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Potential of Microalgal Biodiesel: Challenges and Applications

Ashokkumar Veeramuthu and Chawalit Ngamcharussrivichai

Abstract

In the present scenario, rapid industrialization and urbanization have led to a dramatic increase in the levels of various hazardous pollutants in the environment, and this creates a serious threat to humankind. Today, most of the energy production comes from fossil fuel combustion, which is the key source of CO₂ emissions. Research studies show that the utilization of microalgae could be the best option for the production of renewable and sustainable energy and for the mitigation of CO₂ emission. Production of biofuels from microalgae can be classified as solid (biochar), liquid (bioethanol, biodiesel, bio-kerosene), and gaseous (biogas, bio-syngas, biohydrogen) fuels. Among these biofuels, bio-diesel garners a lot of interest and attention because of its high accumulation of lipids (20–75%), which could be a potential alternative fuel for diesel engines. Algal lipids usually have a higher viscosity than petro-diesel; therefore, the transesterification process is required to decrease the viscosity of microalgal lipids before they can be combusted in the engines. However, microalgae are considered as a potential resource in the current biofuel industries; still, it fails at the commercial level. Thus, in this book chapter, we have discussed the microalgal biofuel production and the challenges behind and the future prospects.

Keywords: microalgae, cultivation, biomass, biodiesel, challenges

1. Introduction

Today's scientific reports revealed that the world's commercial primary energy needs are mostly coming from fossil fuel sources. It is forecasted that the primary energy demand by 2035 will increase to 54% and still fossil fuels contribute 82% of the global need [1]. Besides, an increase in the world population and their anthropogenic activities, such as transportation, land use, deforestation, industrialization, waste generation, etc., has been changing the natural structure of the earth. These activities lead to severe global climate problems in the present scenario. A remarkable change in the lifestyle of human beings is also building extra pressure on the production market to fulfill the demands and desires of society.

Nevertheless, the recent production and consumption models mainly rely on fossil fuel resources, which are affecting the environment and natural resources adversely and irreversibly. It has been reported that the majority of the global CO₂ emissions are due to the transport sector and the number of light motor vehicles is estimated to increase to over 2 billion by 2050 [2]. Hence, to address the significant

issues such as energy depletion and hazardous gas emission, there is an urgent need for a substantial displacement of fossil fuel usage.

In this context, biofuels produced from biomass rather than fossil source are considered as a potential solution to address these challenges. Currently, researchers have been exploring various types of biofuel production such as solid (biochar), liquid (ethanol, vegetable oil, and biodiesel), and gaseous (biogas, bio-syngas, and biohydrogen), and they were categorized based on the type of feedstock used. It has been reported that the first-generation liquid biofuels which are produced using edible feedstock such as corn, soy-bean, sugarcane, and rapeseed have directly competed with food production. Meanwhile, food production is the other most critical challenge to society [3]. The second-generation biofuel production has been developed using the nonedible feedstock such as *Jatropha*, *Switchgrass*, etc.; however, these nonedible feedstocks also compete with food production [4]. Mainly the second-generation biofuel production relies on arable land, freshwater, and nutrients for their cultivation.

Therefore, to solve these critical issues, researchers have explored a third and fourth generation of biofuels using microalgae and macroalgae (third generation) and metabolic engineering of photosynthetic organisms to produce biofuels (fourth generation) [5]. In this regard, algae have received considerable attention in recent years because of their robust growth and potential to accumulate a high amount of lipid, carbohydrate, and protein, and these can be easily converted into various biofuels (biodiesel, bioethanol, and biogas). **Table 1** shows the potential applications of microalgal species for biodiesel production compared with other biomass sources. Besides, microalgae are the potential candidate for CO₂ sequestration, self-purification, and effective land utilization with high environmental benefits. Also, the cultivation and utilization of microalgae do not compete with food production for land, freshwater, and nutrient sources. Many studies have reported that microalgae offer a wide variety of bioproducts that can be utilized by various sectors, such as energy (biodiesel, biohydrogen, and bioethanol), pharmaceuticals, nutraceuticals, and feed and food supplements [6]. In the past few years, a large number of research work have been focused on microalgae for the potential biofuel production.

