Clean Energy Production Technologies

Series Editors: Neha Srivastava · P. K. Mishra

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P. K. Mishra *Editors*

Basic Research Advancement for Algal Biofuels Production

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Neha Srivastava, Department of Chemical Engineering and Technology, IIT (BHU) Varanasi, Varanasi, Uttar Pradesh, India

P. K. Mishra, Department of Chemical Engineering and Technology, IIT (BHU) Varanasi, Varanasi, Uttar Pradesh, India

The consumption of fossil fuels has been continuously increasing around the globe and simultaneously becoming the primary cause of global warming as well as environmental pollution. Due to limited life span of fossil fuels and limited alternate energy options, energy crises is important concern faced by the world. Amidst these complex environmental and economic scenarios, renewable energy alternates such as biodiesel, hydrogen, wind, solar and bioenergy sources, which can produce energy with zero carbon residue are emerging as excellent clean energy source. For maximizing the efficiency and productivity of clean fuels via green & renewable methods, it's crucial to understand the configuration, sustainability and techno-economic feasibility of these promising energy alternates. The book series presents a comprehensive coverage combining the domains of exploring clean sources of energy and ensuring its production in an economical as well as ecologically feasible fashion. Series involves renowned experts and academicians as volume-editors and authors, from all the regions of the world. Series brings forth latest research, approaches and perspectives on clean energy production from both developed and developing parts of world under one umbrella. It is curated and developed by authoritative institutions and experts to serves global readership on this theme.

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Editors
Neha Srivastava
Department of Chemical Engineering
and Technology
IIT (BHU) Varanasi
Varanasi, Uttar Pradesh, India

P. K. Mishra
Department of Chemical Engineering
and Technology
IIT (BHU) Varanasi
Varanasi, Uttar Pradesh, India

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Preface

The global green concept is spreading very rapidly to achieve long-term sustainability in environment and solve energy crises. Renewable energy and biofuels are potential energy sources being developed at a very faster pace worldwide to replace fossil fuels. Biofuel production from renewable resources-based feedstock is a potential and sustainable option. Among different available biofuels, algal biomass is emerging as a potential alternative as feedstock as well as a direct source of biofuels production. Renewable nature, huge availability, and rich in lipids and carbohydrates are the unique properties of algae which make them potential ideal candidates for biofuels production. However, a basic and key understanding of this microbial group is needed to explore the scientific ground for successful batch as well as mass scale biofuels production. Therefore, this book provides details about basic research for potential and practical algal biofuels production. Chapters 1 and 2 present latest trends in algal biofuels production while Chapters 3 and 4 explore algal biomass mats and algal biofuels production as potential and ideal biofuels options. Further, Chapter 5 and 6 discuss algal biomass as an efficient key feedstock for algal biohydrogen and other biofuels production. Chapters 7 and 8 give new insight on algal biofuels and their property as potential biofuels among other existing biofuels whereas Chapter 9 and 10 discuss the versatility of algae for various clean biofuels. The basic research concept and application utility may be useful to understand and set the mass scale goal for practical application of algal biofuels. Therefore, the aim of the current review is to explore the scope of algae for the production of different biofuels and evaluation of its potential as an alternative feedstock.

Varanasi, Uttar Pradesh, India

Neha Srivastava
P. K. Mishra

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Contents

Chapter 1
Recent Advancements in Municipal Wastewater as Source of Biofuels from Algae

Spriha Raven, Arpit Andrew Noel, Jane Florina Tirkey, and Archana Tiwari

Abstract The normal aquatic microflora comprising of bacteria and algae perform a vital role in the maintenance of an ecological balance of water by consuming excess nutrients. Exploring wastewater as a reservoir for nutrients and concomitant generation of value-added products from algae and bacteria is indeed an innovative approach towards sustainability. For the optimum exploitation of current wastewater treatment infrastructure, eutrophic water bodies like lakes, ponds, and water canals can be used for the growth of bacteria and algae, thereby resolving the scalability and economic issues. In this chapter we are elaborating the municipal wastewater remediation potential of bacteria and algae and valorizing the resulting biomass for diverse applications. The microbial enrichment in wastewater can be envisaged as a rapid, economical, and environment-friendly approach for the wastewater remediation coupled with the generation of bioactive compounds. The crucial challenges include the standardization of the culture conditions to grow bacteria and algae in wastewater for nutrient elimination concomitant with the generation of biofuels and valuable products. The biorefinery approach is an efficient tool to combat environmental pollution coupled with the generation of value-added products like biofuels.

Keywords Algae · Bacteria · Biofuels · Remediation · High value products · Wastewater

S. Raven · A. Tiwari (✉)
Diatoms Research Laboratory, Amity Institute of Biotechnology, Amity University, Noida, Uttar Pradesh, India

A. A. Noel
Agri Business Management, National Institute of Agricultural Extension Management, Hyderabad, Telangana, India

J. F. Tirkey
Department of Plant Pathology, Naini Agricultural Institute (NAI), SHUATS, Prayagraj, Uttar Pradesh, India

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1.1 Introduction

With time the global demand for energy is rising, so is the need and usage of fossil fuel. There is still abundant availability of fossil fuel at practicable cost, but most likely to change soon in future. The major concern is the excessive usage of fossil fuels is not so sustainable for longer terms mainly as it contributes to increase in the greenhouse gas release and put-up impact on global warming (Hill et al. 2006). At the same time energy requirement worldwide is increasing constantly. At present fossil fuels are eminent source of conveyance fuel and energy. The demand for fossil oil is anticipated to increase 60% from the present level by 2025 (Khan et al. 2009). Hence, it is very important to identify other renewable sources of fuel which have the potency of carbon neutral (Demirbas 2009; Hill et al. 2006; Rittmann 2008). Biomass, either terrestrial or marine, is one of the renewable sources of energy. Amongst all, algae have the adaptability to develop and cultivate in diverse habitats. It can grow in marine as well as freshwater (IEA Report 1994). The currently available biofuel in majority is mainly bioethanol which is derived from sugarcane or corn starch or biodiesel which is derived from oil crops such as soyabean or rape oilseed. In spite of the fact that biofuels are potentially more beneficial than fossil fuels, there is a dilemma on using these crops for the production of biofuels, whether they are as economical as compared to fossil fuels. Also, this brings more concern over the fact that using these crops as biofuel may impact the availability of food (Demirbas 2009; Hill et al. 2006). Therefore, algae cultivation on wastewater is much more appropriate and feasible which would not affect agriculture. It is sustainable, ecofriendly and cost-effective. Also, algae are capable of using land more efficiently as compared to other traditional biofuel crops (Clarens et al. 2011).

