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The potential of microalgae in biodiesel production

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A R T I C L E I N F O

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A B S T R A C T

In recent years, biodiesel production has grabbed significant attention due to the awareness of fossil fuel exhaustion. Microalgae become interested feedstock candidate of biodiesel production as they have rapid growth rate and high oil content compared to crops. Efforts have been made to increase microalgae productivity and oil content. To investigate the potential of microalgae for biodiesel production, it is essential to knowledge if the microalgae oil is qualified as possible feedstock oil. Moreover, what would be the energy and environmental effect of the production? And whether the production cost would be reasonable? This paper compared the properties of microalgae oil with traditional biodiesel production oils (vegetable oils); the properties of the biodiesel produced from microalgae and vegetable oils; reviewed the net energy ratio (energy output to energy input), GHG emissions, and economic analysis of the process of biodiesel production from microalgae; as well as discussed the factors which would influent the energy, environment, and cost of the process.

1. Introduction

Microalgae have gained extensive interest in current age due to its rapid growth rate and vigorous vitality. They have been utilized as sources of many products including chemicals (vitamins, pigments, antioxidants), oils (omega-3 fatty acids), protein, animal feed (for larval bivalves), and biomass for the production of ethanol and methane [1–4]. Microalgae capable of accumulating high oil content were studied as the alternative of vegetable oils for biodiesel production [5–7]. *Chlorella zofingiensis*, *Chlorella protothecoids*, and *Schizochytrium limacinum* were well-known oil producer as they could accumulate more than 50% oil of the dry body weight [8–11]. The significant advantages of microalgae over agricultural crops are the rapid growth rate and no arable land requirement [6,12]. In addition, carbon sequestration and burning clean (of microalgae biodiesel) are also the attracting aspects of utilization microalgae for producing biodiesel [13–16].

Microalgae as feedstock of biodiesel production have been extensively reviewed [10,13,17–22]. It was explained what were microalgae, why they could be employed, what were the advantages of using microalgae for biodiesel, what types of microalgae (heterotrophic and autotrophic) could be utilized, what was the process (from strain isolation to biodiesel formed), and what were the factors to impact on the process. Any technology entering market from research stage requires feasibility analysis which refers to cost affordability and environmental benefit. To the best of our knowledge, these aspects have been given very little interest. This study reviewed the life cycle assessment (LCA) and techno-economic evaluation of microalgae for biodiesel production and discussed the cause of the difference of the study results.

2. Feasibility of microalgae to biodiesel

2.1. Characteristics of microalgae oil

Generally speaking, it is important that feedstock should have high lipid content, large productivity, and affordable price. However, physical and chemical properties of the feedstock oil are rather essential in biodiesel production as they influent the quality and yield of biodiesel. The properties include fatty acid composition, free fatty acid content, water content, phosphorus content, sulfur content, and saponification value.

2.1.1. Fatty acid composition

The main fractions of feedstock oils or fats are triglycerides (varying from 90% to 98% according to the oil or fat sources) [23,24]. Triglycerides are composed of one glycerol [$C_3H_5(OH)_3$] and three fatty acids (R–COOH) as the major reactive groups, which suggests that fatty acids affect the oil and fat characteristic most. In general, fatty acids include unsaturated (with double bonds) namely mono-unsaturated (one

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double bond,Cn:1) and polyunsaturated (more than one double bonds, Cn:2,3), and saturated (no double bond, Cn:0) fatty acids. The fatty acid composition plays significantly important role in biodiesel qualities as it determines the viscosity, oxidation stability, cetane number (CN) (indicator of ignition quality), cold flow property, flash point, calorific value (also called heat content or energy density), and density of biodiesel. Viscosity indicates the fuel features of spray, mixture formation, and combustion process. High viscosity can cause early injection and increase combustion chamber temperature. Normally, viscosity increases with the increase in the chain length and fatty acid saturation level, while better oxidation stability requires high level of fatty acid saturation [25–27]. CN increases as the increase in chain length and saturation degree of fatty acid [27,28]. Cold flow properties also depend on the saturation level of the feedstock oil in which the higher the saturation level is, the poorer the cold flow property is [29,30]. The flash point will be low when the chain length is short; greater saturation degree gives higher calorific value; and polyunsaturation level seems to be proportion to the density [31].

2.1.2. Free fatty acid (FFA) content

FFA can be described as R-COOH. Alkaline catalytic trans-esterification is the most common industrial biodiesel production route. The presence of FFA in the oil/fat can lead to the increase in the use of catalyst, and complicate the phase separation and product neutralization due to the soap formation (Eq. (1)). In order to avoid soap formation, normally, acid catalytic trans-esterification or acid pretreated alkaline catalytic trans-esterification has to be performed when FFA content is greater than 0.5% (wt/wt) [32–34].

$$RCOOH + KOH/NaOH \rightarrow RCOOK/Na(soap) + H_2O \quad (1)$$

where R represents fatty acid chains.

2.1.3. Water content

Water can cause triglyceride hydrolyzing to FFA, and hence result in soap formation [35,36]. Moreover, the presence of water could also cause emulsions. Therefore, when water content is greater than 0.05% (w/w), water removing step is required [35].