Feedstocks	Lipid content (% dry weight basis)	Biodiesel productivity (tons/year/ha)
Corn/maize (<i>Zea mays</i>)	44	0.152
Hemp (<i>Cannabis sativa</i>)	33	0.321
Soybean (<i>Glycine max</i>)	18	0.562
Jatropha (<i>Jatropha curcas</i>)	28	0.656
Camelina (<i>Camelina sativa</i>)	42	0.809
Canola/rapeseed (<i>Brassica napus</i>)	41	0.862
Sunflower (<i>Helianthus annuus</i>)	40	0.946
Castor (<i>Ricinus communis</i>)	48	0.156
Palm oil (<i>Elaeis guineensis</i>)	36	4.747
Microalgae (low lipid-yielding strains)	30	51.927
Microalgae (high lipid-yielding strains)	70	12.110

Table 1.
Lipid and biodiesel productivity of various feedstocks [7].

Nevertheless, the life cycle and techno-economic analysis have revealed that the biofuels derived from microalgae are not cost-competitive in comparison with conventional petrochemical fuels. Mostly 70% of the cost will be invested for cultivation and biomass harvesting [8]. However, a possible way to reduce the cost is to integrate the microalgal cultivation system with wastewater treatment. Generally, wastewater is rich in nutrients and other bioresources. It was reported that wastewater can produce 6.5 MJ/kL of energy, which constitutes 1% of the total world energy [9].

The nutrients presenting in the form of carbon, nitrogen, and phosphorous can be turned into an economic opportunity by feeding them to microalgae [10]. Microalgae can utilize the organic carbon in wastewater and tailor it into biomass. The use of wastewater for microalgal cultivation in mixotrophy and heterotrophy cultivation mode can balance the respiratory losses, improve energy budget, and give a boost to the biomass productivity. Earlier reports have shown that the utilization of nutrients and water from wastewater and industrial flue gas (CO₂) helps to decrease the cost and makes the algal biofuels commercially viable [11]. In addition, the recovery of other value-added bioproducts, rare earth metals, etc. can compensate for the cost involved during algal cultivation. Besides, the wastewater used for algal cultivation does not require any additional treatment to meet the ecological and environmental regulations. Therefore, the utilization of a large quantity of wastewater for microalgal cultivation could promote waste-free, carbon-neutral, and environmentally sustainable technology.

The previous studies have explored that the microalgal species, such as *Botryococcus braunii*, *Scenedesmus obliquus*, *Chlorella vulgaris*, *Chlamydomonas reinhardtii*, and *Nannochloropsis oculata*, are recognized as promising species for biofuel production [12, 13]. Nevertheless, the biofuels produced from highly potential microalgal feedstock need a powerful downstream processing technology. This book chapter is aimed to provide knowledge about the latest research and development of microalga-based biofuel and its challenges.

2. Microalgae and growth condition

Microalgae are simple microscopic heterotrophic or autotrophic photosynthetic organisms, and these organisms are also named phytoplankton. Generally, they are found in fresh, marine, and brackish water, and they utilize photonic energy (light sources), carbon dioxide (CO₂), and water for their growth. Microalgae are classified as green algae (Chlorophyceae), blue-green algae (Cyanophyceae), red algae (Rhodophyceae), brown algae (Phaeophyceae), and diatoms (Bacillariophyceae). The microalgal growth contains five different phases: (1) lag phase, initial growth period, where the microalgae take time to adapt themselves into a new environment; (2) log/exponential phase, here rapid cell division occurs, and growth is faster; (3) decline phase, this phase contains limiting cell division; (4) stationary phase, the cell density of microalgae is stable because of the limiting factors; and (5) death phase, in this stage almost the cell growth is stopped due to lack of nutrients. Besides, microalgae are easy to be cultivated because they can tolerate a broad range of pH, salinity, and temperature. Some researchers have reported that a lipid content of microalgae is usually between 20 and 50% on a dry weight basis [14], whereas in some microalgal species (e.g., *Botryococcus braunii*), the lipid production can be reached up to 75% on a dry weight basis. Microalgae are not only a good source of lipids, it is also a vital source of producing the bioproducts, such as polysaccharides, pigments, proteins, vitamins, bioactive compounds, and antioxidants.