1.2 Advantage of Biofuel Over Fossil Fuels

Biofuel is an effective fuel for today's generation. Fossil fuel is produced by organic materials over the course of millions of years and it is produced by decomposing plants and animals. Coal, oil and natural gas are examples of fossil fuels. These fuels emit CO_2, and it is harmful to the environment. However, biofuels are very effective and ecofriendly as it is being produced by vegetable wastes, algae, fungi, etc. It is helpful in maintaining the ecological balance and free from carbon dioxide emission. CO_2 emission is bit toxic and it causes global warming. Also, biofuel is a renewable and biodegradable source of energy as it is being produced by organic wastes and materials and practically, we can get enormous amount of fuels. It is safe to be used as it does not involve drilling, mining and other activities for the generation of biofuel. Hence, it is not that dangerous as we need to grow the fuel on farm (Ramos et al. 2016).

Advanced biofuel is being produced by the usage of wastes and residues, such as organic fraction of municipal solid waste, vegetable oil, biological sludge from urban water purification plants. Biofuels such as bioethanol, biodiesel, biohydrogen and other biofuels are produced by the usage of algae, fungi, etc., and it has multiple benefits, such as it reduces greenhouse gas. It is not 100% safe but it is safer than fossil fuels.

1.3 Biofuel Feedstock and Utilization of Wastewater

Microalgae have the ability to produce lipids at a notable concentration. The generated lipids produced, goes up to 80% of the dry weight of its biomass and the type of lipid, i.e., polyunsaturated fatty acids, saturated fatty acids, glycolipid or triacylglycerols depends on the species and its growth habitat (Chisti 2007; Griffiths and Harrison 2009; Hu et al. 2008). Mostly the algae cultured in photoreactor grown cells or batch culture grown cells in laboratory often tend to have maximum lipid production as compared to the algae grown in open pond (Griffiths and Harrison 2009). Recent studies confirm that microalgae which are grown in small batches, bioreactors or small semi-continuous culture showed practicable lipid concentration in microalgae grown in wastewater ranging from more than 10% up to 30% of the dry weight of biomass and the production of lipid could be increased if biomass is cultivated at large scale (Chinnasamy et al. 2010a, b). Recently a study on municipal wastewater along with *Chlamydomonas reinhardtii* was conducted and it was observed that it was very effective in wastewater treatment and total lipid content was 16.6% of the dry weight (Kong et al. 2010). When the microalgae were transferred to biocoil, it continued to grow for 1 month in wastewater, the lipid content increased to 25.5% of its dry weight, lipid productivity to 2505 mg/l/day and biomass productivity to 2000 mg/l/day. Also, there was effective removal of nitrogen and phosphorus (Kong et al. 2010). Likewise, in *B. braunii* level of total lipid content was observed similar in secondary treated municipal wastewater.

The lipid content and biomass were higher as compared to microalgae grown in synthetic grown medium (Órpez et al. 2009). For wastewater treatment microorganism requires large amount of oxygen for degrading organic material biochemically. And for this purpose, aeration devices are used which require electrical power up to 45–75% of plant energy cost (Rosso et al. 2008) which was not economical. Algae when used for wastewater treatment supply oxygen using a little energy required as compared to mechanical aeration. Algae also remove nitrogen and phosphorus which prevent eutrophication with the means of nitrification/denitrification bacteria (Richards and Mullins 2013). Most of the algae species are efficient in sorbing metals and are helpful to treat wastewater containing heavy metals (Li et al. 2009).

1.4 Algal Biofuel Production

Microalgae are a diverse group that helps in providing potential offer to a variety of solution for liquid transportation fuel requirements for a number of avenues. Microalgae are widely used in a variety of purposes. It uses CO_2 efficiently and more than 40% of global carbon fixation occurs and the productivity usually occurs through marine algae (Benemann 2008).

There are various fuels that are produced through algae such as ethanol, biodiesel, biohydrogen. There are many researches going on, but no proper mechanism has been scaled up for biohydrogen. The main algae genera currently cultivated photosynthetically for various nutritional products are *Spirulina, Chlorella, Dunaliella and Haematococcus.* Microalgae are cultivated using sunlight energy and it is produced in open ponds or closed bioreactors. Generation of microalgae for the commercial scale can be done in an open pond. It is much cheaper than closed bioreactors.

Methane is the first source of fuel from microalgae that are considered for their applications in wastewater treatment. Anaerobic digestion of algae is still uncommon but producing biofuel from algae especially biodiesel is the most common attention of algae fuels. Algae-based biofuel production has gained considerable attention in recent years leading to its biodegradability and sustainability (Benemann 2008) (Fig. 1.1).

1.5 Municipal Wastewater as Source of Biofuels

Due to the growth of human population and modern living of people, water pollution is inflated worldwide. Wastewater is primarily by-product produced by various resources such as domestic, municipal, agricultural and industrial sources. The constitution of wastewater is a mirroring of the way of life and various approaches practised. Wastewater compromises organic mass like proteins, lipids, volatile acids, carbohydrates and inorganic content containing sodium, calcium, magnesium, sulphur, bicarbonate, chlorine, ammonium salts, phosphate and heavy metals. Presence of excessive nutrients in the water bodies leads to eutrophication or algal blooms because of anthropogenic waste production.

