Chapter 2
Renewable Biofuel Sources as Bio-Clean Energy: Potential and Challenges

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Abstract Growing population, urbanization, and industrialization have direct pressure-limited fossil fuels. As a result, these fossil fuels are on the verge of depletion, giving rise to great concern about the future source of fuel. Moreover, the environmental concerns of pollution generated by the use of these fuel sources are a major concern to be addressed by the nations of the world. In response to all these issues, research is being carried out into various forms of renewable energy to replace fossil fuels. One such alternative is biofuels derived from biomass. As it is the most abundant organic matter, it has enormous potential to become the next major source of energy. The chapter explores biomass as a beneficial alternative to fossil fuels in terms of sustainability and economic and environmental aspects.

Keywords Biofuel · Biomass · Lignocellulose · Pretreatment · Renewable energy

2.1 Introduction: Sustainable Development and the Concept of Renewable Energy

Sustainable development is generally defined as development that meets the needs of the present generation without compromising the ability of later generations to meet their needs (Future 1987). Among the various factors that have an impact on sustainable development, the continuous supply of energy from sustainable sources

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P. Chowdhary et al. (eds.), *Bio-Clean Energy Technologies: Volume 1*, Clean Energy Production Technologies, https://doi.org/10.1007/978-981-16-8090-8_2

also plays a crucial role. The role that energy plays in the development of a society can be understood from the increasing demand for energy to improve and sustain the modern lifestyle. Energy in the form of electricity is used in households, offices, industrial equipment, as well as fuel for cars, generation of heat, etc. It has been estimated that 75% of the world's total energy supply is consumed by the limited 25% of the modern industrialized economy (Dunderdale 1990). The concept of sustainable development in terms of energy supply involves technological advancements and efficient energy production with renewable sources replacing fossil fuels while trying to reduce energy consumption (Lund 2007).

There are numerous drawbacks in the continuous use of fossil fuels as a source of energy such as global warming, air pollution leading to acid rain and water pollution, and depletion of the ozone layer which are the major environmental problems apart from limited supply and increased fuel prices which are the economic aspects of the problem (Chowdhary and Raj 2020). The use of renewable energy sources is seen as an alternative to solve these challenges. However, their implementation is not as simple as it is sometimes intensely advertised, leading to impractical claims being made (Dincer 2000). The main obstacle is the expansion of the amount of renewable energy generated. Although renewable energy has significant potential to be a major source of energy, its practical application is less than 15% of total primary energy consumption, with hydropower and fuel wood being the only renewable energy sources that contribute, while wind and solar energy contribute negligibly. For successful application of the concept of sustainability in energy supply, the integration of these renewable energy sources into the energy system to increase the amount of energy produced and the development of transportation for their distribution are the two major challenges that need to be addressed (Lund 2007). Other factors such as technological and technical realism, economic viability, reliability, applicability, and public acceptance must also be considered (Dincer 2000).

In the recent past, a growing interest and development in the use of biomass as a renewable energy source for biofuel production has been observed (Fig. 2.1).

Biomass-derived biofuels can be used for a variety of applications, from use as a transportation fuel to the generation of heat and electricity (Caspeta et al. 2013). The various sources and benefits of biofuels, as well as advances in technologies and policies for their successful large-scale application, are described below.

2.2 Sources for Biofuels

The fuel produced using the energy trapped in the form of biomass through the process of biological carbon fixation is called biofuel. Since the amount of carbon dioxide trapped during plant growth is equal to the amount released during combustion, biofuels are considered carbon neutral. Different biomass sources and forms, i.e., solid, liquid, or gas, can be used for biofuel production (Shalaby 2013; Khan et al. 2020, 2021).

