Techno-Economic Analysis of Biodiesel Production from Microalgae: A Review

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The development of the microalgae-based biodiesel technology has become a hot research topic in the bioenergy field in recent years. Presently, the technical possibility of the conversion of microalgae to biodiesel has been confirmed at the laboratory scale. The fundamental issues impeding the industrialization of microalgae-based biodiesel include the high cost of production and the lack of research on the scaling-up technology. In this paper, the technical challenges and economic aspects of biodiesel production from microalgae were analyzed. It was found that the production cost of microalgae-based biodiesel mainly come from three processes: microalgae cultivation, harvest, and lipid extraction, among which microalgae cultivation represented the highest cost. Finally, the prospect of the industrialization of the microalgae-based biodiesel was proposed.

Keywords: Microalgae; Biodiesel; Technical challenges; Economic Analysis; Cultivation; Harvest; Lipid extraction

1. Introduction

Environmental pollution and energy shortages have become important issues that restrict the sustainable development of the world economy. Biodiesel as a green and renewable energy has received more attention. Biodiesel consists of long chain fatty acid methyl esters or ethyl esters, which are produced by esterification or transesterification reaction with animal fats and vegetable oils [1]. Biodiesel is free of sulfur and aromatics components, and used as an additive of diesel fuels that can significantly reduce the sulfur oxides, hydrocarbons, nitrogen oxides, and other pollutant emissions [2]. As a new type of renewable energy, a major problem restricting its development is the serious shortage of feedstock. Currently, biodiesel made from vegetable oils and animal fats can fulfil about 3% of the required diesel fuel, and the increasing use of these feedstock for biodiesel production may result in world food supply problems [3].

Microalgae is the most widely distributed and the largest species in nature, representing a large quantity of biomass resource. Compared to other biomass, microalgae have the advantages of high photosynthetic efficiency, short growth period, high biomass yield, no need for arable land, high efficiency of carbon fixation, high oil content, and environmental friendly resource. It is considered as one of the ideal feedstock for biodiesel production [4].

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2. Production Process of Biodiesel from Microalgae

The production process of microalgae-based biodiesel mainly includes four steps, namely microalgae culture, harvest, oil extraction, and esterification as shown in Figure 1. There are several different process routes to choose for each step in this production process. In order to establish an industrial technology route, it is necessary to study the key technical issues in each step. The existing production processes of microalgae-based biodiesel require high cost and show low production efficiency. Some of the bottlenecks have seriously restricted the development of industrialization. Currently, the microalgae industry is small in scale, and research and development are required.

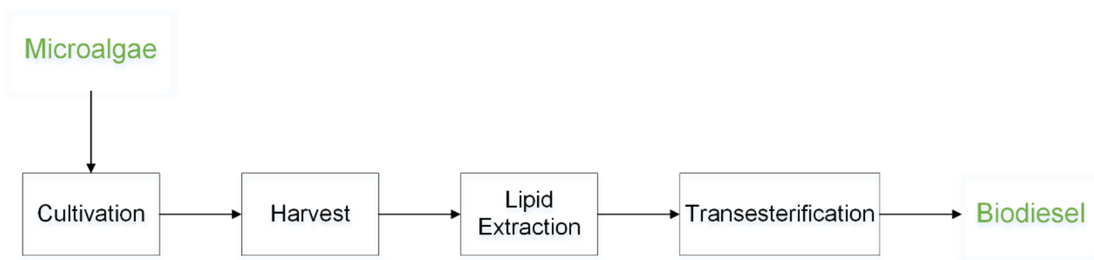

Figure 1. Production process of biodiesel using microalgae

2.1 Microalgae cultivation

Microalgae such as *Prymnesiophytes* (Class *Prymnesiophyceae*), *Eustigmatophytes* (Class *Eustigmatophyceae*), diatoms (Class *Bacillariophyceae*), green algae (Class *Chlorophyceae*), goldenbrown algae (Class *Chrysophyceae*) and blue-green algae (Class *Cyanophyceae*) have shown the potential to accumulate high levels of polyunsaturated fatty acids (also known as microalgal lipids or microalgal oils). Table 1 summarizes the lipid content and the biomass yield of some typical microalgal species.