Municipal wastewater has also been considered domestic wastewater and is generated by domestic sites. In the last few decades, municipal wastewater has increased due to the development of city. It compromises various wastes from human, food and chemical wastes from day today life. Nitrogen and phosphorus are present in less quantity in municipal wastewater as compared to other types of wastewater. Microalgae are expanded in raw concentrate and various algae can convert municipal wastewater into biomass efficiently (Akhtar et al. 2019).

Algae can be grown in various water such as fresh, brackish and marine water, municipal wastewater, industrial wastewater, aquaculture wastewater, animal

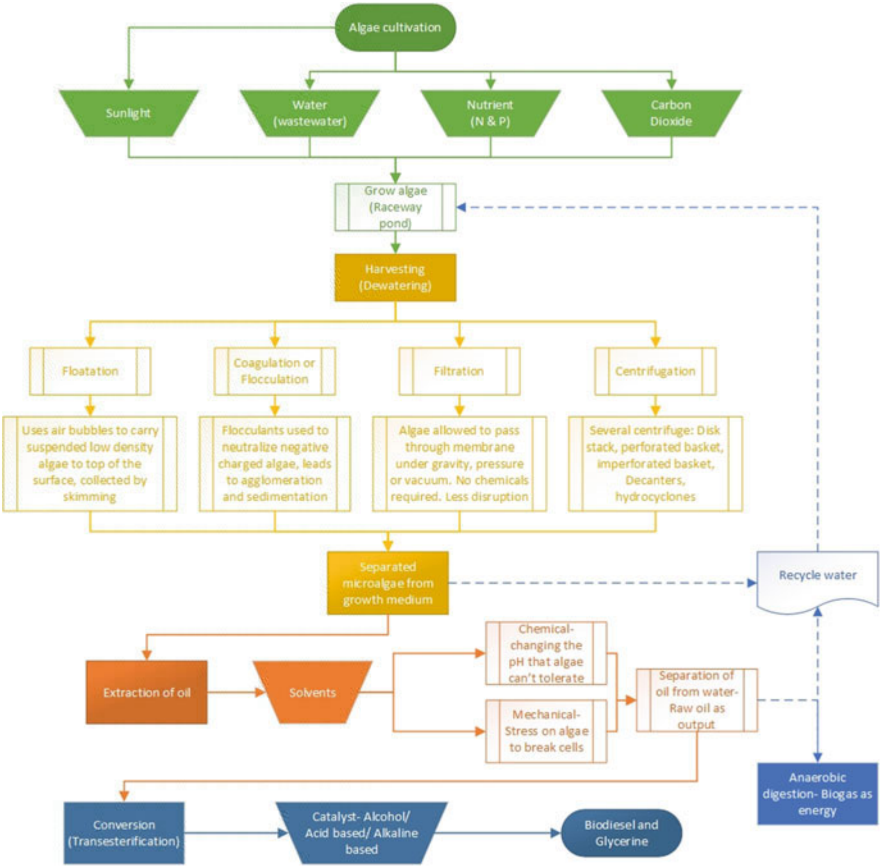

Fig. 1.1 Algal biofuel production

wastewater, domestic wastewater and adequate amount of nutrients such as nitrogen, phosphorus and various trace elements. Wastewater has chemical and physical properties (Mobin and Alam 2014).

1.5.1 Potential of Algae to Grow in Municipal Wastewater

The raising of microalgae for the purpose of biofuel in established wetlands fulfils all the essentials of ecofriendly purification process required for wastewater treatment as it is better to substitute in terms of budget and energy for the process of water treatment (Kadlec and Wallace 2009). Cultivation of microalgae is very advantageous for developing countries as aquatic plants in wastewater require warm climate. Hence it is a boon for developing nation (Zhang et al. 2014). There have been several researches going on about the nutrient and habitat requirement on different configurations of wastewater streams like agro-industrial wastewater, municipal wastewater, etc. (Van Den Hende et al. 2016; Abinandan and Shanthakumar 2015). It was found that the required quantity of water, additives required for green growth development, life cycle are well provided by these wastewater and hence it is beneficial for the growth of microalgae in wastewater as it is economical, ecofriendly (Zhou et al. 2012). Later it was found that the available phosphorus and nitrogen in wastewater sources are used for the green growth for bioremediation processes (Chinnasamy et al. 2010a, b).

Microalgae's chemical and nutritional requirement offers chance for biofuel production and bioremediation which can be achieved with the integration of municipal and industrial utilities with algae system for maximum use of urban resource. This integration is the best example of holistic use of available resource as algae being cultivated on the wastewater treatment system captures carbon dioxide, removes nitrogen, phosphorus from wastewater as it utilizes it for its growth which is being cultivated for biofuel production. These are several benefits that can be achieved from the integration of algae and wastewater treatment. Algae utilize carbon dioxide for its growth, hence, filters it efficiently. Algae uses the available nitrogen phosphorus present in wastewater and helps in wastewater treatment. Algae contain 20–70% lipids of their biomass for biofuel production. It also gives several other by-products such as protein, vitamins, carbohydrate, pigments that are used by fertilizer and pharmaceutical industry. Hence, the integration of algae cultivation with wastewater becomes more cost-effective (Hwang et al. 2016).

1.5.2 Types of Algae for Biofuel Generation

Through pyrolysis algal biomass can be used for the production of biofuel. Macro and microalgae should fulfil certain criteria as listed (Carlsson et al. 2007): it must be high yielding, easy to harvest, capable enough to resist water current in ocean and it should be cost-effective.