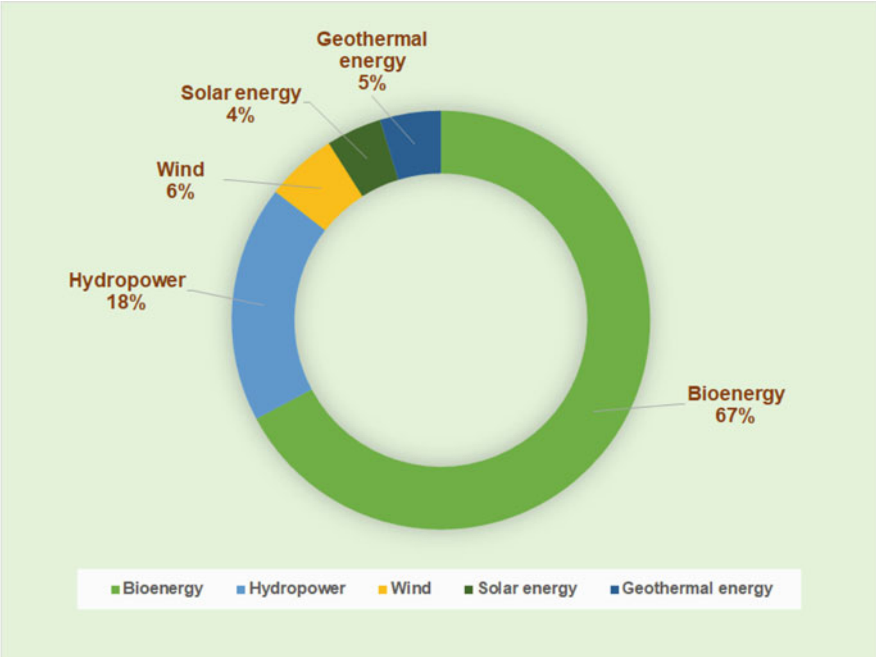

Fig. 2.1 Renewable energy distribution for the year 2018

Biofuels were classified based on the type and source of biomass used for their production. Based on the processing of biomass, biofuels were classified into primary and secondary biofuels (Demirbas 2008). Primary biofuels include traditionally used firewood, agricultural and forest residues, woodchips, etc. as biomass that does not require processing and is used directly for heat production. This type of biofuels is widely used in underdeveloped and developing countries for household applications such as cooking, firewood, etc. (Rodionova et al. 2017). Although this class of biofuels does not require high processing costs, its scope is very limited. The biofuels that are obtained by treating and processing primary biomass and have very high energy content with the ability to be used as an alternative to fossil fuels for commercial purposes are called secondary biofuels. Common secondary biofuels include bioethanol, biohydrogen, biodiesel, etc. (Rodionova et al. 2017; Savla et al. 2020).

Based on the source of biomass, secondary biofuels have been further classified into three generations, i.e., first, second, and third (Surriya et al. 2015). Table 2.1 compares these different generations of biofuels and biomass for their application with common biomass sources described for the production of these different generations of fuels (Fig. 2.2).

Table 2.1 Comparison of the three generations of biofuels based on biomass and energy production

First generation	Second generation	Third generation
Uses food crop as biofuel source	Uses lignocellulosic waste and non-food crops	Algae biomass are used
Requires arable land and water resource	Requires arable land	Can grow in any land or waterbody
Extensive use of fertilizers and pesticide	Does not require fertilizers and pesticide	Does not require fertilizers and pesticide
Less energy intense compared to third generation of biofuels	Less energy intense compared to third generation of biofuels	More energy intense per area of harvest
Raises food security issue since food crops are used as feedstock	Raises food security issue due to competition with agricultural resources	Does not raise any threat on food security
Examples are corn, sugarcane, vegetable oil	Examples are agricultural waste, non-food crops like alfalfa	Examples are *cyanobacteria*, *chlorella* sp.