2.1 Microalgal cultivation methods

Generally, according to the growth nutrient modes, the microalgal cultivation can be divided into three categories, which are autotrophic, heterotrophic, and mixotrophic cultivation. In autotrophic mode, the inorganic carbon and light/solar are the primary sources of energy for microalgal growth. The heterotrophic cultivation mode mainly uses organic carbon and energy from the Krebs cycle. On the other hand, in mixotrophic cultivation mode, the carbon sources for microalgal growth can be supplied by both inorganic and organic forms.

2.2 Large-scale microalgal cultivation and biomass production

In microalgal cultivation, large-scale biomass production can be performed by two major methods, such as open raceway and closed photobioreactor (PBR). The open pond is the traditionally used system for large cultivation of microalgal species, which is economically superior in comparison to PBR. In an open cultivation system, the sunlight and atmospheric CO₂ are used as sources for carbon production to achieve higher biomass productivities. On the other hand, the PBR method is suitable for axenic cultures, and this type of cultivation is widely used for the production of high value-added bioproducts (e.g., pharmaceuticals). Basically, an open raceway pond cultivation system consists of a simple water tank or bigger earthen pond in which the nutrients are added from outsourcing. Besides, the open pond is usually designed in a raceway or track configuration attached with paddle wheel to provide circulation and mixing of the algal cells and growth nutrients. The low-cost open raceway pond is typically made from poured concrete, or they are dug into the earth and lined with a plastic liner to avoid the groundwater. The growth medium is added in front of the paddle wheel for proper mixing and absorption.

PBR is the most common system used for the closed cultivation method. It is designed based on several basic features, including liquid circulation, illumination surface area, and gas exchange to supply CO₂ to PBR [15]. Generally, researchers use the PBR cultivation method for the production of high biomass with a controlled environment and to avoid contamination. This type of cultivation makes it easier to optimize the biomass productivity of selected algal species. Usually, PBR is designed by using glass or plastic, coupled with a gas exchanger to pass the nutrients and CO₂. This system contains an airlift pump usually used to circulate the microalgal culture grown in PBR, which helps to keep the culture in suspension state and improve the CO₂ dissolution. Researchers have identified various types of PBR design, such as polyethylene bags, glass fiber cylinder, tubular inclined, segmented glass plate, flat modular photobioreactor, and annular photobioreactor. In the PBR cultivation method, several studies have been carried out on catalyst improvement, shaping of the PBR, controlling environmental parameters, and axenic culture. During the cultivation period, the operational parameters, such as pH, temperature, and gas diffusion, are a crucial issue, and it should be adequately addressed in PBR [11].

Some studies have been performed to recycle the nutrients from wastewater sources, which is considered as a step-in treatment of industrial wastewater using microalgal species. As the world's population continuously increases day by day, wastewater discharge also increased. Thus, the utilization of this harmful wastewater as a source of microalgal growth nutrients is highly recommended for the environmentally friendly high production of biomass and lipid. Nevertheless, to make microalgal biodiesel production at commercial scale, an integrated biorefinery approach of wastewater utilization will strongly influence the future sustainability

by addressing high-energy production, reducing greenhouse gas (GHG) emission, and lowering the production cost.