1.5.2.1 Macroalgae

Listed below are the strains of microalgae for biofuel production:

For the production of methane, the feedstock that could be used are *Laminaria* sp. (Chynoweth et al. 1993), *Sargassum* sp. (Bird et al. 1990), *Macrocystis* sp. (Chynoweth et al. 1993), *Ulva* sp. (Adams et al. 2009). For the production of ethanol *Ulva* sp. (Morand 1991), *Kappaphycus alvarezii* (Khambhaty et al. 2012). For the production of hydrogen feedstock that can be used as *Gelidium amansii* (Park et al. 2011), *Laminaria japonica* (Shi et al. 2011).

Using macroalgae for the production of biofuel is not economical with the present available technology, but if the process of production is amalgamated with other activities such as removal of pollutant and manufacture of several biobased products then it can be cost-effective (Savage 2011; Pittman et al. 2011).

1.5.2.2 Microalgae

Microalgae are mainly photosynthetic organisms found in fresh as well as marine habitat. At hand research enterprises have confirmed that microalgal biomass is one of the most hopeful sources of renewable biodiesel and it is efficient to fulfil the global demand.

Microalgal biomass has a huge percentage of oil content that can exceed more than 80% of its dry weight (Rodolfi et al. 2009).

Some of the microalgae with its oil range of 20–50% are listed below (Chisti 2007; Rodolfi et al. 2009) (Table 1.1):

Various strains of microalgae that are used for bioethanol production are *Chlorococcum humicola* (Harun and Danquah 2011), *Chlorococcum infusionum* (Harun et al. 2011), *Chlamydomonas reinhardtii* (Choi et al. 2010), *Spirogyra* sp. (Eshaq et al. 2011) (Table 1.2).

Table 1.1 Microalgae with its oil range

Feedstock	Oil content (% dry weight)
Botryococcus braunii	25–75
Chlorella sp.	28–32
Chlorella vulgaris	19.2
Chlorococcum sp.	19.3
Chaetoceros muelleri	33.6
Chaetoceros calcitrans	39.8
Crypthecodinium cohnii	20
Cylindrotheca sp.	16–37
Dunaliella primolecta	23
Isochrysis sp.	25–33
Monallanthus salina	>20
Nannochloris sp.	20–35
Nannochloropsis sp.	31–68
Neochloris oleoabundans	35–54
Nitzschia sp.	45–47
Phaeodactylum tricornutum	20–30
Pavlova lutheri CS182	30.9
Schizochytrium sp.	50–77
Scenedesmus sp. *F & M-M19*	19.6
Scenedesmus sp. *DM*	21.1
Skeletonema sp.	31.81
Tetraselmis suecica	15–23

Table 1.2 Types of algae and phylum

Phylum	Name	Type of algae	Reference
Cyanobacteria	*Cyanobacterium aponinum Cyanobium sp. Phormidium sp. Pseudoanabaena sp*	Freshwater/marine Freshwater Freshwater Freshwater	Hopkins et al. (2019) Mendes et al. (2011) Mendes et al. (2011) Mendes et al. (2011)
Haptophyta	*Isochrysis galbana*	Marine	Ammar et al. (2018)
Chlorophyta	*Chlamydomonas reinhardtii* *Dictyosphaerium sp.* *Dunaliella tertiolecta* *Monoraphidium sp.* *Scenedesmus sp.* *Amphora coffeaeformis*	Freshwater Freshwater/marine Marine Freshwater Freshwater Freshwater/marine	Badrinarayanan et al. (2017) Al-Ghouti et al. (2019) Ranjbar et al. (2015) Das et al. (2019) Das et al. (2019) Godfrey (2012)
Ochrophyta	*Chaetoceros gracilis* *Chaetoceros muelleri* *Nannochloropsis oculata*	Marine Marine Marine	Godfrey (2012) Godfrey (2012) Ammar et al. (2018)

1.5.3 Innovative Algae Cultivation System

The cultivation of microalgae depends on several factors such as light, temperature, pH, carbon source. Its main goal is to produce high lipid concentration and biomass with costeffective methods. Cultivation of algae in wastewater treatment is similar to any other biological wastewater treatment. But difference in pH and temperature can affect the growth adversely. Wastewater comprises of various nutrients which are favourable for the growth of algae, however for increased lipid concentration components such as metals, nutrients, etc. has to be monitored. Also, the salinity has to be controlled as it affects algal cultivation. Most commonly used reactors for algal cultivation are open air, closed air and biofilm system (Hwang et al. 2016).

1.5.3.1 Open Air System

It is the oldest form of algae cultivation system practised in open ponds. It requires less investments, uses solar energy and less energy as compared to others. The temperature and light cannot be controlled. In this method it can be easily contaminated and is preferred for mixed culture cultivation. There is a limitation of time and place in open cultivation (Kumar et al. 2015a, b). There are four basic types of open system: circular pond, shallow big pond, tank and high-rate algal pond (Kumar et al. 2015a, b).

1.5.3.2 Closed System

In closed system (PBR) factors such as light, gas exchange and contamination can be controlled. Hence, monoculture of certain algae is possible. But the limiting actor is the cost of establishment. Also, in closed system temperature rises and overheat is enough to cause damage to algae growth (Pruvost et al. 2016). There have been constant research going on to work on the limitations, it also has difficulty in dissolving oxygen at large scale. Air sparging is a solution to it but it adds to the cost (Hwang et al. 2016). There have been several structures of PBRs designed to make it more economical and effective, most popular once are ultrathin immobilized configurations, flattened plate-type systems and tubular system (Pulz 2001).

1.5.3.3 Biofilm System

It is least common method of cultivating algae but provides good biomass (Hwang et al. 2016). There is still a lot of information required to practice algae cultivation using biofilm for wastewater treatment regarding removal of nutrients, being sustainable and economical (Kesaano and Sims 2014).