Microalgal lipids are similar to vegetable oils, which can be used as a substitute of vegetable oils for biodiesel production or even cooking [5]. At present, there are a lot of studies on utilization of microalgal lipids, and reported microalgal species include *Chlorella* sp., *Isochrysis galbana*, diatoms, and *Scenedesmus.* These microalgae perform photosynthesis using water, carbon dioxide, and simple inorganic elements with the sunlight as the energy source. The resulting lipids can be converted into biodiesel (fatty acid methyl ester or ethyl ester) via esterification. Microalgal residues after lipid extraction can be used for production of animal feed, organic fertilizer, and methane.

The amount of lipids accumulated in microalgal cells is closely related to the cultivation conditions. Adequate carbon sources and other nutrient deficiencies are an induction factor in production of a higher lipid content. Generally, microbial production of lipids can be divided into two stages, namely, cell proliferation and lipid accumulation period. Different carbon-nitrogen ratios can be applied for these two stages. The role of nitrogen source is to promote cell growth. The low carbon and nitrogen ratio during the first stage is favorable for biomass production, while lipid-producing stage requires a high carbon to nitrogen ratio [6]. The effect of temperature on the accumulation of lipids is various among different microalgal species. The light intensity is one of the important factors that affect the growth and biochemical composition of microalgae. In general, a low light intensity can induce synthesis of polar lipids, while a high light intensity can lead to accumulation of neutral lipids [7].

The way that was used to grow microalgae is another key factor affecting the rate of microalgal biomass synthesis. The growth modes of microalgae include autotrophic, heterotrophic, and mixotrophic. Autotrophic is the most common way of microalgal growth. Different microalgal species have very different lipid contents during autotrophition. Generally, the lipid content of algal cells can be improved by reducing either nitrogen source or other nutrient elements in the culture medium. However, due to the need of adequate light, the cell density of autotrophic algae is relatively low. The cell density is even lower under nutrient deficiencies and nutritional stress, which greatly reduces the efficiency of microalgae production and make harvest more difficult [8].

Heterotrophic cultivation of microalgae is generally carried out using traditional fermentation equipment, in which microalgae are not affected by environmental conditions and grow fast without light. This method can shorten the culture cycle, and reduce the cost of harvest. However, some scholars believe that heterotrophic culture of microalgae will discharge CO_2, instead of fixing it [9]. The need of additional organic carbon sources rises the cultivation cost. The autotrophic feature of microalgae is lost, but the ability of lipid production still cannot compete with oleaginous microorganisms.

Mixotrophic grown microalgae obtain energy mainly via photosynthesis, but the external organic carbons and CO_2 are also necessary. This culture condition reduces the release of CO_2, but the microalgae lipid content and cell density are not significantly improved. So, this method is not extensively applied.

Table 1. Lipid content and yield of some microalgal species [8]

Microalgal species	Growth condition	Lipid content (wt% of cell dry weight)	Growth rate (g/(L·d))	Lipid production rate (mg/(L·d))
Chlorella protothecoides CCAP 211/8D	Autotrophic	11.0~23.0	0.002~0.02	0.2~5.4
Chlorella protothecoides	Heterotrophic	50.3~57.8	2.2~7.4	1209.6~3701.1
Chlorella protothecoides	Mixotrophic	58.4	23.9	11800
Chlorella vulgaris #259	Autotrophic	33.0~38.0	0.01	4.0
Chlorella vulgaris #259	Mixotrophic	21.0~34.0	0.09~0.25	22.0~54.0
Dunaliella tertiolecta ATCC 30929	Autotrophic	60.6~67.8	0.10	60.6~69.8
Isochrysis sp. F&M-M37	Autotrophic	27.4	0.14	37.8
Nannochloropsis oculata NCTU-3	Autotrophic	22.7~29,7	0.37~0.48	84.0~142.0
Pavlova lutheri CS 182	Autotrophic	35.5	0.14	50.2
Scenedesmus sp. DM	Autotrophic	21.1	0.26	53.9

The autotrophic culture system for microalgae can be divided into two categories: outdoor open pond and closed photobioreactor. Table 2 summarizes the properties of open ponds and enclosed photobioreactors. Open ponds may adopt one of the raceway type, round pool, and slope type designs. Closed photobioreactor designs can be columns, tubes, plates, and some other special types [10]. The raceway pond is the most important culture system for commercial cultivation of microalgae. The system is generally a shallow pool with 15-30 cm depth and natural light as the light source and the heat source. The rotation of the impeller(s) mixes the culture medium, prevents algae precipitation, and improves the light utilization. Air or CO_2 gas may be pumped into the system via bubbling or airlift stirring. The raceway pond can be covered with a transparent film that can prevent pollution and reduce water evaporation.

