the grid, or where grid supply is not feasible, or where electricity transmission losses are high. Bioenergy is off-grid energy and can be supplied to local communities and can cut down on their fuel costs. At the same time it will replace use of fossil fuels which are GHG emitters.

2.6.8 Less Landfills

As bioenergy production relies on organic waste from agriculture, forests, food processing industries, municipal waste, etc. it prevents all these wastes from entering the landfills. Landfills, apart from using a big land parcel, cause stench, breeding of insects and germs, and lead to pollution of soil and ground water.

2.6.9 Energy Security

Bioenergy acts as a domestic and local source of energy which can run uninterrupted, thus, enhancing the regional energy reliability and security. During times of peak electricity demands, bioenergy can also supplement the large thermal power plants to fulfill the energy needs.

2.6.10 New Technologies and Applications

With the advent of research in this area, there are reliable technologies in place for generating fuels, heat, and electricity from biomass. Production of bioenergy and biofuels also leads to generation of additional bioproducts. For instance, organic digestates is an excellent fertilizer, produced as a byproduct of anaerobic digestion of biomass.

2.6.11 Alternatives to Prescribed Forest Burning

To deal with the problem of prescribed burning of forests, bioenergy production serves as an excellent alternative wherein, biomass removal for bioenergy is done to reduce toxic fuels. This is especially beneficial in areas where risks associated with prescribed burning are severe. Thus fuel reduction combustion is replaced with biomass harvesting. Thus, biomass harvesting is a practice widely encouraged and used in forests and woodlands in different countries.

2.6.12 Environmental Benefits from Bioenergy Crops

Special crops called bioenergy crops can also be produced for supplementary vegetation cover in different areas. For instance, farms can be used to grow trees which can be harvested for their wood (acting as biomass), in addition to providing aesthetics, shelter, salinity control and acting as carbon sinks. Some species even have an ability to reshoot and hence can be harvested continually.

2.7 Uses of Biofuels as Sustainable Renewable Energy

As biofuel is considered to be a safe alternative fuel, there are various uses of biofuel that help in reinforcing its replacement with diesel or other fossil fuels. Biofuel can be used in various sectors like transportation and power generation and can help in making our net negative impact on the environment negligible, if not zero. Some of the possible uses of biofuel have been listed below (French 2004; Huang et al. 2012; Marquard and Bahls 2020; Nunez 2019; Miller and Mudge 1997; Rodionova et al. 2017; Tirado 2018).

2.7.1 Transportation

The transportation sector is highly dependent on fossil fuels and thus is accountable for global warming. Worldwide, transport takes accounts for 24% of energy consumption and more than 60% of absorbed oil. This suggests that over one-third of the oil is used to operate vehicles. This not only accounts for greenhouse emissions but also puts pressure on limited resources to meet the demands of the globe. Nowadays, various factors like oil price hikes and awareness generation have influenced consumers to switch to biofuels to save money and reduce their dependence on oil. Biofuels such as ethanol, biodiesel, methanol, methane, can be used as fuels for transportation. For instance, ethanol, one of the most widely used biofuel worldwide, is found being used in various ways, either separately or along with other fuels. Biodiesel is a renewable substitute for diesel. In diesel engines, it is used as a fuel additive in the ratio of 20% blends (B20) with petroleum diesel. The cost of the fuel and the desired benefits are considered while creating other blend levels to suit the purpose (Shell n.d.).

As a result of intensive researches conducted, biofuel is not only used for road transportation, but also in aviation and railway industries. For example, United Airlines, in 2011, became the first airlines in the world to fly aviation flight on a microbially derived biofuel. Not only that, various railway trains are run on biodiesel. For instance, in 2007, Disneyland started the park trains on B98 which is 98% biodiesel. Also, in 2004, the then Indian Railway Minister announced to use 5% bio-diesel in Indian Railways' Diesel Engines (Business Standard 2014).