1.5.4 Algal Biomass Harvesting Techniques

Algae harvesting means separating or detaching algae from its growth medium (Gulab and Patidar 2018). Harvesting of algal biomass leads to huge operational cost due to dilute nature of the harvest microalgal cultures. The choice of which harvesting technique to use depends on the type of algae species and required final product (Uduman et al. 2010). At present, algae biomass harvesting techniques include mechanical, chemical, biological and electrical methods (Gulab and Patidar 2018). When mechanical method is combined with coagulation and flocculation, then overall efficiency increases with reduced operational and maintenance costs (Demirbas 2010). Several techniques of algal biomass production are coagulation/flocculation, floatation, filtration, centrifugation and electrical based processes (Abdelaziz et al. 2013; Barros et al. 2015).

1.5.4.1 Coagulation/Flocculation

Microalgae are negative charged and are in dispersed state. This natural state leads to slow natural sedimentation. To increase the process of harvesting, flocculation can be done (Chen et al. 2011). Flocculation can happen naturally without adding any chemicals by changes in nitrogen, pH and dissolved oxygen. It is called auto-flocculation (Uduman et al. 2010). Microalgae biomass is also produced by electrolytic oxidation where algae are destabilized and floc towards anode. This is called as electrolytic process (Chen et al. 2011). Bio-flocculation is a process where some micro-organisms produce flocculants that flocculates algae in suspension (Shelef et al. 1984).

1.5.4.2 Membrane Process

Algae culture is subjected to move through the filters managing under gravity, pressure to hold back algae in a thick paste form. Such system is available in continuous or discontinuous. The standard of the harvested biomass is fine with respect to other harvesting approaches as the cells are few disrupted and no chemicals are needed in the membrane harvesting (Wicaksana et al. 2012).

1.5.4.3 Coagulation and Flocculation

Microalgae cell is found in dispersed condition. It has negative surface charge density close to the growth medium. Such stable system ends in easy natural sedimentation and microalgae are easily harvested by preflocculation or coagulation (Chen et al. 2011). Chemicals known as flocculants that neutralize the negative charge and permit agglomeration of microalgae are considered. Flocculation is regarded as a superior method for harvesting microalgae as it is considered for large-scale production. This process can be induced by electrostatic patch (or patching), bridging flocculation. Surface charge neutralization are the major process that are involved in microalgae flocculation (Chen et al. 2011). Flocculants are supposed to be sustainable and renewable that lead to no biomass pollution, and it permits reprocess of culture medium, inexpensive, non-poisonous, productive in low doses or withdrawn from renewable resources.

1.5.4.4 Floatation Process

Flotation is a gravity dissociation procedure in which air or gas bubbles are considered to bring the suspended material to the top of a liquid surface and they can be controlled by skimming procedure (Singh et al. 2011). Because of low density and self-float feature of various micro-algal species floatation process can be relatively rapid and more productive compared to sedimentation. The separation process has manifested systematic harvesting of freshwater and marine microalgae.

1.6 Recent Approaches for the Enhanced Production of Algal Biofuels

The process of cultivation is the foremost aspect for optimizing the best productivity of lipid and biomass production. Algae production needs abundant production of CO_2, water and sunlight for the production of algal biofuels.

CO^2 concentration has a strong impact on the production of biofuel and lipid (Sangela et al. 2018).

1.6.1 Harvesting Algal Biomass

Harvesting is the best procedure to recover raw or unprocessed biomass of algae for the production of secondary metabolites. In order to make biodiesel low priced we need to reduce the harvesting cost, and it would be considered an important step for biodiesel generation. Natural sedimentation is not suitable to harvest the microalgal biomass procedure like centrifugation, filtration, bio-flocculation, electro-flocculation, chemical-flocculation, floatation and co-cultivation are currently in use for harvesting purposes. Flocculation is regarded as the best method to obtain algal biofuels (Sangela et al. 2018).

1.6.2 Lipid Extraction

Lipid production from oil yielding algae is not simple; it has some hurdles for large-scale production. In order to make lipid production low priced and systematic, it is essential to choose a fit solvent for extraction. There are numerous solvent mixtures for lipid extraction, for instance, chloroform:methanol, hexane:diethyl ether, nitro hexane, dichloromethane, etc. in use. However, none of these mixtures results in biofuel production. In order to execute extraction within the solvent, numerous thermal and mechanical procedures are used for cell wall disruption like microwave assisted extraction pulse electric fields, etc. (Sangela et al. 2018).

1.6.3 Conversion of Extracted Lipid into Biodiesel

For biodiesel generation, it is essential to know the profile of fatty acid of feedstock. It is important to have $<1\%$ of free fatty acid (FFA) amount. Various characteristics such as amount of catalyst, solvents, co-solvents, temperature and reaction time have notable result on biodiesel yield. Phosphoric acid (H3PO4), hydrochloric acid (HCl) and acid sulfonates are to execute esterification and transesterification as acid catalysts (Sangela et al. 2018).

1.7 Biofuel Industry Analysis

1.7.1 Market Size

Biofuel industry is gaining substantial growth, as it is an alternative fuel for petroleum derived fuels which is the major reason for global warming. The global market size of biofuel has been US$ 141.32 billion in 2020 which is expected to grow by 8.3% CAGR by 2030 to US$ 307.01 billion (Precedence Research 2021) (Fig. 1.2).

Talking in terms of Petajoules, total world fuel production from biofuel is 4113 PJ, which is just 0.8% of the total world fuel production (Bp plc 2020).

Out of 4113 PJ of global energy production by biofuels, 2552 PJ is from bio-gasoline and 1561 PJ is from biodiesel (Bp plc 2020) (Fig. 1.3).

Global ethanol production is expected to increase from 116 billion litres in 2015 to 128 billion litres by 2025, half of which will originate from Brazil. Global biodiesel production is expected to grow from 31 billion litres in 2015 to 41 billion litres by 2025 (OECD-FAO Agricultural Outlook 2016) (Fig. 1.4).