2.3 Harvesting technologies

Generally, two types of cultivation techniques are followed, i.e., batch and semi-continuous or continuous cultivation mode. During the cultivation period, biomass will be harvested and processed. It has been reported that the biomass harvesting accounts for approximately 20 and 30% of the total cost of microalgal downstream processes [16]. Therefore, the harvesting cost is one of the major hurdles, which makes the algal cultivation unsuccessful at commercial scale. Hence, many researchers are finding more effective techniques for microalgal cell harvesting to overcome this issue. The microalgal harvesting process is expensive and energy-consuming because the density of algal cells in the culture medium is generally low and most of the microalgal cells carry a negative charge, which makes the cells in a suspension state. To achieve a maximum biomass production during the harvesting process, researchers explored several types of harvesting methods, such as filtration, centrifugation, sedimentation ultrasound, and floatation [14]. Nevertheless, these methods are not as efficient as flocculation because of their high cost and lower efficiency. The flocculation harvesting method is much more comfortable, with higher efficiency, than other methods; however, still, a lot of challenges are needed to be addressed. On the other hand, the harvesting of microalgal biomass using flocculants can contaminate the slurry concentrate; thus, it reduces the algal biomass market value, lipid conversion into biodiesel via transesterification process, and the application of this biomass for food industry and animal feeds. Therefore, the feasible way to minimize harvesting costs is only by improving the harvesting technologies. Besides, the suitable method for biomass harvesting mostly depends on the algal species.

2.4 Microalgal biomass and biodiesel production

The lipid accumulation differs from species to species; besides, it depends on the algal cultivation methods. It has been reported that the microalgal species, such as *Dunaliella*, *Chlorella*, *Isochrysis*, *Nannochloris*, *Scenedesmus*, *Tetraselmis*, and *Nannochloropsis*, accumulate the average lipid content of 15–60% on a dry weight basis (Table 2). Due to their relatively high lipid accumulation, the microalgal species are considered as a promising feedstock for biodiesel production [17]. The lipids obtained from microalgae are chemically similar to the conventional vegetable oils and so have been considered as a promising source for biodiesel [18]. The microalgal triglycerides can easily be converted into biodiesel, which is renewable, biodegradable, and environmentally friendly when compared to fossil fuel sources [19]. Besides, the microalga-derived biodiesel has a higher heating value (HHV) of 39–41 MJ/kg; thus, it is considered as a potential alternative for displacement of liquid transport fuels derived from petroleum crude [20]. Generally, microalgae produce a high level of triacylglycerols (TAG), which are accumulated in the plastids or found in the cytoplasm in the form of lipid bodies. It was observed that in algal species, during cultivation, the nitrogen starvation and other stressful situations, such as salinity, temperature, CO₂ concentration, and light intensity, stimulate the lipid biosynthesis, resulting in an enhanced lipid production [21, 22]. A study reported that the microalga *Haematococcus pluvialis* produces a high amount of neutral lipids when it is under a stressful environment (i.e., high light intensity and nitrogen starvation) [23].

Division	Microalgae	Volumetric productivity of biomass (g/L/day)	Lipid content (% dry weight biomass)
Freshwater microalgae			
Green microalgae	<i>Ankistrodesmus</i> sp.	—	24–31
	<i>Botryococcus braunii</i>	0.02	20–75
	<i>Chlorella emersonii</i>	0.036	25–63
	<i>Chlorella protothecoides</i>	2	14–57
	<i>Chlorella sorokiniana</i>	0.23–1.7	19–22
	<i>Chlorella vulgaris</i>	0.02–0.2	5–58
	<i>Chlorella pyrenoidosa</i>	2.9	2
	<i>Neochloris</i>	29–65	—
	<i>Chlorococcum</i> sp.	0.28	19.3
	<i>Haematococcus pluvialis</i>	0.06	25
	<i>Scenedesmus obliquus</i>	0.74	11–55
	<i>Scenedesmus quadricauda</i>	0.19	1.9–18
	<i>Scenedesmus</i> sp.	0.26	19–21
Blue-green microalgae	<i>Spirulina platensis</i>	0.6–4	4–16
	<i>Spirulina maxima</i>	0.21–0.25	4–9
Red microalgae	<i>Porphyridium cruentum</i>	0.36–1.5	9–18.8
Marine microalgae			
Green microalgae	<i>Dunaliella salina</i>	0.22–0.34	6–25
	<i>Dunaliella primolecta</i>	0.09	23
	<i>Dunaliella tertiolecta</i>	0.12	16.7–70
	<i>Nannochloropsis</i> sp.	0.17–1.4	12–53
	<i>Tetraselmis suecica</i>	0.12–32	8.5–23
	<i>Tetraselmis</i> sp.	0.3	12.6–14.7
	<i>Pavlova salina</i>	0.16	30.9
	<i>Pavlova lutheri</i>	0.14	35.4
	<i>Isochrysis</i> sp.	0.08–0.17	7.1–33
	Diatoms		
	<i>Nitzschia</i> sp.	—	16–47
	<i>Skeletonema</i> sp.	0.9	13.3–31
	<i>Skeletonema costatum</i>	0.8	13.5–51