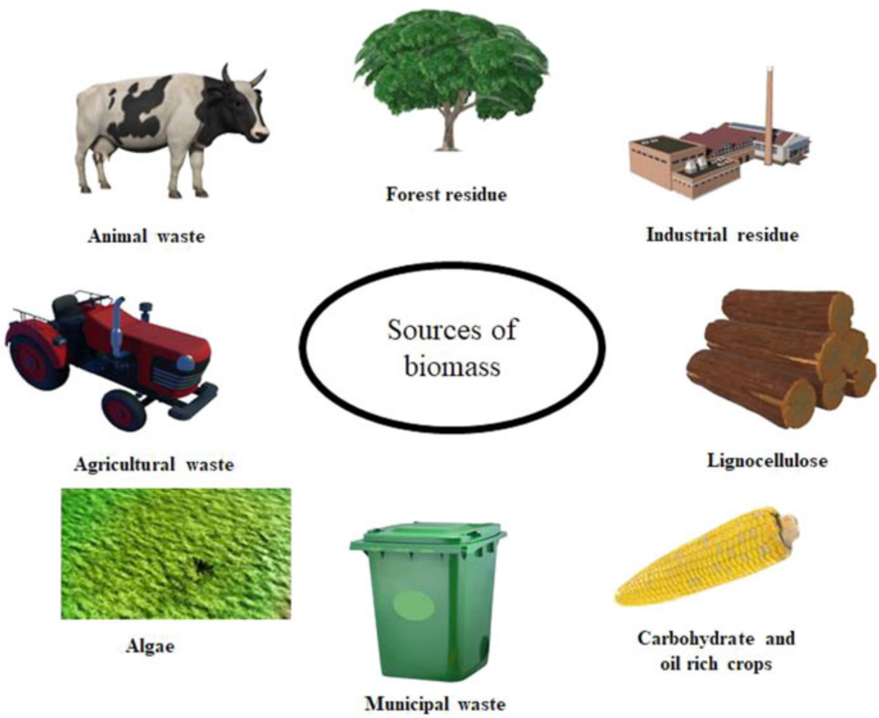

Fig. 2.2 Different potential sources of biomass for biofuel production

2.2.1 Carbohydrate and Oil-Rich Crops (First-Generation Biofuel)

Edible food crops, for instance, corn, wheat, barley, sugarcane, rice, rapeseed, soybean, sunflower seeds, etc., which are rich in carbohydrates and oils, are used as a biomass source for the production of first-generation biofuels (Hirani et al. 2018). Bioethanol is produced by fermentation or sequential hydrolysis and fermentation of starch and other polysaccharides present in these plants, with corn being the leading biomass for bioethanol production (60 billion liters), followed by sugarcane (20 billion liters), with the USA and Brazil being the principal supplier, respectively, for the year 2012 (Sawin et al. 2013). Oil plants are used to extract the oils, which are then esterified by mixing with alcohol to produce biodiesel. Palm oil with a value of 40% has a very high oil content and is a common oil crop used in Asian countries of Indonesia and Malaysia (Balat and Balat 2010). Rapeseed with an oil content of 35% is widely used in the European Union (EU) to produce biodiesel. Similarly, soybean with an oil content of 21% is a common feedstock in the USA (Ramos et al. 2009). In 2012, Germany was the largest producer of biodiesel, followed by the USA and Argentina (Sawin et al. 2013). These two main biofuels are commercially produced as substitutes for diesel and gasoline, respectively.

Although first-generation feedstocks have the advantage of easier processing and low cost for biofuel production, there are several drawbacks to using these feedstocks for long-term energy production (Voloshin et al. 2019). Competition with food raises the issue of food security and also leads to an increase in their prices, which has directly sparked the debate on the use of food as fuel (Gasparatos and Stromberg 2012). Since the production of these crops also requires arable land and water facilities, there is also competition for these basic resources (Fargione et al. 2008). Production and processing cost greatly increase the price of these fuels, making them unable to compete with fossil fuels (Doornbosch et al. 2007). The consistency of greenhouse gas (GHG) emission control and environmental impact of using these biofuels, when the total land-use change is considered, makes the use of first-generation biofuels not worthwhile (Paris 2008). Therefore, several factors need to be considered in the use of these edible biomass resources such as availability of limited resources like land, impact on water due to extensive use of agrochemicals to increase production, impact on food security, etc. (Singh et al. 2013). Therefore, the overall assessment of the impact of the use of these biofuels on the environment and socioeconomic conditions led to the search for alternative biomass sources for biofuel production (Ho et al. 2014).

2.2.2 Lignocellulosic Material (Second-Generation Biofuel).

Second-generation commodities include non-edible lignocellulosic biomass from agricultural, forestry, municipal, and industrial wastes. This biomass was classified into three groups: (1) homogeneous biomass, which consists of wood chips from energy crops and has a value of US$100 to US$120 per ton; (2) quasi-homogeneous biomass, which consists of residues from forestry and agriculture and has a value of US$60 to US$80 per ton; and (3) non-homogeneous biomass, which includes municipal and household wastes with a value of US$0 to US$60 per ton (Lavoie et al. 2011). Perennial grasses such as switchgrass, reed canary grass, alfalfa, etc. are grown as energy crops on land with low soil quality, along with *Jatropha* and woody crops with short rotation. Agricultural and forestry residues such as bagasse and wood waste do not require land or other resources and are readily available to be used for biofuel production. Municipal and industrial wastes such as putrefaction products, vegetable and fruit peels, and paper industry wastes are also used under the concept of waste to energy (Ho et al. 2014).

