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Mini Review

Energy aspects of microalgal biodiesel production

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Abstract: Algal biodiesel production will play a significant role in sustaining future transportation fuel supplies. A large number of researchers around the world are investigating into making this process sustainable by increasing the energy gains and by optimizing resource-utilization efficiencies. Although, research is being pursued aggressively in all aspects of algal biodiesel production from microalgal cell cultivation, cell harvesting, and extraction and transesterification steps to the final product separation and purification, there is a large disparity in the data presented in recent reports making it difficult to assess the real potential of microalgae as a future energy source. This article discusses some of the key issues in energy consumption in the process of algal biodiesel production and identifies the areas for improvement to make this process energy-positive and sustainable.

Keywords: microalgae; biodiesel; energy balance; extraction; transesterification; sustainability; cultivation; separation and purification

1. Introduction

Depleting fossil fuel reserves and escalating environmental pollution associated with their consumption have created an urge for researchers around the world to investigate into renewable and sustainable energy and fuel supplies such as biofuels. The stimulus for research in biofuel production comes from their additional benefits of high energy density and ease in process utilization. Current biodiesel technologies are not economically feasible since they require government subsidies to be profitable to the producers and affordable to the users. This is mainly due to: 1) high feedstock costs; and 2) energy-intensive process steps involved in their production. Moreover, the feedstock should be derived from non-food related renewable materials to be sustainable and have less environmental impacts when compared with fossil fuels. Microalgae, a high oil-yielding feedstock, can be used to reduce production costs and make biodiesel competitive with petroleum diesel. Microalgae as a feedstock do not compete with any of the current human interests and offer many environmental benefits that make them an attractive feedstock for biodiesel production. Microalgae have much higher growth rates and productivity when compared with conventional forestry, agricultural crops, and other aquatic plants, requiring much less land area than other biodiesel feedstock of agricultural origin, i.e., up to 49–132 times less when compared to rapeseed or soybean crops (basis: 30% w/w of oil content in microalgae biomass [1]. Therefore, the competition for arable land with other crops, in particular for human consumption is greatly reduced by using microalgae as biodiesel feedstock [2]. Microalgae show great promise as a potential future energy source due to their environmental-friendliness and high oil yielding capacity per given area. Although microalgae can be grown in most of the tropical climates, dry and wet weather conditions and even in marginal lands where solar insolation is high, the lipid yield from algal biomass varies around the world [3]. In addition, current algal biodiesel production methods are not efficient since the process steps involved from algal biomass cultivation to final biodiesel separation/purification are all energy-intensive and cost-prohibitive. Therefore, rigorous research is being pursued all over the world to develop novel and energy-efficient process techniques for sustainable algal biodiesel production.

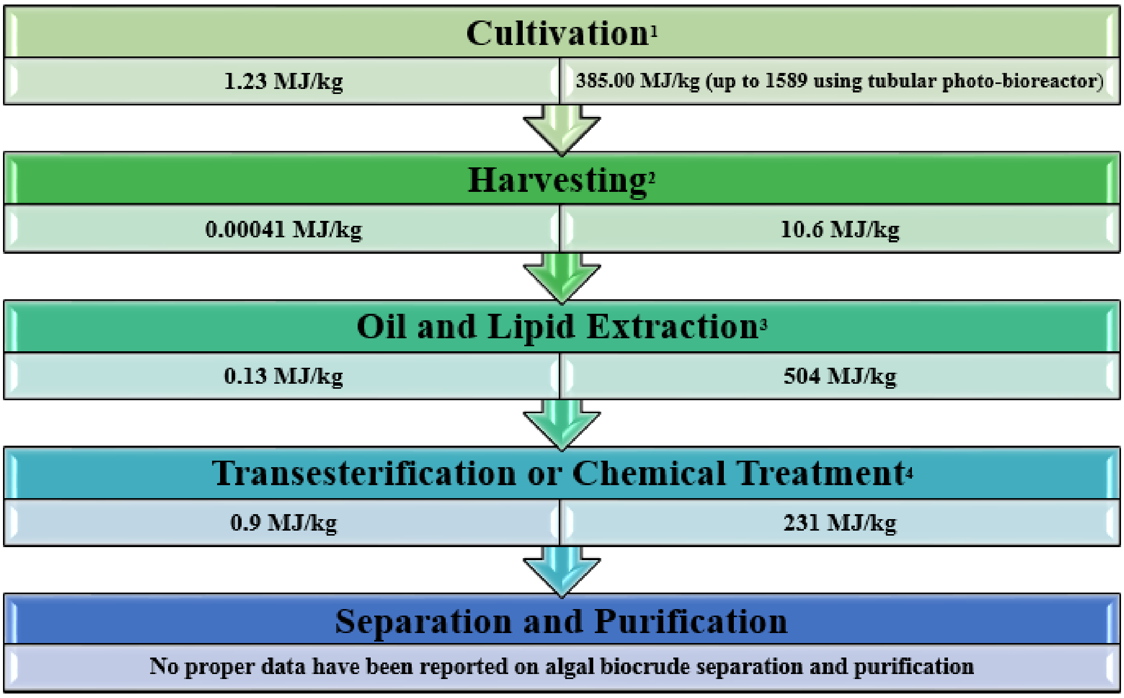
2. Net energy balance—microalgae case study

