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Using microalgae to produce liquid transportation biodiesel: What is next?

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A B S T R A C T

In response to the energy crisis, global warming and climate changes, microalgae have received increasingly global attention as a renewable, alternative and sustainable source for the production of biodiesel. Much original research regarding microalgal biodiesel production has been reported. However, microalgal biodiesel faces plenty of challenges that current cultivation and biodiesel conversion is economically unfeasible for industrial applications on a large scale. This perspective paper first briefly discusses the latest advances in liquid transportation biodiesel production from microalgal biomass, including microalgal growth, biomass harvesting and drying, lipid extraction and biodiesel conversion. Subsequently, strategies for the future development of microalgal biodiesel have been proposed and discussed, in an attempt to reduce the cost gap. From the microalgal biodiesel production chain perspective, genetic and metabolic engineering, isolation of suitable species, high-efficiency bioreactor development, efficient culturing system development, optimal harvest process design, high-efficiency lipid extraction and transesterification method development will have critical roles to play. It is worthy of note that the increase of the outcome credits can also realize the reduction of the economic gap, and the main measures include appropriate glycerol recovery and reutilization, integration with wastewater treatment and CO_2 mitigation together with microalgal biorefinery for the production of multiple co-products with high values. Finally, concluding remarks are put forward.

1. Introduction

Global pressures in resource depletion, energy security and climate change have triggered and driven obvious advances in the development of renewable and sustainable energy. Biodiesel has been successfully commercialized as a substitute to petroleum-based diesel for running automobiles since around a decade ago [1]. At present, biodiesel is the second largest classification of global biofuels, occupying approximately 6.9 billion gallons worldwide in 2013 (22.6% of total biofuel production), and still the most widely used biofuel in Europe, accounting for around 80% of total biofuel market shares [2]. It is widely accepted that biodiesel is a type of chemically non-toxic, renewable and biodegradable fuel. Biodiesel, which is the mixture of fatty acid methyl esters, is usually produced by the transesterification of oil from either animal fat or oily crops, such as rapeseed, corn, soybean, palm and castor bean [3,4]. However, these feedstock sources have low oil yields and entail high demands for water, land and fertilizers [5]. Therefore, it is extremely necessary to seek alternative sources for biodiesel production in an effort to search for sustainable development.

Microalgae, as third generation biofuel feedstock [6], have many advantages as an alternative to conventional biodiesel feedstock sources. First, most microalgal species have high lipid contents. Under some stress conditions such as nutrient depletion or limitation, some microalgae can easily accumulate lipids up to 50% or even 60% [7]. Second, microalgae experience a high growth rate and photosynthesis rate. In comparison to all of the terrestrial crops investigated so far, one unit of microalgal biomass and oil produced requires much less growing area [8]. Third, microalgae can be grown on unproductive land, such as polluted land, infertile farms, arid or semiarid areas, saline soils and other land with low economic values, avoiding competition with food crops for farmland [9,10]. Forth, microalgae can be cultivated with saline waters and wastewaters, thus saving fresh water resources and reducing the utilization of fertilizers [11]. Fifth, since some microalgal species can tolerate CO_2, SO_x, NO_x, particulates and other elements, flue gas (rich in CO_2) can be introduced to microalgal culturing systems as a carbon source [12]. Sixth, during the microalgal cultivation, no pesticide or herbicide is required [13].

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Seventh, microalgae do not have embryos, leaves, stems and roots, facilitating the harvest process (although it is costly) and thus expediting the entire biodiesel production process in practice. Finally, biodiesel from microalgal oil has comparable physical and fuel properties (e.g. viscosity, density, heating value, acid value, etc.), compared with fossil fuel diesel. It is suggested that microalgal biodiesel can be used to fuel diesel engines, either in blend with fossil fuels or after simple engine modification [14].

Literature shows two main processing pathways for the conversion of microalgal biomass into different forms of fuels: thermo-chemical and bio-chemical processes [15]. A number of biofuels can be produced from microalgal biomass, including biodiesel, bioethanol, biogas, biohydrogen and many others such as biobutanol and syngas. However, biodiesel production from microalgae represents as the mostly focused research topic at present. Cultivating microalgae *Chlorella vulgaris* with recycled aqueous phase nutrients from a hydrothermal carbonization process, Du et al. [16] achieved 9.7–11.2% of biodiesel yields. Zhu et al. [17] investigated the wintering cultivation of microalgae with artificial wastewater outdoors in Southern China, and found that pH regulation of the culture with the addition of acetic acid could improve the biodiesel yields up to 19.44% of dry weight with the biodiesel productivity of 11.18 mg L^{-1} day^{-1}. Biodiesel yields of 9.19–11.15 g-biodiesel/100 g-dry weight were obtained by Yuan et al. [18], who cultivated *Chlorella zofingiensis* with piggery wastewater in photobioreactors. In another study, six different pre-treatment methods were applied to evaluate the optimal method to extract oil for biodiesel production, and maximum oil yields were achieved at time of 150 min, temperature 55 °C, particle size 0.10 mm, agitation rate 500 rpm and solvent-to-solid ratio 6:1 [19]. To produce biodiesel from algae, Sitthithanaboon et al. [20] also developed a single-step process for a direct conversion of wet microalgal biomass that contained around 80% water into biodiesel under subcritical methanol conditions, and found the best conditions were as follows: methanol to wet biomass ratio of about 6:1, temperature around 225 °C, and reaction time 90 min.