Table 2. Properties of open ponds and enclosed photobioreactors [10]

Cultivation system	Advantages	Disadvantages
Open pond	Low construction cost, low operation cost, ease to clean, mature technology, ease to scale-up	Need large area, ease to be contaminated, hardly to grow monoculture, low biomass yield, water evaporation, difficulty of harvesting, affected by environmental conditions, hardly to supply extra CO_2.
Closed photobioreactor	Grow monoculture, low possibility of contamination, high biomass yield, ease to harvest, low water evaporation, ease to control, hardly affected by the environment	High construction cost and operation cost, forming biofilm, hardly to clean, need enhanced mass transfer, heat transfer and light, technologies under development

2.2 Harvest of Microalgae

Microalgae harvest from the culture broth has been a bottleneck in the industrial scale microalgae production. Individual microalgal cells are small (1-30 µm diameter). The cell surface often possesses with hydroxyl, carboxyl, amino, mercapto, and phosphate groups and shows a negative charge [11]. It is possible to form a stable dispersion system in the culture medium, and the biomass concentration in the culture medium is very low (usually 0.5 to 5.0 g/L), so that the harvest of microalgae is difficult. The cost of harvesting microalgae accounts for 20% to 30% of the cost of microalgae farming that includes cultivation and harvesting [12]. Therefore, there is an urgent need to develop high efficiency and low-cost harvesting methods.

Due to the special nature of microalgae and its culture medium, the traditional solid-liquid separation technology cannot be directly applied for microalgae harvesting. Generally, microalgae are first physically or chemically treated, and then separated [13]. The harvesting methods include sedimentation, flotation, dissolved air floatation (DAF), filtration, and centrifugation. Sedimentation and flotation are the preferred harvesting methods for open large ponds due to the low cost [14]. The flotation method uses a flocculant such as Fe^{3+}, $Al_2(SO_4)_3$ or a cationic polymer. The flotation method is only applicable to few species like *Chlorella* and *Scenedesmus*, and it must combine with other methods to work effectively. Sedimentation is suitable for microalgae easily settled. Some microalgae can be precipitated by changing pH. Meanwhile, the DAF method can easily, safely, and efficiently concentrate the microalgae cells via adjusting the pH value, increasing the reflux ratio, and prolonging the dissolved gas time and contact residence time [15]. Centrifugation and ultrafiltration are suitable for the harvest of microalgae from photobioreactors, in which microalgae can usually achieve higher cell density. Centrifugation is a fast harvesting method, but it is also more energy intensive and only applicable when extracting high-value products from microalgae. Ultrafiltration is not suitable for the large-scale harvest due to the high cost of the membrane. The development of low cost membrane materials can also serve as an effective way to reduce the cost of microalgae biodiesel.

2.3 Extraction of Microalgal Lipids

Microalgal lipids are mainly distributed in the forms of triglycerides or fatty acids in the cells. The extraction of intracellular lipid components is also an important part of microalgae biodiesel production process. The extraction technologies of microalgal lipids include mechanical crushing, organic solvent extraction, water enzymatic, supercritical fluid extraction, thermal cracking, etc. These methods require microalgae as a dry powder [16].

Cell density of microalgae in the large-scale culture is generally less than 10 g/L. Even after solid-liquid separation (such as centrifugation, flocculation, flotation, membrane filtration, etc.), the microalgae slurry still has a high water content of 95.5% to 67%. The drying methods for microalgae slurry include sun drying, drum drying, spray drying, fluidized bed drying, freeze drying, and refractance window dehydration technology. According to the life cycle analysis (LCA), the energy output of the products produced by using dry microalgae is less than the energy input [17]. In order to avoid the energy intensive drying process, the development of conversion technologies that use wet algae as raw material has become an important research direction.

Mechanical crushing is the simplest method for microalgal lipid extraction. With the assistance of the high osmotic shock and ultrasonic assisted technologies, the cell rupture and intracellular release of substances can be accelerated. But these technologies are energy consumption, and different extrusion methods must be selected according to the specific physical characteristics of microalgal species.