Algal biodiesel production consists primarily of five steps: a) microalgae biomass production; b) biomass harvesting; c) oil and lipid extraction; d) transesterification or chemical treatment; and e) separation and purification [4]. All steps involved in algal biodiesel production are both energy- and cost-intensive. Currently, major hurdles for the algal biodiesel production are dewatering the algal biomass (algal cell concentration) and drying and oil extraction [4,5]. The algal culture is usually concentrated to 15–20% from its original concentration of 0.02–0.05% through various physical and chemical processing techniques. Apart from this, extraction of algal oil is not as simple as that would be from other crop seeds (which are usually done by mechanical pressing and solvent extraction methods) due to their rigid cell wall structure. As such, these three steps add significantly to the cost of the algal biodiesel product.

Algal biodiesel production can be sustainable only if the net energy gain from entire process is higher than one. The net energy ratio is defined as the ratio of the energy available from the end product (algal biodiesel) to the energy invested in its production cycle. Microalgae have an energy content of 5–8 kWh/kg (18,000–28,800 kJ/kg) of dry weight depending on the species and lipid content [4]. Therefore, in order for algal biodiesel production to be feasible, the amount of energy required to produce the microalgae and to process it into a useable fuel must be less than this amount. Therefore, the Net Energy Ratio can be written as:

$$E_{NER} = \frac{E_{out}}{E_{in}} = \frac{Energy\ in\ algal\ biofuel}{Energy\ invested}$$

Figure 1 shows the energy requirements for algal biodiesel production. Energy consumption for cultivation and algal biomass production depends on the cultivation methods. Low specific energy consumption is often reported for open raceway ponds. Photobioreactors are currently energy-intensive. Major energy consumption (60–70%) occurring in harvesting, drying, and extraction steps is unavoidable to prepare lipids suitable for the transesterification reaction. High energy consumption for lipid extraction is often combined with drying the biomass. This clearly suggests the need for alternative methods to dry microalgae biomass, or eliminating the need for drying entirely by hydrothermal liquefaction processes.



[1] Cultivation (freshwater or brackish-to-saline water): open ponds (raceway) and photobioreactors (i.e. flat-plate, tubular, and biofilm PBR) [4,9-13]

[2] Harvesting: centrifugation, gravity sedimentation, filtration (natural), filtration (pressurized), tangential flow filtration, vacuum filtration, polymer flocculation, electro-coagulation, electro-flotation, electro-flocculation [4,9,14-16]

[3] Oil extraction or lipid extraction (dry or wet): chemical extraction or direct extraction (i.e. oil mill and mechanical pressing), hydrothermal liquefaction [4,9,16]

[4] Transesterification (in-situ transesterification often combines the extraction and transesterification step into a single step): conventional (sub-critical water, solvent-conventional heating), non- conventional (microwave, ultrasound, ultrasonic bath, hydrodynamic cavitation, pyrolysis) heating technologies, supercritical alcohol transesterification (supercritical methanol, supercritical ethanol) [4,17-30]

Figure 1. Energy consumption in algal biodiesel production (low and high values of energy consumption in each step).