Usage of maize and sugar crops as feedstock is very common for ethanol production. Lot of research is going on for utilizing cellulose-based biomass as feedstock and it is forecasted that its share will increase to 0.7% by 2025. In case of biodiesel, vegetable oil holds the highest market share of 82% which is expected to

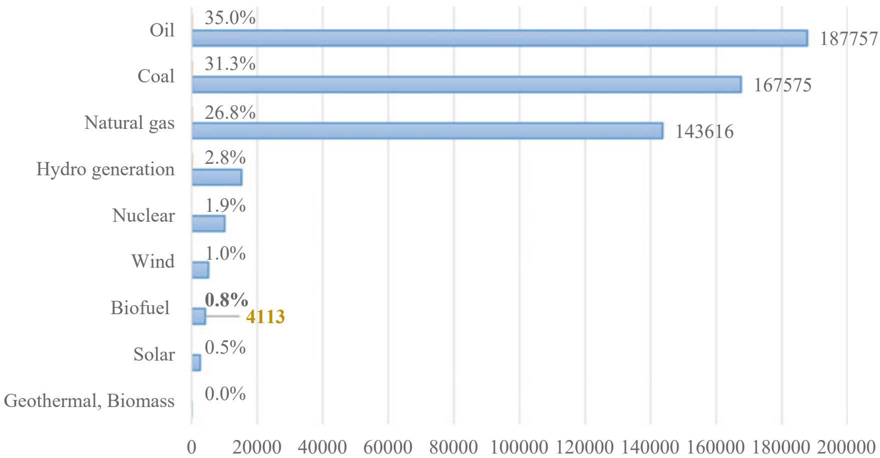

Fig. 1.2 Total world energy production (petajoules) 2019–2020 (Source: Bp plc 2020)

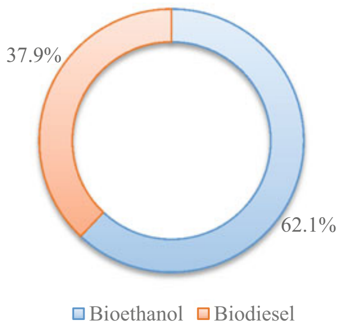

Fig. 1.3 Types of biofuels' market share % (Source: Bp plc 2020)

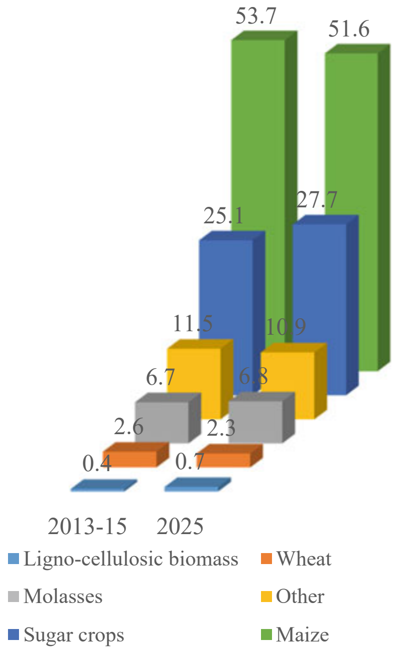

Fig. 1.4 Share of feedstock used for ethanol production % (Source: OECD-FAO Agricultural Outlook 2016)

come down to 72.7%, as companies are exploring opportunities to utilize waste oil from Horeca segments (OECD-FAO Agricultural Outlook 2016) (Fig. 1.5).

North America has captured most of the biofuel market (39%) owning to the government policies favouring biofuel industry over petroleum industry; also feedstocks such as coarse grain, sugar crop, vegetable oil, jatropha and molasses are easily available in abundant. There has been increase in research and development investment in biofuel industry in various regions of Asia-Pacific. Also, there is increase in awareness regarding use of renewable energy source. We can expect a rapid growth of biofuel industry in Asia-Pacific regions as well (Bp plc 2020) (Fig. 1.6).

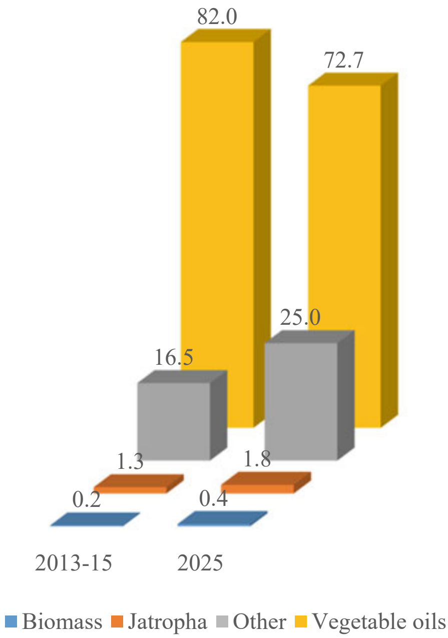

Fig. 1.5 Share of feedstock used for biodiesel production % (Source: OECD-FAO Agricultural Outlook 2016)

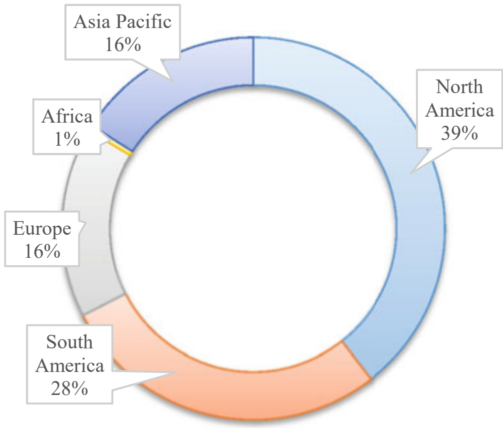

Fig. 1.6 Market share based on production, sub-continent wise (2019–2020) (Source: Bp plc 2020)

1.7.2 Major Companies

Some leading companies competing in global biofuel market are (Table 1.3):

Some other major companies are:

- BTG International Ltd
- Cargill Incorporated
- DowDuPont, Inc.