Table 2.
Microalgal species and its productivity [25].

Thus, the microalgae accumulate a higher amount of lipids, especially TAG, which enhance a potential production of biodiesel. In microalgae, however, the biomass and lipid production plays a crucial role in biodiesel production at commercial scale; the quality of the lipids depends on algal species which greatly influences the biodiesel property. Nascimento et al. [24] investigated 12 algal species for potential biodiesel production, and results revealed that *Chlorella* and *Botryococcus* species accumulated high-level lipid content, which can be easily converted into biodiesel.

Some studies showed that the biodiesel obtained from the microalgae *Scenedesmus obliquus* and *Chlamydomonas* sp. contains a high level of saturated fatty acids (SFA) and has the highest cetane number (CN) of 63 along with enhanced oxidation stability. The lipids of some microalgal species, such as *Ankistrodesmus fusiformis*, *Kirchneriella lunaris*, *Ankistrodesmus falcatus*, and *Chlamydocapsa bacillus*, are rich in polyunsaturated fatty acids (PUFA), and the obtained biodiesel has low oxidation stability, high iodine value (IV), and low CN (42.5). The microalgal lipids with a high content of SFA and monounsaturated fatty acids (MUFA) give biodiesel with improved quality. Besides, the CN value is significantly correlated with a ratio of SFA to PUFA, which can be used to evaluate the delay between compression and ignition. Mostly, the algal biodiesel has higher CN value than that of the fossil fuels, which helps to shorten the delay in the ignition and complete combustion of the algal biodiesel.