Although these biofuel sources are expected to compete for land and water resources for food production, the total energy yield, in this case, is higher on a given land area, unlike first-generation biofuels. Further, nutrient-poor soils can also be used for their growth (Chakraborty et al. 2012). Moreover, the production cost of these biomasses is either zero or lower compared to first-generation biomasses like vegetable oil, sugarcane, etc. (Lee and Lavoie 2013). This is a major advantage of second-generation biofuels and has attracted a lot of attention for research to develop techniques to use these feedstocks to produce the most common forms of energy, i.e., heat and electricity. The whole process is considered to be carbon neutral or sometimes even negative for the combustion of the biofuel produced by these feedstocks (Alalwan et al. 2019). Moreover, some of the feedstocks can be used for the production of additional value-added products, which is the main concept of biorefineries.

However, the major drawback in using this type of biomass as feedstock is its complex nature which makes its treatment for biofuel production a challenging task (Nigam and Singh 2011). Since the success of any biofuel production technology lies in its economic aspect and cost friendliness, the success of second-generation biofuels is also directly related to the pre-treatment and production cost of lignocellulose, with the high cost of pre-treatment being the major obstacle (Lee and Lavoie 2013). Technical progress is expected to overcome this obstacle in the near future, as intensive research is already underway (Ho et al. 2014).

2.2.3 Algae (Third-Generation Biofuels)

Third-generation biomass consists of algal biomass, which has gained considerable attention in recent years for biofuel production. Algae are aquatic microorganisms with photosynthetic ability and rapid growth that live in various habitats such as wastewater, salt water, coastal seawater, or non-cultivable land (Chen et al. 2011; Chowdhary et al. 2020). They can photosynthesize carbon dioxide to produce large amounts of carbohydrates and other substances such as lipids, proteins, or pigments, which are stored as biomass. Algal biomass has great potential for use as a feedstock for biofuel production and has been extensively researched. The algae *Botryococcus* and *Chlorella* sp. have a high lipid content of 50–80%, which makes them a suitable candidate for biodiesel production, while *Cyanothece* sp., *Spirulina platensis*, and *Chlamydomonas* sp. which produce large amounts of carbohydrates are used for bioethanol production. The algae are also used for biohydrogen and biomethane production (Costa and De Morais 2011).

The high growth rate of the algae, with the ability to double its biomass within 2–5 days, leads to a very high yield of dry biomass, which in the case of *Pleurochrysiscarterae* is about 60 tons/ha per year, from which an oil quantity of almost 20 tons is extracted. This is a major advantage of using algal biomass as the production rate is almost five times that of palm oil, which is the oil crop pant with the highest yield (Ho et al. 2014). The lower content of hemicellulose along with the absence of lignin provides the added advantage of high efficiency of hydrolysis, which has a direct positive effect on the fermentation rate, resulting in higher yield and making the process economical (Li et al. 2014).

The disadvantage in the successful application of algal biomass for biofuel production is the cultivation system, where the open pond cultivation requires low capital investment, but the biomass yield is also low, while the closed system requires high capital investment (Chen et al. 2011). The difference in growth rate, yield efficiency, and nutrient requirement of different algal species is another major problem (John et al. 2011). Downstream processing, photobioreactor design, and extraction strategies and techniques need to be developed to improve the commercial viability of using algae as biomass for biofuel production (Ho et al. 2014).

2.3 Technological Advances in Biofuel Production

This section focuses on technological developments in the biochemical routes of lignocellulosic biomass-based biofuel production (e.g., bioethanol, biobutanol, biogas, biohydrogen, etc.). This may involve modifications either in the process or in the biological components involved (microorganisms and plants). The conversion of lignocellulosic biomass into biofuels involves three main steps, namely, biomass pre-treatment, enzymatic/microbial hydrolysis of the pre-treated biomass to simple sugars, and fermentation for biofuel production. Enzymatic hydrolysis has been shown to be a rate-limiting step in overall biofuel production; thus, increasing the efficiency of the hydrolysis process is the most important part of biofuel synthesis. Efficient biomass pre-treatment also contributes to improved enzymatic hydrolysis. Therefore, researchers have focused more on improving these two steps in the past; however, direct intensification of the fermentation process has also been effectively attempted.

Lignocellulosic biomass, which is mainly available in the form of agricultural/ forestry residues (Clauser et al. 2021), is a potential low-cost substrate for biofuel production. Lignocellulosic biomass is mainly composed of cellulose, hemicellulose, and lignin, of which the cellulose and hemicellulose can be hydrolyzed to produce biofuels. By nature, the lignocellulosic biomass is highly crystalline, and the cellulosic fraction is densely entangled with hemicellulose and lignin, which hinders the enzymatic action on the cellulose to release fermentable sugar monomers (Kumar et al. 2009). This necessitates the pre-treatment of raw biomass prior to enzymatic hydrolysis for biofuel production. Therefore, the main objectives of pre-treatment are to reduce the biomass/cellulose crystallinity, increase the available surface area of the biomass for enzyme action, and remove the lignin. The various pre-treatment methods practiced for different lignocellulosic biomasses can be classified as physical, chemical, biological, and physicochemical pre-treatments.