For alternative methods to be effective, the goal will be to extract all of the lipid content from the biomass and transesterify in the steps that follow. Microalgae have a very rigid cell wall that is hard to break or penetrate through mechanical or chemical extraction methods. Mechanical pressing proved to be inefficient for algal oil extraction for this reason. Chemical extraction using solvents can be expensive as well as creating other byproducts and waste products and separation/recovery problems. From the data reported by several researchers, a minimum energy consumption of 1.7 kWh/kg of dry algal biomass with a net energy gain ratio of up to 4.7 may be possible if all of the steps involved in algal biodiesel production are achieved with minimum energy consumption [4,6-8]. Energy requirements higher than 8 kWh/kg of dry algal biomass are not beneficial and sustainable. With drying operation taking up to 60% of the total energy, it provides an opportunity to save energy by eliminating the step or by finding other energy saving alternative. As such, hydrothermal processes that maximize recovery of carbon content in the final product in the form of biocrude are highly desirable.

3. A closer look at the process steps and energy consumption

A closer look at the energy requirements for biodiesel production from two different forms of algal feed stock (dry and wet microalgae) is shown below [4]. It can be noted that drying and extraction steps consume about 84.2% and 72.8% of the total energy requirements for dry and wet algal biomasses respectively (Table 1). Microalgae cell harvesting and oil extraction steps also make significant contributions to the energy balance. The following sections discuss the energy requirements for algal cell harvesting and extraction and transesterification steps in algal biodiesel production.

Table 1. Energy requirements for different steps in algal biodiesel production [9].

Biodiesel production step (basis: 1 kg of algal biodiesel)	Dry algal biomass (MJ)	Wet algal biomass (MJ)
Microalgae culture and harvesting	7.5	10.6
Drying	90.3	0
Extraction	8.6	30.8
Oil transesterification	0.9	0.9
Total	107.3	42.3

3.1. Harvesting methods

Microalgae can be harvested from the culture medium (water) by chemical (coagulation-flocculation); and physical (membrane filtration, hydrocyclones and centrifugation) methods. Microalgal cells carry a negative charge that prevents aggregation of cells in suspension. The commonly used salts to separate algal suspensions include ferric chloride ($FeCl_3$), aluminum sulfate ($Al_2(SO_4)_3$, alum) and ferric sulfate ($Fe_2(SO_4)_3$) [31-35]. These mineral coagulants (alum and ferric chloride) produce large volumes of sludge which are toxic to animals when consumed due to high concentration of residual aluminum and iron in the biomass harvested [36,37]. The main problem with membrane filtration is membrane fouling and clogging due to the small size of the microalga. Membrane processes operate at high pressure which means high energy requirements and high capital costs [38-40]. Centrifugation is the application of centripetal acceleration to separate the algal growth medium into regions of greater and less densities. Once separated, the microalgae can be removed from the culture by simply draining the excess medium [41]. However, shear forces experienced during spinning can disrupt cells, thus limiting the speed of centrifugation [11].

Macro-filtration is widely used for larger microalgae species like *Arthrospira*. Belt filters are able to filter up to 20% with an energy consumption of 0.5 kWh m^{-3} (2.04 kJ/kg) if the feed is pre-concentrated at 4%. Micro-filtration with appropriate pore size can retain the majority of common species. However, micro-filtration could be even less economical than centrifugation for the recovery of microalgal cells on a large scale [11]. Recent studies showed that harvesting by submerged filtration in combination with centrifugation could achieve concentration up to 22% and reduce energy needs to under 1 kWh m^{-3} (4.09 kJ/kg) [42]. Ultrafiltration is a possible alternative in particular for very fragile cells, but has not generally been used for recovery of microalgae since operating and maintenance costs are high [11,43]. Energy consumption is believed to be between 1 and 3 kWh m^{-3} (4.09 and 12.27 kJ/kg). Disc stack centrifuges are suited for separating particles of the size (3–30 μm) and concentration (0.02–0.05%) of microalgae cultures up to 15% solids while consuming 0.7–1.3 kWh m^{-3} (2.86–5.32 kJ/kg) [43]. The unit conversion was done by using the average biodiesel density of 0.88 g/mL [44,45]. Table 2 shows the comparison of several algal cell harvesting techniques [15]. It should be noted that the final product concentration is dependent on the separation mechanism.