Solvent extraction method commonly uses chemical solvents such as benzene, ether, and n-hexane, as well as mixing co-solvent extraction. Mixing co-solvent extraction refers to mixing a polar solvent and a non-polar solvent to form a single-phase system to extract microalgal lipids. At present, the methanol-chloroform system is the most commonly used method for extraction of microalgal lipids. This methanol-chloroform system is based on the principle of "similar compatibility". Microalgae are fully contacted with the methanol-chloroform mixed solvent. The polar solvent of methanol binds to the polar lipids of the cell membrane, and thereby destroying the hydrogen bonds and electrostatic interactions between the lipid and the protein molecules; while the non-polar solvent of chloroform diffuses into the cell and dissolves the intracellular hydrophobic neutral lipids. After extraction, water is added to the system. Methanol is dissolved in the water phase, and separated from the lipid-containing chloroform phase. Crude microalgal lipids can be obtained after evaporation of chloroform [16].

Water enzymatic method is the use of enzymes to decompose the cell wall and release microalgal lipids. The major limitation of this method is the high cost of enzymes.

Supercritical carbon dioxide extraction is another potential extraction method of microalgal lipids. Supercritical carbon dioxide possesses the characteristics of both liquid and gas, which can greatly speed up the extraction process of lipids with a high oil recovery rate. But the expensive equipment and operating conditions make it difficult for industrialization.

2.4 Production of biodiesel

Biodiesel preparation methods can be categorized as physical and chemical methods. Physical methods include direct mixing and micro-emulsion method, while chemical methods include thermal cracking and transesterification [13]. The most widely used biodiesel preparation method is a chemical method - transesterification, in which methanol reacts with natural lipids that is in the form of triglycerides. The triglycerides are broken into three long-chain fatty acid methyl esters and glycerol, thereby reducing the length of the carbon chain. The viscosity of the oil product (often called biodiesel) is reduced and the fluidity is improved. The biodiesel product meets the requirements of the transportation fuel. Fatty acids that are suitable for producing biodiesel have a chain length of 16 to 18 carbon, and the majority of high-lipid content microalgae accumulate triglycerides with a fatty acid content falling into this range. The transesterification reaction can reduce the molecular weight of the original lipids by 1/3 and the viscosity by 8 times, improve the volatility, and make the products compatible with diesel.

2.4.1 Biodiesel Production by in-situ Transesterification

During in-situ transesterification, the dried microalgae powder reacts with an alcohol (such as methanol) to produce fatty acid methyl esters in presence of a strong acid catalyst such as HCl and H_2SO_4. In-situ esterification eliminates the need for lipid extraction steps, and effectively simplifies the production process of biodiesel. It is suitable for methyl esterification of fatty acid contents in microalgal biomass with a high oil content. Studies on the in-situ esterification of microalgae showed that the reaction can be done within 1 h at 100°C in a closed vessel, and purification of fatty acid methyl esters can be done simultaneously by adding n-hexane [18]. By mixing the substrate alcohol with a weakly polar solvent such as diethyl ether or toluene, the yield can be improved by changing the polarity of the reaction medium. Alternatively, microalgae can be converted into liquid biodiesel under supercritical methanol transesterification conditions [19].

2.4.2 Biodiesel Production by Hydrocracking

Recently, some researchers in the United States and Europe are exploring the technology for the preparation of microalgae-based diesel by using hydrocracking. The technology is different from the transesterification technology [20]. The final products obtained by transesterification are fatty acid methyl esters – biodiesel, while the hydrocracking technology yields the green diesel (also called renewable diesel) whose composition is identical to that of petrochemical diesel. The green diesel can be mixed with petrochemical diesel in any proportion. The existing hydrocracking technology and equipment in the refinery can be directly used to refine microalgal crude lipids. Because this technology requires less investment and can be industrialized easily, it has been considered as a promising conversion pathway of microalgae.

2.5 Challenges in Production of Biodiesel from Microalgae

The use of microalgae for biodiesel production is still in its infancy, though it has shown many advantages. Currently, the biodiesel production technology for vegetable oil processing is relatively mature. Because microalgal lipids are similar to the vegetable oil, conversion of the microalgal lipids to biodiesel is technically feasible. However, according to the existing microalgae processing technologies, there is still a considerable distance to commercial applications. The bottleneck is the difficulty of obtaining enough microalgal biomass, which results in the high cost of microalgae-based energy products [21]. The main problems include:

(1) Selection of high quality energy microalgae

The lipid content and composition of microalgae are an important factor to determine the yield and quality of biodiesel. The selection of high quality microalgae species satisfying the industrial demand is a necessary condition for the mass production of microalgae-based biodiesel. The growth rate and the final cell density of microalgae are relatively low, and the cultivation process and harvesting costs are high. To solve these problems, mixotrophic or heterotrophic microalgae can be adopted to improve the oil production rate, and engineering fast-growing lipid-rich microalgal species is necessary [22].