2.3.1 Physical Pre-Treatment

Physical pre-treatments include comminution of biomass by using various physical methods such as grinding, milling, steam explosion, compressed hot water treatment, and energy radiation such as γ-radiation, microwave, etc. Mechanical comminution such as crushing, grinding, and milling involves comminution of raw biomass resulting in increased surface area and decreased crystallinity of biomass/cellulose. In one report, sequential chopping, grinding, and milling resulted in a material size of 10–30 mm after chopping and 0.2–2 mm after grinding or milling (Sun and Cheng 2002). Timothy and alfalfa grass were processed by mechanical crushing, hammer, and knife grinding (Alvo and Belkacemi 1997). Ball milling was applied to corn cobs, resulting in increased biohydrogen production (Zhang et al. 2019). Significantly higher glucose yield (~98%, g/g) was observed in enzymatic hydrolysis after compressed hot water and disk milling of oil palm mesocarp fibers (Zakaria et al. 2015). However, the energy required for mechanical comminution depends on the final particle size and biomass properties (Cadoche and López 1989) and incurs high energy and capital costs (Ghosh and Ghose 2003).

Another very suitable physical pre-treatment method for the production of liquid biofuels is steam explosion, in which the biomass is subjected to a sudden high pressure at a very high temperature (Ibrahim et al. 2011). Steam explosion of wild grass at 121 °C, 15 psi for 1 h, yielded a significant amount of sugar for ethanol fermentation (Das et al. 2013).

Liquid hot water pre-treatment is an emerging method where the treatment is carried out at elevated pressure to maintain the water in a liquid state (Yu et al. 2010), resulting in improved cellulose digestibility and dissolution of the hemicellulosic portion of the biomass. This method is advantageous in terms of the absence of fermentation inhibitors in the hydrolysate and the release of hemicellulosic pentose sugars ready for direct fermentation for bioalcohol production.

High-energy radiation such as γ-radiation (Su et al. 2020), electron beam (Fei et al. 2020), microwave heating (Ma et al. 2009), and ultrasound for biomass pre-treatment has also been extensively studied in the recent past. The mechanism behind the ultrasonic treatment of biomass has been extensively studied by some researchers to explore the physical and chemical effects (Singh et al. 2014a).

2.3.2 Chemical Pre-Treatment

Lignocellulosic biomass can be pre-treated by acids, alkalis, oxidizing agents, surfactants, and ionic liquids. The hemicellulosic portion of the biomass can be readily hydrolyzed with dilute acid and also dissolves the lignin to some extent. The resulting pentose sugars can be easily fermented for alcohol production (Bharadwaja et al. 2015). However, cellulose and lignin fractions, which are more crystalline than hemicellulose, can be treated with alkali to dissolve mainly lignin and leave a cellulose-rich residue (Singh et al. 2014a). Alkaline treatment also reduces the crystallinity of cellulose, resulting in improved digestibility during enzymatic hydrolysis (Ayeni et al. 2013).

Oxidants such as H_2O_2 have been used for biomass pre-treatment either alone or in combination with acid, alkali, or ammonia (Lee et al. 2021). Various studies show that hydrogen peroxide promotes lignin degradation and breaks lignin-carbohydrate bonds (Singh et al. 2014a, b, Lee et al. 2021). Biomass pre-treatment can also be carried out using surfactants (Gong et al. 2021). Surfactants are surface-active agents that improve mass transfer and increase the wettability of biomass by reducing the surface tension of water.

2.3.3 Biological Pre-Treatment

Biological pre-treatment mainly involves the use of wood-degrading microorganisms that lead to a change in the chemical composition and/or structure of the lignocellulosic biomass. Biologically pre-treated biomass is easier to degrade enzymatically, and this type of pre-treatment is also environment-friendly as it leaves no harmful by-products. Brown rot and soft rot fungi mainly affect cellulose with little effect on lignin, whereas white-rot fungi actively degrade lignin (Zheng et al. 2009). Biological pre-treatment of the field weed *Parthenium* sp. was attempted using the fungi *Trametes hirsuta* and *Marasmiellus palmivorus* PK-27 (Rana et al. 2013). For biogas production, biological pre-treatment of maize straw with mixed microbes accelerated biomass degradation rate and increased lignin degradation efficiency (Li et al. 2020).