2.7.2 Power Generation

Apart from vehicular fuel, biofuel has a power generating application that is available for electricity. Biofuel can act as a stable and renewable source of energy that not only is cost-effective but also can replace coal-based thermal power plants. For effective production of power through biomass, the feedstock should be of high calorific value with low moisture content. One such application can be observed in the operations of waste to energy plants that recover the energy from calorie-rich organic waste. Biomethanation is a technology used in to convert waste to energy in plants that digest the organic mass anaerobically and thereby producing biogas. Electricity can be produced feeding this biogas in the gas engine. The electricity then produced can be used in facilities like schools, hospitals, and residential apartments.

2.7.3 Heat Generation

Biomass has been used since ancient times to produce heat, known as bioheat. Materials like wood, cow dung, dried leaves have been used extensively in rural and urban regions to generate heat. The key component of bioheat is vegetable oil and animal fats. The primary advantage of bioheat is that it is nontoxic, renewable, and biodegradable. Also, it is considered to be less polluting than the petroleum-based alternative.

Biofuel such as biodiesel can be utilized in burning stoves to produce heat. This will replace the otherwise used gas or electricity and would also reduce the emission of nitrogen and sulfur dioxide. This application of biofuels to provide heat can be used in homes and replace the electric heaters that produce carbon monoxide and are considered harmful to humans.

2.7.4 Remediation of Oil Spills

Since many decades, crude oil has been polluting the water bodies. Biofuels can be used as a cleaning agent (faster and more effective than other cleaning agents) to prevent this pollution from further deteriorating the environment and marine life. It lives up to its ecofriendly reputation, when it comes to cleaning oil spills and grease. It has a significant capacity to dissolve crude oil and lowers the viscosity of crude oil because of its methyl ester component.

2.7.5 Cooking Fuel

Although the most common ingredient to be used for stoves and nonwick lanterns is kerosene, biodiesel works equally well. Methanol, which is another type of biofuel, is considered to be very versatile and can also be utilized as cooking fuel. However, the use of solid biofuels like fuel wood and cow dung in rural households for cooking purposes poses a lot of health risks and causes indoor pollution.

2.7.6 Other Uses

In addition to its application in the above sectors, biofuel has other noteworthy uses. Biofuels can also be used as lubricants in the automation industry because of high viscosity and can be used in diesel engines. Like biodiesel, it has better flammability and can be transported easily when compared to petrol or diesel. It has high flash point which identifies it to be a safe good. Due to all these properties, biofuel also helps in extending the life span of vehicle engines. Another notable use is that it can be used in removing paints and adhesives. Commonly used paint removing agents are toxic in nature, and biofuels provide a complete ecofriendly solution to remove paints and adhesives even though they are a bit pricey. Also, due to its less toxic nature, biofuel can be used as an industrial solvent and is suitable for cleaning industrial metals.

2.8 Conclusion

While the energy demands are increasing globally, the finite resources are on the verge of depletion, in addition to causing irreparable environmental damage. Combustion and use of fossil fuels leads to emission of GHGs and adds carbon dioxide to the atmosphere. Thus, there is a shift of attention toward clean, sustainable, and renewable sources of energy. These sustainable sources of energy are critical to solve the arising energy crisis in the world. Bioenergy is an excellent resource for meeting our energy demand. It is derived from living organic materials called biomass, and can be converted to fuels, heat, electricity, and other useful products. Biofuels being derived from organic mass are sustainable and are less toxic to the environment. These fuels have possible applications in various industries and can reduce our dependence on diesel or petrochemicals. Such resources are way forward and would help us operate in an ecofriendly manner in our day-to-day lives. Based on current progress and application of biofuel, it is believed that the large-scale production of biofuels is urgent and achievable. With the advent of innovative and contemporary high efficiency bioenergy technologies, it has become possible to improve energy security and access in a sustainable manner. Furthermore, government policies, programs, research, and development would supplement the adoption and utilization of biofuels on a larger scale. Bioenergy is significant for enhancing regional energy independence by decreasing dependence on fossil fuels. Further, it is important in meeting GHG reduction targets for climate change mitigation and achieving other sustainable development goals and objectives.

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