(2) Large-scale, low-cost, high-efficiency cultivation system and cultivation technology

Developing microalgae cultivation systems that can reach a high cell density is one way to improve the economy of harvest. An optimal design of photobioreactors can ensure maximized use of light energy, high growth rate and cell density, reduction of the all over cost, and ease to scale up culture system [13].

(3) Optimizing the microalgae separation process

Separation of microalgae from the culture media may involve mechanical mixing, centrifugal harvesting, drying, etc. These processes require a high energy consumption, and making energy input and output not economical. The dry matter content in the microalgae culture media is usually less than 1 wt%. Concentration and drying steps extend the production cycle of biodiesel, and affect the efficiency of oil extraction [16].

(4) Comprehensive biorefinery of microalgae Production

Lipid-rich microalgae contain a large amount of protein, polysaccharides, pigments, and other nutrients. If these high value-added products and microalgae biodiesel are manufactured at the same time, it is possible to reduce the cost [5].

Industrialization of microalgae-based biodiesel is a project of complex system engineering. Microalgal growth for energy production requires large scale systems. A large amount of waste culture media may cause serious environmental pollution if handled improperly. Therefore, when planning a site for the large-scale microalgae cultivation, combining the treatment of wastewater, waste gas, and solid wastes should be considered. Industrial flue gas containing CO_2 may be used to culture autotrophic microalgae, while carbon-rich or nitrogen-rich agricultural wastes and industrial wastewater may culture heterotrophic microalgae.

3. Economic Analysis of Microalgae Production

3.1 Microalgae Cultivation

As aforementioned, open ponds and photobioreactors are two major systems for microalgae cultivation. Through the technical and economic analysis of these two kinds of cultivation methods, it is found that there is an obvious economy difference between two approaches (Table 3) [23, 24].

Zhang *et al.* [25] studied the life cycle (LCA) of microalgae cultivated in open race way ponds. It was found that microalgae culture is the costliest part of the whole production process. Their assumptions included that the cell concentration of microalgae in the pond was 0.5 kg/m^3; its location was close to the power plant, and the flue gas discharged from the power plant was used to cultivate microalgae; the medium in the pond was continuously stirred to keep the flow rate; and the diesel was used as the fuel for both transport and equipment maintenance. So the calculated parameters for the growth process of microalgae were: the microalgae yield per hm^2 (dry weight) is about 54.8 t, which requires 10 L diesel oil and 148.9 GJ electricity. If taking into account the nutrients consumption (like nitrates, sulfuric acid, salts, and phosphates) during microalgae cultivation, producing 1 t microalgae biomass needs to consume nitrates 349.74 kg, phosphates 52.969 kg, and sulfates 47.526 kg. The fossil energy consumed in the cultivation process of microalgae accounts for 73.8% of the total fossil fuel consumption, so the comprehensive utilization of energy is related to the energy balance of the whole microalgae-based biodiesel industry.

Table 3. Economic estimates of microalgae culture in open ponds and photobioreactors [23]

Economic assessment	Open ponds	Photobioreactors
Production scale		
Algae productivity	25(g/m^2/day)	1.25(kg/m^3/day)
Algae cell density (g/L)	0.5	4
Lipid yield (dry wt%)	25%	25%
Operating days/yr	330	330
Lipid production (MM gal/yr)	10	10
Biodiesel production (MM gal/yr)	9.3	9.3
Resource assessment		
Net water demand (MM gal/yr)	10,000	3,000
-water evaporated/water blowdown to treatment (gal/gal lipid)	570	250
- water blowdown to treatment/discharge (gal/gal lipid)	430	50
Fresh CO2 demand (ton/yr)	145,000	145,000
Fresh NH3 required for algae growth (ton/yr)	5,100	5,100
Fresh DAP required for algae growth (ton/yr)	4,800	4,800
Power coproduct exported to grid (MM kW h/yr)	80	100
System cost		
Total capital cost (direct + indirect) ($MM)	$390	$990
Net operating cost ($MM/yr)	$37	$55
Total coproduct credits ($MM/yr)	$6	$7

Presently, the comprehensive utilization technologies of energy mainly include the concentrated solar power [26] and the flue gas and wastewater co-utilization (FWC) technology [27]. Concentrated solar power converts the solar energy into heat that is stored in water, oil, sand, or other media. When needed, the stored heat will be used to generate electricity to supply the microalgae culture system, which can minimize the weather effects and provide continuous and stable energy supply. The FWC strategy uses the wastewater to provide N, P, and other nutrients, and industrial flue gas as the CO_2 source for microalgae culture. FWC saves resources and controls the pollution. The types of wastewater include domestic sewage, aquaculture wastewater, fermentation wastewater, papermaking wastewater, and so on.