An earlier study has reported that *Amphora* sp., a marine and freshwater diatom, produces a significant amount of MUFA, which can be considered as a potential feedstock to produce high-quality biodiesel [26]. Among several algal strains, such as *Phormidium* sp., *S. obliquus*, *C. vulgaris*, and *Dunaliella tertiolecta*, grown in a bubble PBR for biodiesel production, *Chlorella vulgaris* produces a significant amount of biomass and lipid. Besides, it is considered as the best choice for CO₂ sequestration at a rate of 17.8 mgL⁻¹min⁻¹. In addition, the alga *Chlorella vulgaris* biodiesel meets the ASTM 675 and EN 14214 standards because the lipids of these strains are rich in SFA of 43.5% and MUFA of 41.5% [27]. The microalga *Scenedesmus abundans* lipid is a rich source of MUFA (76%), which enhances the quality of resulting biodiesel to meet the European biodiesel standard (EN 14214), South African standard (SANS1935), and Germany's standard (DIN 51606) [28]. Some recent studies investigated different microalgal groups, such as green algae *Chlorella* sp., *Scenedesmus* sp., and *Selenastrum* sp.; red algae *Batrachospermum* sp.; diatoms *Navicula* sp. and *Phaeodactylum* sp.; and blue-green algal species (*Lyngbya* sp., *Isochrysis* sp., and *Prymnesiophytes* sp.), and observed that *Scenedesmus* sp., *Chlorella* sp., and *Isochrysis* sp. produce a significant amount of lipids, which are considered as a promising feedstock for biodiesel production [29]. A previous study isolated 96 microalgal strains from Singapore coastal area, which was then well screened for growth, biomass, and lipid productivity. The results revealed that the marine microalga *Nannochloropsis* sp. was found to be the most promising biomass material for biodiesel production because of its high lipid accumulation of 45% on a dry weight basis [29]. Islam et al. [30] investigated several microalgal species, such as *Ankistrodesmus* sp., *Botryococcus* sp., *Chlorella* sp., *Chlamydomonas* sp., *Coelastrum* sp., *Desmodesmus* sp., and *Scenedesmus* sp., for biodiesel production. The author observed that *Botryococcus* sp. produced a high lipid yield and the quality of the resulting biodiesel met the ASTM 6751-02 and EN 14214 standards. The quality of biodiesel obtained from different microalgal species, such as *Nannochloropsis* sp., *Scenedesmus* sp., and *Dinoflagellate*, was explored [31]. The biodiesel properties included density, kinematic viscosity, acid value, phosphorous content, sulfated ash content, and sulfur content, according to the Chinese National Standards (CNS). The results showed that the biodiesel characteristics were almost in the same range as fossil oil; nevertheless, the oxidative stability of those microalgal biodiesel was lower than that of the CNS standard. Also, they demonstrated that the oxidative stability of microalga-derived biodiesel could be improved by hydrogenation catalyzed over carbon-supported palladium (Pd/C). Some researchers reported that the microalga *Botryococcus* sp. produces lower biomass yield and higher lipid productivity, up to 75% on a dry weight basis, than other microalgal species, such as *Nannochloropsis* sp., *Nitzschia* sp., *Neochloris* sp., *Porphyridium* sp., *Dunaliella* sp., *Isochrysis*, and *Chlorella* sp., with a lipid content ranging from 20 to 50% but appropriate biomass yield.

3. Current challenges in microalgal biofuels

In the present scenario, rapid population growth and extensive fossil fuel usage increase the energy demand and significant environmental-related problems, which lead to global warming. Therefore, researchers have seriously searched for an alternative and sustainable solution to overcome those issues. In this context, microalgae are considered a promising candidate for an alternative fuel source and an excellent option for cleansing the environment. The previous studies have shown that the cost of biodiesel produced from microalgae is estimated at \$20.53 and \$9.84 per gallon using a PBR and open raceway pond cultivation method, respectively. This shows that microalgal biodiesel is a promising avenue for sustainable energy production. From the literature survey, it is clearly noted that even though several microalgal species are available for biodiesel production, only a few algal species are considered as the best choice because of its quality and quantity of lipid accumulation. Raja et al. [32] reported that, on earth, more than 25,000 microalgal species are available; however, only a few species are in use.

At present, the utilization of microalgae as a feedstock for the production of bioenergy and bioproducts still faces a lot of limitations and challenges, and we must be addressing these issues by improving the technologies from laboratory scale to commercial scale. The most critical problems are to improve the algal biomass productivity, dewatering and biomass productivity, pretreatment and extraction, and biodiesel production. Despite several advanced technologies are available for a large-scale biomass production and lipid conversion into biodiesel, still, microalgal biodiesel is too costly since the cultivation system design requires temperature and growth limiting condition control (viz., CO₂, water sources, nutrient source, and optimization). The other most crucial obstacle is biomass dewatering because this process is energy-intensive and so costly.