Table 1.3 Some major companies manufacturing biofuel

Companies	Production (Gallons)	Fuel produced	Raw material used
Wilmar International Ltd	1,20,80,57,859	Biodiesel	Palm oil
Royal Dutch Shell PLC	66,04,30,000	Bioethanol	Corn, sugar
Renewable Energy Group (2020)	49,50,00,000	Biodiesel	Used cooking oil, waste oil, animal fats, plant oil
VERBIO Vereinigte BioEnergie AG	24,05,27,641	Biodiesel, Bioethanol, Biomethane	Rapeseed oil, palm oil, wheat straw, sugarcane and beet
Abengoa Bioenergy S.A.	19,43,46,537	Bioethanol, biodiesel, jet fuel	MSW (Municipal Solid Waste), fats and waste oil
POET, LLC	6,00,00,000	Bioethanol	Corn and cellulose

- Archer Daniels Midland Company
- My Eco Energy
- China Clean Energy Inc.

1.7.3 Their Core Competency

1. *Renewable Energy Group, Inc.:* REG believes in providing the society with right product at right time and place. They are providing cleaner fuel solutions for more than 20 years. They have 12 biobased diesel plants. The total production of 495 million gallons of biofuels in 2019 resulted in 4.2 million metric tonnes of carbon reduction which is equivalent to carbon dioxide removed by 5.5 million acres of forest in one year. The feedstocks they generally use are low carbon emitting like waste and by-products from fats and oils. The energy returned from the biofuels produced is 5.5 times the fossil used for production. The carbon emission is 50–90% lower (Renewable Energy Group 2020).
2. *Abengoa Bioenergy S.A.:* Abengoa is at the top of industry in energy sector, in terms of hybridization of technologies, construction of complex and value-added project. They have more than 280 patents under them. They convert municipal solid waste into jet fuel by gasification and synthesis process. They have presence in all the sub-continents. They produce more than 194 million gallons of biofuels per year that include biodiesel, bioethanol and Jet fuel. A biorefinery that will produce ten million gallons per year of jet fuel from solid urban waste is under construction (Abengoa 2020).
3. *Wilmar International Ltd.:* They have 14 biodiesel plants. 12 are located in Indonesia and 2 are in Malaysia. In 2020, Indonesia has expanded it biodiesel blending mandate from B20 to B30, that is 30% of diesel is biodiesel and 70% is from crude. Although due to low crude oil prices and reduced diesel consumption

due to COVID-19, Indonesia biodiesel consumption came down from 7.5 million MT to 7.2 million MT which is a 4% decline, affecting Wilmar's production and consumption. They produce Palm oil methyl ester which is used in biodiesel. Wilmar's biodiesel contains virtually zero sulphur, there they burn cleaner than traditional petroleum-based fuel (Wilmar International Limited 2020).

4. *POET LLC:* POET is a major producer of bioethanol in the USA. They produce bioethanol in 27 locations. They use dry mill process to produce bioethanol. The raw material used to produce bioethanol is either corn or cellulose. Corn is used in making starch-based bioethanol. Non-grain material/feedstock that provides the cellular structure for all plants is used in making cellular bioethanol. Their estimated annual revenue is 7.2 billion dollars (POET, LLC 2021a, b).
5. *Archer Daniels Midland Company:* ADM produces both biodiesel and ethanol. They have patented processes for production of biodiesel. The process is known as transesterification where vegetable oil is heated with alcohol in presence of catalyst to form mono-alkyl esters which are biodiesel. ADM has biodiesel production plant across the world in EU, Brazil, Canada and the USA. ADM also produces ethanol from corn through an efficient process which also produces animal feed and is partnering with institutes to produce biofuel sourced from cellulose (Stiefel and Dassori 2009).
6. *VERBIO Vereinigte BioEnergie AG:* Verbio is an independent manufacturer of biofuels including biodiesel, bioethanol and biomethane. Verbio is a German based company. They rely on raw materials which are not used for food production. They have a patent pending for a state-of-the-art biorefinery. They had the capacity utilization of 84.8% for biodiesel plant in 2019–2020 due to the increased demand from North America and increased greenhouse gas reduction quota from 4% to 6%. For ethanol, they had capacity utilization of 91% and the sales revenue also increased from 255 million euros (2018–2019) to 275 million euros (2019–2020). This increase in revenue, even when the sales volume almost remain unchanged is because of the high sales price in the pre-COVID period (Verbio 2020).
7. *My Eco Energy (MEE):* MEE is based in India which produced biodiesel marketed as Indizel. Indizel meets Indian and European standards. Indizel is an alternative to diesel having low emission and is compatible with all diesel engines. MEE has 8 fuel stations currently across India (My Eco Energy 2021).
8. *Royal Dutch Shell PLC:* Shell is a global group of companies with 87,000 employees in around 70 countries. They use advanced technology and innovative approach to build sustainable energy for future and developing fuels for transport such as bioethanol. In 2020, 2.5 billion litres of biofuel were formed by Shell. In February 2021, Raízen (JV in brazil) acquired Biosev, which will add to 50% of production capacity in low-carbon fuels. This will increase the production capacity to 3.75 billion litres (Shell 2020).

1.7.4 Supply Demand Gap

In 1990s, when the biofuel industry was at the very nascent stage, growth was stagnant. Consumption of biofuel was more than production. Major reasons of less production were no active government policies and high capital-intensive industry. Research and development in biofuel production from agricultural product was not significant. Large-scale production of biofuel was not considered an alternative source of oil and was not even advised to cover significant fraction of it (Giampietro et al. 1997).