2.3.4 Physicochemical Pre-Treatment

This category of pre-treatment can be a combination of the physical and chemical pre-treatments mentioned in the previous sections or can occur individually, such as the ammonia fiber expansion process (AFEX). The combined processes that are very commonly used are the chemical (CO_2, SO_2, acid or alkali) catalyzed steam explosion (De Bari et al. 2007), and the recently explored strategies are the ultrasound-assisted chemical (acid/alkali) pre-treatments (Singh et al. 2014a, Suresh et al. 2014). In another very recent physicochemical pre-treatment, a two-step sequential approach using UV-catalyzed alkaline hydrogen peroxide (UHP) and ionic liquid treatment (IL) was applied to sisal waste. It resulted in a significant amount (69.2 g/100 g dry sisal waste) of sugar release after enzymatic hydrolysis. The analyses showed the main effects in terms of delignification and decrystallization of sisal waste biomass (Cao et al. 2021).

2.4 Advantages, Policies, and Challenges for Commercial Application

The use of biofuels has several advantages with long-term effects both in economic terms and for sustainable development. Biofuels are not only a potential substitute for fossil fuels but also have a significant impact on social, economic, and environmental aspects around the world. The environmental aspect of reducing greenhouse gas emissions and addressing climate change are important benefits of using biofuels as biofuels are carbon neutral (Gheewala et al. 2013). Another major advantage of using biofuels is the reduction of dependence on fossil fuels and the constant availability of an adequate amount of energy at a reasonable cost, thus ensuring energy security. The imbalance in the distribution of fossil fuels and the ever-fluctuating crude oil prices are the issues that are directly related to the economic and political influences, where the countries that have to import these fossil fuels are vulnerable. Renewable energy production can provide strategic benefits to these countries, especially developing countries, by giving them economic and political liberty in this context (Coelho et al. 2005). Renewable energy also provides social benefits in terms of improved health quality through the provision of cheap biofuels as alternatives, especially in rural households that rely on firewood as a common fuel source. Increased employment opportunities at the local level and rural development dependent on the bioenergy system is another positive aspect of using biofuels as renewable energy (Chum et al. 2011).

However, there are certain challenges in the production of bioenergy, the most important being the economic aspect. The high cost of enzymes used for both pre-treatment and fermentation processes for biofuel production is a major hurdle. Further, it is important to design the pre-treatment method in such a way that maximum benefits are obtained in an economical manner. Cost-effective pre-treatment requires the successful release of sugar polymers for enzymatic activity without the production of inhibitory compounds or residues, requires less energy and chemicals, and is a cost-friendly material for reactor design. The efficiency of fermentation also plays a crucial role, using several screening techniques along with genetic and protein engineering techniques to identify new as well as genetically modified organisms (GMOs) and enzymes with high production rate and stability under the industrial fermentation conditions (Gaurav et al. 2017).

Considering these advantages and limitations of biofuels, public policies for bioenergy production and utilization are being developed and implemented by the government worldwide. The Indian government formulated a national policy in December 2007 to promote bioenergy as a transportation fuel, where the biofuel was intended to use as a blend with gasoline at a level of 20% (Raman and Mohr 2014). To maintain the competitiveness of biofuels in terms of production, transportation, and distribution, the integration of the private sector in the regulatory framework is an important step. The Ministry of New and Renewable Energy (MNRE) has initiated several programs to promote bioenergy production, such as the National Biogas and Manure Management Program (NBMMP) and energy recovery from urban, agricultural, and industrial wastes (Gaurav et al. 2017). Nevertheless, research and development work are still required for the successful and economical implementation of biofuel policy.

2.5 Discussion and Future Prospective

As energy demand is a continuous process, the search for different energy sources will always exist. The biggest challenge of the coming generation is to find an energy source that provides sufficient energy, can be relied upon in the long run, and has little or no negative impact on the environment. Therefore, the future world will rely more on the various renewable energy sources to meet their needs. Among the numerous renewable energy sources, bioenergy, which is derived from abundant biomass, is the most reliable. The various biomass sources are already being used commercially, but further improvement of the technology supported by strong government policies to promote the use of renewable energy from biofuels is needed.

Acknowledgments The authors would like to thank the Department of Microbiology, Sikkim University, for providing the computational infrastructure and central library facilities for procuring references.

Conflict of Interest The authors declare that the study was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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