Generally, in a large-scale algal cultivation, the closed PBR system is more expensive than the open raceway ponds. The PBR system also faces major operating challenges, such as overheating and fouling, due to gas exchange limitation. In microalgal cultivation, open ponds, especially mixed raceway ponds, are much cheaper to be built and operated and are easily scaled up to several hectares, which make them the right choice for commercial-scale biomass production. About 95% of commercial microalgal biomass production is performed using open raceway ponds even for high value-added bioproducts, which sell for prices over a hundred/thousand dollars. Nevertheless, the open cultivation methods meet several limitations, mainly due to contaminations by other microalgal species, algal grazers, fungi, amoeba, etc., and temperature. A literature survey revealed that though hundreds of research papers were published, still now, no proper information is available on cultivation designs, operations, yields, and other important aspects at the commercial level [33]. A major bottleneck in microalgal biofuel production is the high capital and operating costs. However, several research studies have focused on microalga-based biofuels, still, there is a vast technological gap that was found during commercialization. In a large-scale biomass production, there is a large demand for water, CO₂, nitrogen, and phosphorous, which is believed as another major hurdle. The wastewater can be utilized as a source of nutrients; nonetheless, there is a serious concern on contamination by bacteria, pathogens, and chemical compounds presenting in wastewater. Earlier studies reported that 0.16 kg of nitrogen and 0.022 kg of phosphorous are required for producing 1 liter of algal oil [34]. Besides, for producing 1-liter algal oil, the microalgae need 3.5–9.3 kg of CO₂, which implies that algae utilize a large amount of CO₂ for its growth and biomass production.

Another major challenge is algal lipid extraction prior to biodiesel production. In this part, after biomass drying, the lipid extraction using expensive solvents

significantly increases the production cost. Many researchers are searching for significantly advanced technologies without drying or solvent extraction of the algal slurry in order to reduce the biomass pretreatment cost.

The biodiesel production based on current methods is expensive since it requires neat lipid feedstock, free from free fatty acids (FFA), and water. For this kind of extraction technique, the biomass must be dried; however, biomass drying is another important process, and it requires a higher cost. To reduce the FFA content of lipid feedstock, the esterification process is carried out via either acidic or enzymatic route; however, this process is still at the research stage. The esterification through the enzymatic process using lipases may be considered as the best choice because it has added advantage of running even at low temperatures. Nonetheless, the primary issue in this method is glycerol formed as a by-product, which can inhibit the lipase activity. Some researchers demonstrated that using methyl acetate, as a substrate instead of methanol, avoids glycerol formation and lipase inhibition since triacetin is generated as a by-product [35].

3.1 Microalgal biofuels and future prospects

It has been reported that the current costs in biofuel produced from microalgal biomass are approximately estimated up to 50 \$/L, and thus this makes algal biofuel unsuccessful at commercial scale [36]. Nevertheless, to reduce the cost and make the algal biofuel production at commercial success, research works are still ongoing. However, the most promising and sustainable way for biofuel production is to reduce the cultivation cost, particularly growth nutrient cost. The utilization of wastewater for large-scale cultivation of algal biomass is attracted between the researchers. It is possible to grow the algae at zero nutrient cost using wastewater obtained from various sources, such as industrial, municipal, and agricultural [17]. Recent researchers are extensively investigating an integrated biorefinery concept for producing the algal biomass at zero nutrient cost; besides, it is a possible way for treating the wastewater using zero-cost technology. Some studies focused on commercial interests in a large-scale microalgal culturing using coal-fired power plants or sewage treatment facilities. This approach not only provides the raw materials for the system, such as CO₂ and nutrients; besides it also produces valuable biofuels with a cleansed environment (**Figure 1**). Today, the price of crude oil is lower, so the biodiesel produced from microalgae is economically uncompetitive with fossil diesel [33]. From the above study, it clearly shows that low-cost biomass production