3.2 Microalgae Harvesting Process

When the density or the lipid content of microalgae reaches a certain concentration, microalgae will be harvested. The cost of harvesting microalgae accounted for 20 to 30 percent of the total production cost. Commonly used harvesting technologies are flocculation, centrifugation, and filtration. The cost and energy consumption of these harvesting techniques are summarized in Table 4.

Membrane filtration often uses modified cellulose as the filter, which is easy to be polluted, though the counter-current operation may improve the efficiency to some extent. Centrifugation is a commonly used method for cell separation, which uses centrifugal separation without introducing other chemical reagents, but requires a high energy cost [28]. Flocculation is an industrial separation technology. This method requires the addition of $AlCl_3$, $FeCl_3$ or chitosan as flocculant to fix microalgae cells into flakes. However, the flocculant is difficult to be removed during the downstream separation processes. Microbial flocculation is a new method developed in recent years. Kim studied the flocculation of several green algae by using bacteria, and the recovery ratio was over 90% [29]. The microbial flocculation method has the advantages of low cost, safety, and pollution-free.

Table 4. Summary of harvest costs and energy consumption of microalgae [27,30]

Technique	Pros	Cons	Cost（$·hm^{-2}）	Energy consumption (kwh·m^{-3})
Flocculation	Low capital cost	Low water removal ratio	2,000	~0
Centrifugation	Fast separation rate, high recovery rate	High cost and high energy cost	12,500	3.29
Filtration	High efficiency, medium cost	Limited application, pollution of filters	9,884	0.5~5.9

hm^2: square hectometer

3.3 Microalgae Dehydration and Lipid Extraction

The most effective dewatering technology can only reduce the water content of microalgae slurry to 65-80 wt%. Drying microalgae to a lower water content of less than 80% requires dehydration processes, which increase energy consumption and cost [31]. Such dehydration processes include drying microalgae with sunlight, fixed bed or spray dryers. The energy input of the microalgae-based biodiesel process using dry microalgae is more than energy output. Traditional lipid extraction processes separate microalgal lipids from the water phase with organic solvents, such as methyl ether and n-hexane. But the extraction efficiency is low and it is difficult to recover the extraction solvent. Table 5 compares the cost of microalgae dehydration and lipid extraction.

Table 5. Summary of costs of microalgae dehydration and lipid extraction [27]

Operation	Capital cost ($)	Operation cost ($)	Methods
Dehydration	250,000	45,251	Solar drying/fixed bed drying
Extraction	150,000	7,332	methyl ether, n-hexane

4.Conclusions and Prospects

At the present stage, the production of biodiesel from microalgae is still not an economical process, and it is difficult to achieve industrialization in China. Reducing the cost is the major goal in the future [32, 33]. The cost of microalgae processes decreases in following order: microalgae culture > microalgae harvest > dehydration and lipid extraction. These three steps account for the major cost of microalgae-based diesel production, and they are closely related to each other. The low microalgae concentration is the reason of the high harvest cost, while the concentration of microalgae harvested is the key to the cost of lipid extraction. Therefore, the development of the novel microalgae technology should not only focus on the main steps, but also consider coupling between different processes.

Such technologies may include metabolic engineering, comprehensive utilization of energy, and well-developed scaling-up technology. For the microalgae cultivation, with the progress of genetic engineering, it is expected to develop ideal algal species, which can be cultivated with the improved culture system. To reduce simultaneously the cost of equipment and energy consumption of harvesting microalgae, the new technologies like biological flocculation might be used. For the microalgal lipid extraction, some new techniques may avoid the dehydration step and combine harvesting and extraction steps together, and thus develop an economical biodiesel production process. Furthermore, microalgae are rich in pigment, protein, polysaccharides, unsaturated fatty acids, and other bioactive substances, which can be used for the chemical, food, pharmaceutical and feed industry, etc. These useful components should be co-produced with the biodiesel to reduce the processing cost.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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