Table 2. Comparison of algal cell harvesting techniques [15].

Method	Advantages	Drawbacks	Dry solids (%)	Energy Requirements (kWhm^{-3})
Centrifugation	rapid, efficient, suitable for most microalgae species	high capital and operating costs	10–22	0.7–8 (2.86–32.73 kJ/kg)
Filtration	high system variety	species specific, fouling	2–27	0.5–3 (2.04–12.7 kJ/kg)
Flotation	faster than sedimentation	species specific, high capital costs	2.5–7	0.015–1.5 (0.06–6.14 kJ/kg)
Sedimentation	low capital and operating costs	species specific, low final concentration	0.5–3	0.1–0.3 (0.41–1.23 kJ/kg)

3.2. Oil extraction methods

Microalgal oil extraction alone may cost up to $15 per gallon of oil produced involving use of non-renewable energy and/or high quality electrical energy with yet another energy-intensive step of drying [46]. It is crucial to consider the costs for large scale production feasibility of the algal biodiesel. Well known methods for oil extraction are namely mechanical pressing, milling, solvent extraction, supercritical fluid extraction, and enzymatic extraction. These methods require high volumes of solvents, long extraction times, and mechanical or thermal energy resulting in environmental pollution and hazardous byproduct formation/disposal. Once the oils are extracted from microalgae, biodiesel can be produced thorough widely known technique “transesterification”. Transesterification process is simply the replacement of one group of ester with another to make the carbon chain less complex. Transesterification of vegetable-, waste cooking-, non-edible-oils (jatropha, kharanja, and animal fats) and other feedstocks under microwave and ultrasound irradiations were reported by many researchers [47,48].

3.3. Dry vs wet routes in biodiesel production

Biodiesel production using dry algal biomass as feedstock can be less energy intensive as it was reported earlier [19,20]. Because, biomass drying can be performed using solar energy which is available "free". However, the details and requirements for such process are yet unknown. Table 3 shows the energy requirements for single-pot extractive-transesterification of algal biomass (*Nannochloropsis sp.*) [19,20]. It can be shown that the dry microalgae processing under microwaves for biodiesel production is less intensive. While the supercritical methanol process is a non-catalytic process which requires less separation and purification steps, the process time was longer and the feed sample was large due to the water content in the paste.

Table 3. Energy requirements for dry vs. wet routes.

Species	Feed type	Process	Optimum parameters	FAME (%)	Feed (g)	MeOH (mL)	Energy consumption (kJ)	Reference
Nannochloropsis (CCMP1776)	Wet	SCM	250 °C 8 (wt/vol) 25 min	84.15	4	32	thermal 525 mechanical 75 Total 600	[21]
	Dry	MW	65 °C Cat. 2 wt% 9 (wt/vol) 6 min	80.13	2	18	thermal 240 mechanical 15 Total 255	[21]

SCM: supercritical methanol; MW: microwaves.

3.4. Microwave and ultrasound for extraction and transesterification

It is critical to develop energy-efficient methods that would reduce the chemical and energy consumption and processing time of the overall algal biodiesel production. Ultrasonic-assisted extraction combined with microwaves could be an attractive option for algal oil extraction since it does not require excess solvents or mechanical energy [49]. Individually, microwaves and ultrasound have received considerable attention in recent years due to their unique process enhancing effects. Numerous studies accounted for their process intensification benefits in pharmaceutical, chemical, and industrial applications. Microwaves and ultrasound have also been extensively used and equally investigated for their benefits in biofuel synthesis ever since their discovery, although it is fairly recent for biodiesel production. Microwaves enhance the reaction rates by ionic conduction and dipolar polarization mechanisms. Due to these effects localized superheating of the reactants results in hotspots increasing the rate of reaction tremendously. Advantages of microwave technique can be short extraction time and higher oil recovery since the microwaves have the ability to penetrate through algal cell walls to heat the lipid pockets and force them to be excreted out of biological matrix into extraction medium [47,48,50-52]. Ultrasound technology was employed in various stages of biodiesel production. Stavarache et al. [53] used low frequency ultrasound energy for biodiesel production and compared the results with conventional biodiesel production processes. They used three different types of alcohols and NaOH as a catalyst. The study showed that ultrasonication had a positive effect on transesterification process and reduced the process time and saved energy in the biodiesel production [53]. Santos et al. [54] studied the effect of ultrasonication in biodiesel production from soybean oil and showed the positive effect of ultrasound on biodiesel yield enhancement. Cintas et al. [55] used high power ultrasound in a continuous system for biodiesel production from soybeans. They used ultrasound after heating the oil and premixing with a mechanical stirrer. Their results showed considerable improvement on reaction time and energy savings.