1.1. Objective and structure of this study

Microalgal biodiesel production includes a series of steps which are algal growth, preparation of dry microalgal biomass, extraction of microalgal lipids or oil, and catalytic conversion of lipids or oil into biodiesel. To date, plenty of review articles have been published, dealing with the potential of microalgal cultivation as a feedstock for biodiesel production. A critical review on algal production in wastewater is conducted, focusing on the affecting factors in terms of species and cultivation conditions such as carbon dioxide, light, nutrients and operation modes [21]. Focusing on stress culturing conditions, Markou and Nerantzis [22] provide a review on microalgal growth for the accumulation of high-value ingredients together with lipids or carbohydrates. The various methods of algal biomass harvesting and dewatering for biofuel production are reviewed by Milledge and Heaven [23]. In addition, Galadima and Muraza [24] present a critical review on the prospects of algae oil for biodiesel production via heterogeneous catalysis, exploring its advantages and discussing available heterogeneous catalysts, optimal reaction conditions and the prospects. However, these works often focus on the different procedures involved in microalgal biodiesel production, such as growth, harvest, lipid extraction and biodiesel production without briefly systematizing the whole process and emphasizing the future development of microalgal biodiesel industry. This perspective study aims to help fill this gap, and its objective is to systematically summarize state of the art of life-cycle microalgal biodiesel production chain in the form of tables and diagrams and highlight the main development directions in future. This article can help serve as a starting point for authorities, stakeholders and practitioners to better understand the microalgal biodiesel production technologies and their significances for future development in practice. In the coming sections, the authors first illustrate the main processes during microalgal biodiesel production, including cultivation, harvest and drying, lipid extraction and biodiesel conversion (Section 2). Afterwards, strategies for the development of microalgal biodiesel industry in future are presented and discussed in detail (Section 3). Finally, a summary of this study is concluded (Section 4).

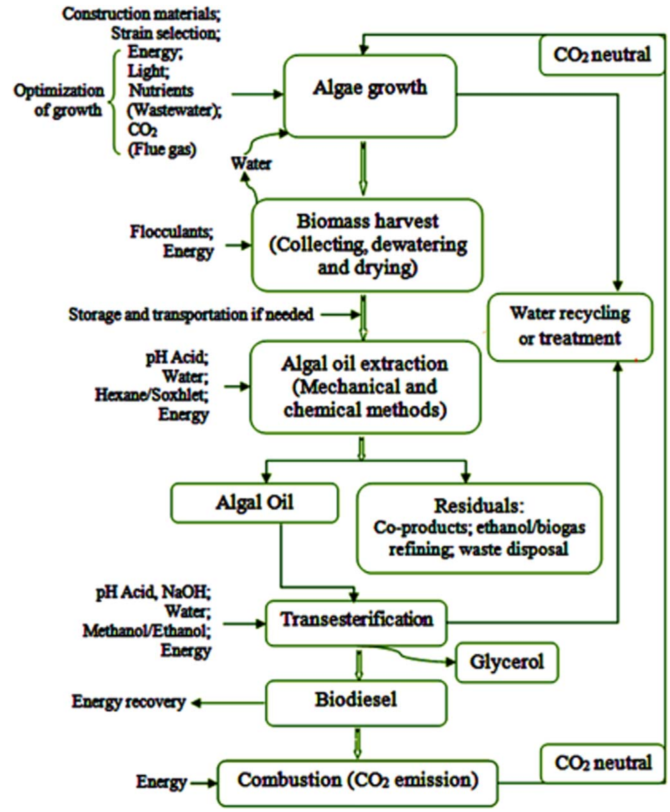

Fig. 1. A schematic diagram of microalgae production for biodiesel conversion.

2. Microalgal biodiesel value chain processes

Life cycle process of microalgal biodiesel production, which includes microalgal cultivation, harvest and drying, lipid extraction and biodiesel conversion, is shown in Fig. 1. In this part of the article, advances in each step are briefly discussed.

2.1. Microalgal cultivation technologies

Microalgae are simple microscopic eukaryotic or prokaryotic photosynthetic organisms, ranging from unicellular to multi-cellular in form [25]. Eukaryotic microalgae consist of diatoms and green algae, while prokaryotic microalgae include cyanobacteria (blue-green algae). Microalgae have a good ability to utilize water, CO_2, and sunlight to synthesize biomass via photosynthesis, thus transforming solar energy into organic chemical energy stored in microalgal cells. Apart from water, CO_2 and sunlight, phosphorus and nitrogen present as two major nutrient inputs for microalgal growth. Together with macro-elements such as N, P, Na, Mg, K, and Ca, micro-elements such as Mn, B, Mo, Zn, Co and Fe are also needed [26]. Three main types of growth conditions can be found: photoautotrophic, heterotrophic and mixotrophic culture.

Photoautotrophic culture is the most commonly used cultivation method. Similar to other photosynthetic plants, photoautotrophic algae utilize CO_2 and sunlight as the carbon and energy source, respectively. Many species have been found to be photoautotrophic, including