2.1.4. Phosphorus and sulfur content

Phosphorus can damage catalytic converters used in emissions control systems of the vehicles [37]; therefore, phosphorus content in feedstock oil, which will finally transferred to biodiesel, should be controlled to protect the systems. Similarly, sulfur presence can choke catalytic converter up and harm the emission control systems of vehicles. In fact, sulfur content of the current commercial biodiesel is nearly zero. It is the reason that normally in order to decrease the sulfur content in petrodiesel, biodiesel is used to blend with the petrodiesel [35].

2.1.5. Saponification value (SV)

An Index of the average size and weight of fatty acids. Fatty acid methyl esters with carbon chain length from 12 to 20 are considered as biodiesel. The saponification value indicates the chain length of triglycerides. Shorter chain length leads to higher SV [38].

By comparing the feedstock properties, microalgae oils have similar properties as plant seed oils and animal fats (Table 1). Comparing the property of biodiesel produced from microalgae oil, plant seed oil and animal fat (Table 2), it showed that microalgae were potential replacement of crops and animals.

2.2. Life cycle assessment of biodiesel production from microalgae

2.2.1. Energy ratio

Life cycle assessment has been extensively involved in evaluating the energetic and environmental benefits of biofuel production. The assessment normally starts from building-up process, defining boundaries, fixing parameters, and finally calculating energy ratio and greenhouse gas – GHG emissions. The process of microalgae-based biodiesel production majorly includes microalgae cultivation and harvesting, lipid extraction, and trans-esterification. The cultivation can be in open ponds (OP), photo-bioreactor (PBR), or closed fermenting system. The LCA depends on the process selection and the assumptions. Some of the LCA studied on microalgae to biodiesel have been summarized in Table 3.

In most of the LCA studied (Table 3), the process included microalgae cultivation, microalgae harvesting, lipid extraction, and trans-esterification, and few considered the biodiesel distribution part as well. In fact, the distribution parts have little effect on the net energy ratio: NER (energy produced/energy consumed) as it took up only around 0.6% of the total energy input [39–41]. Similarly, it has almost no impact on GHG emission. The parameters including cultivation mode (open ponds, photo-bioreactor, and fermenter), microalgae yield, lipid content in the microalgae, dewater technology (filtration, centrifugation), drying method (solar, steam), lipid extraction efficiency, and trans-esterification efficiency, utilized in LCA have great impact on the studies as well. Lipid extraction and trans-esterification are mature technologies, and generally the efficiencies were assumed to be 90% and 95%, respectively [42,43]. Thus, these two parts are not the great contributors to cause the difference of LCA results.

Open ponds and photo-bioreactor are the most applied system. The two systems can be fed with flue gas which is the power plant waste and rich in carbon dioxide. It is a solution of carbon sequestration and obtaining free carbon source for autotrophic microalgae cultivation system. The advantages of photo-bioreactors are high productivity, small land area requirement, low risk of contamination, avoiding water loss, and less depending on the climate compared to open pond cultivation. The major problem of the system is the high capital and operating cost [44]. Additionally, oxygen is produced during cultivation which can inhibit the growth of microalgae. In photo-bioreactor system, oxygen concentration builds up while cultivation, and thus can cause the low yield of biomass. Unlike photo-bioreactor, the oxygen produced can be spread to atmosphere during the mixing (paddle wheels and CO_2 bubbling) in open pond cultivation system. In fact, the main advantage of pond system is the low energy consumption and cost requirement. The weaknesses of the process are high contamination level, large amount of water loss, climatic dependence (annul average temperature > 15 °C), low biomass concentration which requires large dewatering energy input, and large land demand [45].

Even though, open pond system has its limitation, it is still commercially utilized in nutrient production for animals as it is cost affordable. Study has reported that open pond system (NER = 8.34) had higher net energy ratio than photo-bioreactors (NER = 4.51) to produce the equal amount of microalgae biomass [44]. The calculation was based on that the productivity of open pond and photo-bioreactor were 11 $g/m^2/d$ and 27 $g/m^2/d$, respectively. It indicates that open pond is not compatible with photo-bioreactor on the productivity but it still provides higher energy gain than photo-bioreactor. In the similar cultivation system, obviously, higher the microalgae yield and lipid content provided higher energy gain and GHG emission reduction [46]. 10% increase of lipid content could bring the NER from less than 1 to greater than 1 with other parameters being kept constant [47].

After cultivation, dewatering is normally followed to concentrate the biomass. The dewatering technologies currently applied are flocculation, centrifugation, screening, filtration, floatation, and settling [48,49]. The performance of each dewatering technology had been summarized by Uduman et al. [49]. It revealed that flocculation, centrifugation, filtration, and flocculation followed by flotation were stable and efficient, but centrifugation (8 $kW\,h/m^3$) and flocculation followed by flotation (10–20 $kW\,h/m^3$) required large energy input [50,51]. Filtration (natural or pressured) -screening (0.4–0.88 $kW\,h/m^3$) dewatering technology had shown similar performance as centrifugation but consumed much less energy [52]. In the LCA studies, mostly