Table 4 summarizes the specific energy consumption reported in various studies. These processes include supercritical and subcritical processes, and microwave and ultrasound techniques for extraction and transesterification of algal lipids including traditional methods such as bead mills. It can be noted that a wide range of specific energy consumption from 1.1 MJ/kg to 504 MJ/kg was reported for various processes. From this data, it is clear that traditional bead mill is an inefficient method. However, the data reported from across the studies is not consistent. For example, some studies reported the data for pre-treatment only while others reported the specific energy consumption for the entire process. Some studies report the data based on the enthalpy of the reaction contents which does not represent the actual energy supplied to the process. There are several variables that can be identified in these results. The feedstock is different across the studies. The algal biomass physical cell characteristics are species-specific meaning that optimized conditions for one algal species may not work for another algal species. Some studies were performed at gram-scale while the other reported at kilogram-scale which may introduce some process and reaction specific differences. In microwave and ultrasound mediated extraction and transesterification processes, different power levels and different frequencies were identified to be effective. Apart from that a wide range of extraction solvents, purification agents are utilized in the final steps. All these parameters introduce experimental errors and variations.

4. Research needs

Chisti (2013) suggested that a net energy ratio (profit) of 7 is desirable for algal biodiesel production to be cost-competitive with other conventional fuel supply options [56]. However, as shown in Figure 2, net energy rations of less than 1 as well as higher than 4 are reported in the literature [4,6,7,12,57-67]. To achieve the goal of net energy gain of 7, algal biodiesel production process should be improved in several aspects and process steps [68]. Energy extraction has to be maximized not only from the biodiesel production, but also from the spent biomass through biogas production or incineration. This may add to greater overall energy gains.

Table 4. Energy requirements for algal biodiesel production reported in literature.

Process Conditions	Method	Energy (MJ/kg)	Reference	Comments
Nannochloropsis salina: 220 °C, 7.5% biomass (80 mL) loading, 25 min, 24.2 bar, 15 mL hexane. 4 kg of hexane are required to separate crude extract.	conventional heating subcritical water (C-SCW) extraction	12.2	[17]	Calculations are based on specific enthalpy of water and latent heat of evaporation of hexane
Nannochloropsis salina: 220 °C, 7.5% biomass (60 mL) loading, 25 min, 24.2 bar, 15 mL hexane. 4 kg of hexane are required to separate crude extract.	Microwave assisted subcritical water (MW-SCW)	11.26	[17]	Calculations are based on water's enthalpy and latent heat of evaporation of hexane
4.3 g wt algal biomass (1 g dry), 5 mL DI water, 1021 W, 5min, 15 mL of ethanol	Microwave	54.6	[18]	Based on 70% solvent recovery with distillation setup. Includes 8.77 MJ/kg from harvesting
4.3 g wt algal biomass (1 g dry), 5 mL DI water, 635 W, 5min, 15 mL of ethanol	Microwave	54.5	[18]	Based on 70% solvent recovery with distillation setup. Includes 8.77 MJ/kg from harvesting
1 kg of wet microalgae, methanol 114 g, KOH	Solvent/conventional heating extraction	106.4	[4]	Balance −2.6 MJ/kg. Includes harvesting (7.5 MJ/kg) and drying (81.8 MJ/kg)
1 kg of dry microalgae, methanol 114 g KOH	Solvent/conventional heating extraction	41.4	[4]	Balance: 105 MJ/kg. Includes harvesting (10.6 MJ/kg)
100 g of *Chlamydomonas sp*., 100 mL ethanol, 350 W, 10 min	Microwave	2.1	[22]	Cell disruption step (pre-treatment) only
Nannochloropsis sp. (18 mL, 6 min, 400 W, 2 g)	Microwave	72	[21]	Accounts for power output in extraction-transesterification only