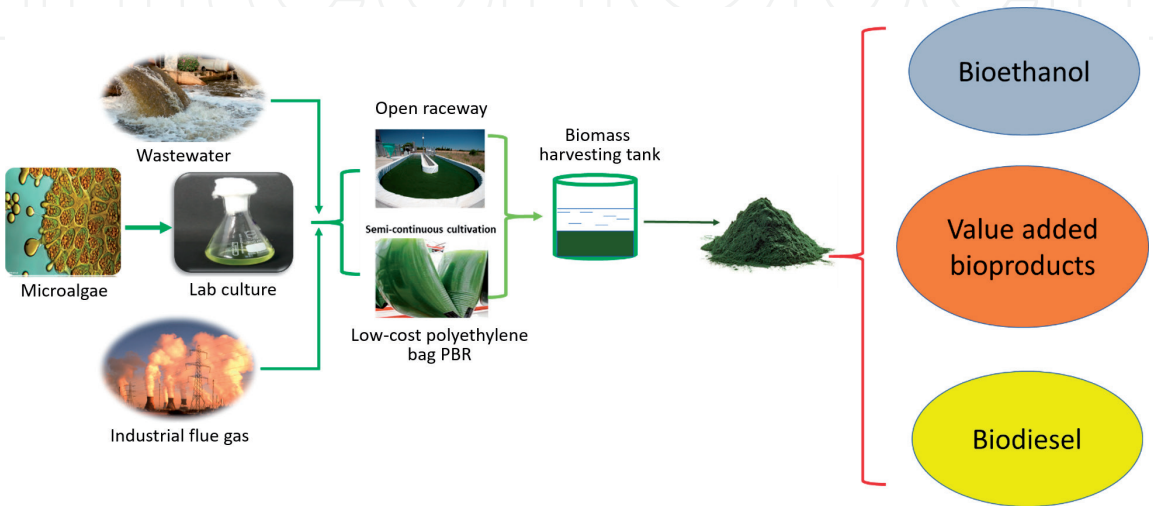


Figure 1.
Integrated microalgal biorefinery approach.

is a key issue towards the commercial production of algal biodiesel. Research efforts have been devoted to address the following problems: (1) to enhance the photosynthesis efficiency, biomass, and lipid production through genetic and metabolic engineering; (2) using high-efficient and low-cost biomass production system (open raceway pond or low-cost designed PBR); (3) cultivation mode (batch or semicontinuous); (4) utilization of wastewater and industrial flue gas in algal cultivation; (5) introducing novel microalgal harvesting methods; and (6) implementing low-cost with high-efficient oil extraction and transesterification methods (e.g., simultaneous oil extraction and transesterification, using novel heterogeneous acid catalysts, etc.).

4. Conclusion

Today, microalgae offer interesting characteristic features to qualify them as promising alternative feedstocks for various industrial and environmental applications. Nevertheless, many efforts are required to address different challenges particularly on low cost with high-efficiency biofuels, wastewater treatment, and CO₂ mitigation. Based on the research data available, it is clearly found that so far, microalgal biodiesel production is mainly stuck in a cost factor. It is clearly noticed that zero nutrient cost technology for biomass production, inexpensive large-scale harvesting, and biodiesel conversion process are yet to be improved through a detailed investigation. In this point of view, this review shows a clear outlook on algal cultivation for biofuel production and what are the challenges behind with future prospects. The production of microalgal biofuel at commercial scale can play a key role in the present global energy scenario and concern towards the related environmental issues. Researchers believe that microalgal as a third-generation candidate will be satiating the energy demand and its challenges in the future. The paramount challenges in algal biodiesel production are cultivation and harvesting techniques, and the limitations with an emphasis on the cost factor are discussed. Therefore, establishing a new and innovative biorefinery-based low-cost technology should be developed to overcome these problems. Recently, the microalga-based biorefinery is the emerging technology, which is aiming to address the above severe issues and make the algal biofuels sustainable and alternative. Besides, it helps wastewater treatment at zero-cost technology, CO₂ mitigation, and attractive value-added bioproducts. These economic processes could be improved by adapting various cost-cutting activities, such as utilizing wastewater and industrial flue gas as nutrient and carbon sources, respectively. Finally, the microalga-based biorefinery process seems to be the most feasible approach in the forthcoming years to compete with fossil fuels and to develop a sustainable and renewable bioenergy source.

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Author details

Ashokkumar Veeramuthu¹ and Chawalit Ngamcharussrivichai^{1,2*}

1 Center of Excellence in Catalysis for Bioenergy and Renewable Chemicals (CBRC), Faculty of Science, Chulalongkorn University, Bangkok, Thailand

2 Center of Excellence on Petrochemical and Materials Technology (PETROMAT), Chulalongkorn University, Bangkok, Thailand

*Address all correspondence to: chawalit.ng@chula.ac.th

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