But in the twenty-first century, industry started blooming exponentially. Both production and consumption increased from 200 KBoed to 1800 KBoed. Also, this time, production was more than consumption. This was due to the partial response to climate change; provision of government subsidy and minimal changes in retail distribution was required (Rajagopal et al. 2007).

Increasing the production of biofuel in the USA also affects the crude oil price globally. As USA is the major importer of crude oil, the shift in dependency on crude oil to biofuel will increase the supply of crude oil in the global market, thereby decreasing the price (Osborne 2007) (Figs. 1.7 and 1.8).

1.7.5 Porter's 5 Forces

1.7.5.1 Threat of New Entrant (Low)

As per Jones et al. (1978), The major barriers to biofuel industry are:

- Patent
- Large capital requirements
- Economies of scale
- Government's regulations
- Product differentiation
- Predatory behaviour by cartels
- Ownership of resources

Biofuel industry is at a very nascent stage. Still a lot of research and development is going on. All the major companies are having some patents regarding formula, processes and manufacturing. Patents drive the cost reduction and differentiation (Dos Santos et al. 1999).

1.7.5.2 Threat of Substitutes (High)

Crude oil is the major substitute for biofuel. Due to low price and easy availability, consumers generally prefer crude oil. As gasoline is a product of crude oil, the price

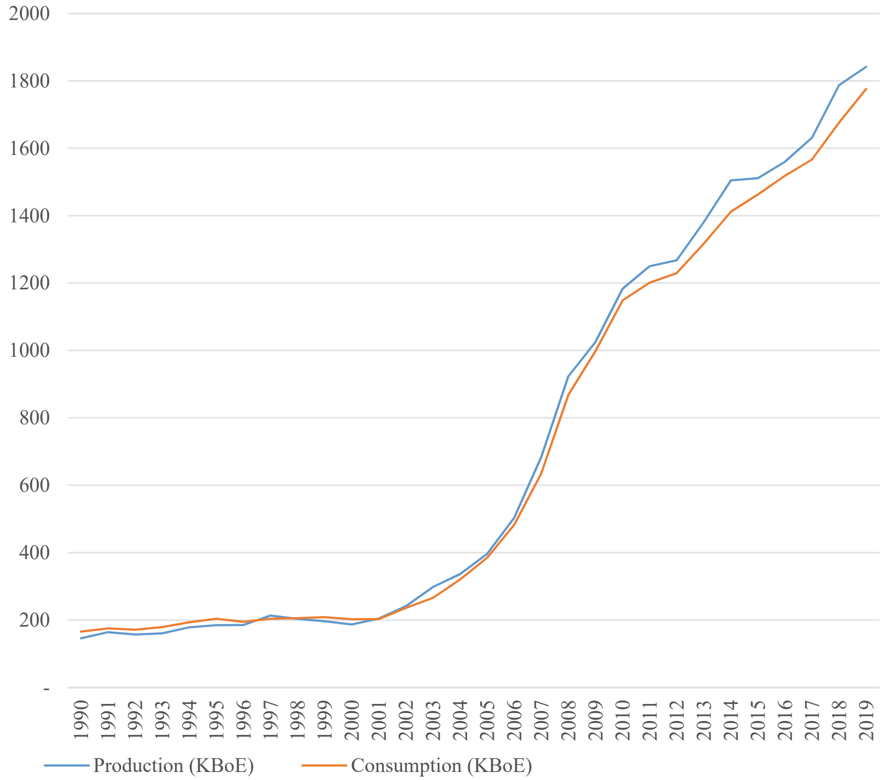

Fig. 1.7 Production vs. consumption of biofuels (Kboed) (Source: Bp plc 2020)

Fig. 1.8 Porter's 5 forces analysis—biofuel industry

of gasoline is driven by the price of crude oil. In 2005, ethanol prices fell below gasoline price. Major reason suggested was expansion in production of ethanol (Pokrivčák and Rajčaniová 2011).

1.7.5.3 Bargaining Power of Suppliers (Medium)

Providing residue to the biofuel manufacturer is an extra income for the farmers. However, excess residue from the agriculture field is made available for ethanol production only after soil conservation and local animal feed needs are fulfilled. Farmers only provide feedstock like corn only if price offered is high enough to compensate for the harvesting, storage and transport of the feedstock (Kumarappan et al. 2009).

1.7.5.4 Bargaining Power of Buyer (High)

Customers will easily switch to the non-renewable and traditional sources of energy as the cost of switching is really low (Indian Brand Equity Foundation 2017). In markets like Sweden where 70% of the biofuel is imported and rest is produced, buyers tend to compare quality and price with the imported one. Here, the buyers are distribution companies who sell to the end consumers. They buy large volumes, therefore for them quality and price are really important. Hence, bargaining power of buyer is high (Folea et al. 2010).

1.7.5.5 Competitors Rivalry

Industry itself is at its nascent stage, players are still establishing themselves in the market, the sector has still not reached the stage of competition. Therefore, competitive rivalry is low (Indian brand Equity Foundation. Renewable energy 2017). Bioethanol and biodiesel are highly standardized products and that is why it is very difficult for any company to introduce a new product and increase its portfolio. Any degree of rivalry can only happen if any company comes up with new producing technology such as cellulose-based bioethanol (Folea et al. 2010).

1.8 Major Challenges in Algal Biofuels Production from Wastewater

Algal biofuel is blooming due to high growth rates, high oil contents that have been a significant part in the capital to turn algae into biofuels. But to generate biofuels from algae, there are multiple procedures and it requires various steps such as where and how to grow algae, to improve the oil extraction and fuel processing. The major challenges include strain isolation, nutrient sourcing and utilization, production management, harvesting, coproduct development, fuel extraction, refining and residual biomass utilization (Saad et al. 2019).