Chlorella pyrenoidosa (1 g, 400 W, 40 s)	Microwave	16	[23]	Accounts for power output during extraction and transesterification only
Chlorella sp. (4 g, 48 mL, 5 min, 350 W)	Microwave	26.3	[19]	Accounts for power output during extraction and transesterification only
Chlorella sp. (4 g, 48 mL, 5 min, 490 W)	Ultrasound	44.1	[20]	Accounts for power output during extraction and transesterification only
Nannochloropsis (5 min, 770 W, 1 g)	Microwave	231	[24]	Accounts for power output during extraction and transesterification only
(5 g, 42.5 mL, 40 min, 29.7 W/L; 25 mL, 20 min)	Ultrasonic bath	1.1	[25]	Accounts for power output during extraction and transesterification only
Nannochloropsis (10g, 30 min, 150 W)	Ultrasonic bath	27	[26]	Accounts for power output during extraction and transesterification only
Scenedesmus sp. (2 g, 30 min, 100 W)	Ultrasound	90	[27]	Accounts for power output during extraction and transesterification only
Nannochloropsis sp. (4 g, 32 mL, 25 min, 350 W)	Supercritical Methanol	131.25	[21]	Accounts for power output during extraction and transesterification only
Nannochloropsis oculata (100 g (30% DW), 1000 W, 30 min)	Ultrasound	60	[28]	Accounts for power output during extraction and transesterification
Botryococcus, *Chlorella*, *Scenedesmus* (100 mL, 5 kg/m^3 , 840 W, 5 min)	Bead Mills	504	[29]	Accounts for power output during extraction and transesterification only
Saccharomyces cerevisiae (50 L, 10 kg/m^3, 5.5 kW, 50 min)	Hydrodynamic Cavitation	33	[30]	Accounts for power output during extraction and transesterification only

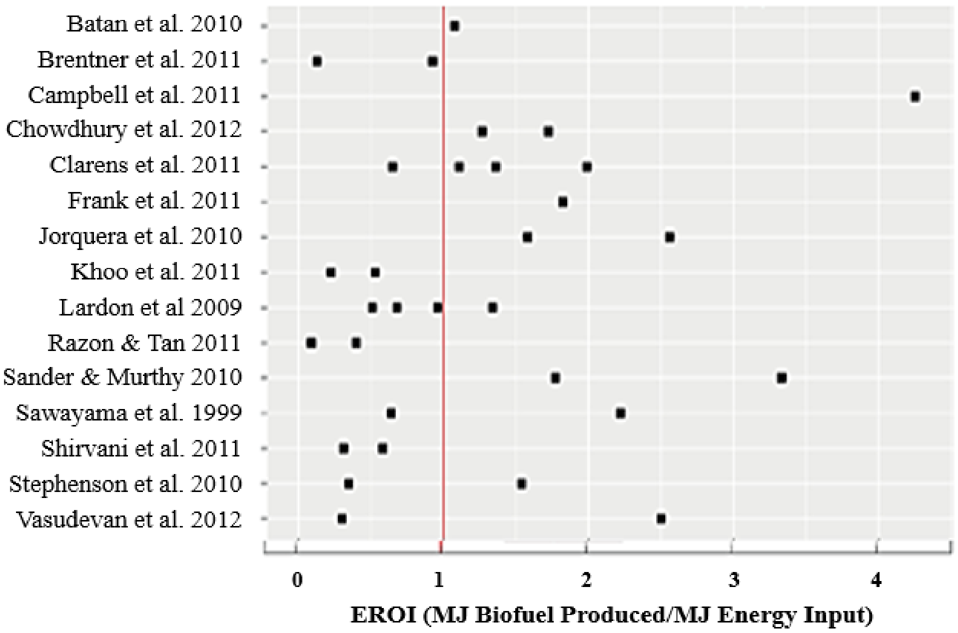


Figure 2. Net energy ratios for algal biodiesel production [4,6,7,12,57-67].

4.1. Microalgae growth and lipid yield estimations

Many reports focusing on algal biomass growth and lipid yields are available. But the estimations show large variations in microalgae productivity levels. This is in terms of land requirements, energy needs, water footprints, climate parameters and geographical locations. As this is the case, it is challenging to perform accurate techno-economic or life cycle impact analysis for algal biofuel production. In addition, these disparities are even worse in the case of process pathways reported for microalgae biomass processing and biodiesel conversion. For algal growth systems, the main differences occur between the raceway ponds and photobioreactors. To address this issue, Moody et al. [3] modeled various growth systems in the different assessments, including open raceway ponds and photobioreactors. Their results represented a promising production scenario based on cultivation in closed photobioreactors, which have been demonstrated to be robust culture platforms albeit cost-intensive.

4.2. Microalgae harvesting techniques

Among the harvesting methods, centrifugation and membrane filtration are not suitable for large scale application due to high energy consumption by these processes. Bio-flocculation, traditional chemical coagulation-flocculation-sedimentation methods with natural coagulants such as extracellular polymeric substances and chitosan should be studied more aggressively to provide a cost-effective solution. Novel techniques such as ultrasonic wave treatment combined with biopolymers and other energy-efficient methods should be considered [69-73].

4.3. Microalgae extraction and transesterification methods

A wide range of procedures have been followed to extract the algal lipids. There are many altered and customized procedures deviating from the well-established Bligh and Dyer [74] and Folch et al. [75] methods. In addition, transesterification step was performed using different experimental protocols. Extraction of lipids followed by transesterification or extractive-transesterification (also known as "in situ") are the most commonly reported methods in recent years [71-73]. These methods will need to be standardized soon. Energy consumption should be reported in commonly acceptable expressions such as MJ or kWh per unit biomass. A large disparity remains in the results reported to date.

4.4. Specific energy consumption calculations

As much as possible, specific energy consumption for the entire algal biodiesel production should be reported. These calculations should consider theoretical limitations but should be formed around the practical feasibility. For example, studies based on theoretical estimates tend to be more unrealistic either reporting ambitious values or too pessimistic scenarios. This should be given proper attention. From the discussion presented in other sections, it is clear that the process schemes utilizing centrifugal or mechanical separation/extraction for algal cell harvesting and drying or supercritical conditions for extraction and transesterification steps will not result in desirable energy gains. In addition, nutrient demands in algal cultivation stage should be given proper attention. Because production of these nutrients results in non-renewable energy consumption. Resource recovery, recycling and reuse of these chemical compounds should be considered a priority. Water footprint for algal cultivation is another area of concern. Adequate amounts of water supplies should be made available. Water extraction, conveyance, treatment (if any) and transport requires significant quantities of energy. This is also location and climate specific and species-specific. For example, *Chlorella vulgaris* cultivation has less water footprint when compared with other algal species identified to be suitable for biofuel production [76]. Above all, algal biorefinery schemes for multiple product recovery should be developed. This will improve overall process economics and achieve higher energy gains [77].

4.5. Separation and purification methods

There is no single standard procedure for separation and purification of the final product (biocrude). This introduces a large disparity in the results as well. Very high or low estimates of oil yield and product conversion can be reported if proper protocols are not developed. Efficient (in terms of energy, chemical and costs) methods should be identified and used in all studies regardless of the differences in the extraction and transesterification schemes. This will address the reproducibility and reliability issues.

5. Conclusion

Algal biodiesel production has yet to overcome several hurdles before it can be commercialized. All steps involved in the feedstock preparation to the final product purification steps need significant improvements. It is not possible to achieve energy-positive algal biodiesel production with single product recovery since the process steps are energy- and capital-intensive. Biorefinery schemes that increase the valuable bio-product recovery as well as utilization of spent biomass should be developed to make the overall process affordable and energy-positive. Conventional mechanical separation, harvesting and oil extractions steps should be avoided as much as possible. Theoretical studies should include more realistic assumptions to estimate the lipid yields and process benefits for future scenarios. Novel process intensification techniques such as microwaves and ultrasound should be developed further with more uniform specific energy consumption data to address the reliability issues. Finally, biocrude separation and purification steps are labor intensive consuming significant amounts of chemicals. Proper protocols and procedures should be developed for this step as well. All these efforts will provide exciting opportunities for research and development for scientists, engineers and practitioners all over the world.

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Conflict of interest

No conflicts of interest.

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