Life cycle assessment of biodiesel production from algal bio-crude oils extracted under subcritical water conditions

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Abstract

A life cycle assessment study is performed for the energy requirements and greenhouse gas emissions in an algal biodiesel production system. Subcritical water (SCW) extraction was applied for extracting bio-crude oil from algae, and conventional transesterification method was used for converting the algal oil to biodiesel. 58 MJ of energy is required to produce 1 kg of biodiesel without any co-products management, of which 36% was spent on cultivation and 56% on lipid extraction. SCW extraction with a thermal energy recovery reduces the energy consumption by 3-5 folds when compared to the traditional solvent extraction. It is estimated that 1 kg of algal biodiesel fixes about 0.6 kg of CO₂. An optimized case considering the energy credits from co-products could further reduce the total energy demand. The energy demand for producing 1 kg of biodiesel in the optimized case is 28.23 MJ.

Key words: Life cycle assessment, LCA, subcritical water extraction, biodiesel, greenhouse gas emissions.

1. Introduction

Increase in energy consumption by developing countries forced the search for alternatives for fossil fuels sooner than expected. Biofuels are considered better alternatives for fossil fuels, which also addresses the issues concerning the increase in CO₂ emissions. First generation biofuels are bio-alcohols produced from fermentation of sugars and biodiesel from vegetable oils and animal fat. Several vegetable oils like corn oil, camelina oil, palm oil, soybean oil, canola oil are being used to produce biodiesel (Chisti, 2007). Though the technologies for producing biodiesel from vegetable oils are well developed, it is uncertain that it will be a permanent alternative for fossil fuels. Apart from the fact that using vegetable oil crops for fuel production creates a huge scarcity in the food industry; it also contributes to increase in deforestation (Scharlemann & Laurance, 2008).

Biodiesel from microalgae is a promising solution for the alternative fuel requirements. Microalgae are microscopic organisms which require sunlight and CO₂ for their growth. The biomass content in the microalgae will increase up to two times in less than 24 hours (Zamalloa et al., 2011). One of the main advantages of microalgae is they can be cultivated in waste water or salt water (Sheehan et al., 1998). Microalgae also require less cultivation land when compared to other crops which are used for biodiesel production (Chisti, 2007; Rodolfi et al., 2009). The growth cycles of microalgae are very short when compared to other vegetable oil crops. These factors together with the high lipid content make microalgae a better alternative feedstock for biodiesel production. Microalgae are also used to produce methane by anaerobic digestion of biomass (Collet et al., 2011;

Spolaore et al., 2006), biohydrogen (Ghirardi et al., 2000; Melis et al., 2007), and bioethanol by fermentation of microalgae feedstock (Harun et al., 2010).

The potential future of algal biofuels has interested researchers around the world. The main bottleneck in the production of biofuels from microalgae is the cost associated with it. At present, the energy required to produce algal biofuel is greater than the energy contained in the biofuel (Khoo et al., 2011; Lardon et al., 2009). It is impossible for algal biodiesel to compete with fossil fuels without co-products management. Algae are not only a potential feedstock for biodiesel production; they are also widely used to produce polyunsaturated fatty acids, carbohydrates, vitamins, and dietary fibers in pharmaceutical, biomedical, and nutraceutical industries. It is important to develop technologies that would lead to the production of biofuels and the valuable co-products using the same feedstock.

Several methods are currently being used to produce algal biofuels. There are four major steps involved in the algal biofuel production: 1. Algae cultivation, 2. Harvesting, 3. Lipid extraction, and 4. Conversion of lipids to biodiesel. Harvesting and extraction are the most energy intensive step in the production of algal biofuels. Dry extraction methods require huge amounts of energy in drying the algae and the extracting lipids from them (Lardon et al., 2009). Several extraction techniques are being used to extract algal oil from microalgae. The most common processes include solvent extraction, supercritical CO₂ extraction, and extraction using expeller press (Aresta et al., 2005; Brennan & Owende, 2010). These processes require dry algae as feedstock. The energy consumed during the drying process is so high that it almost accounts for 90 % of the total energy required for algal biodiesel production (Lardon et al., 2009). To address the high energy consumption

wet extraction processes have been explored. Supercritical alcohol conversion of wet algae directly into bio-diesel without extraction using methanol and ethanol has been studied by researchers (Patil et al., 2013; Reddy et al., 2014a). It is not possible to scale-up the process due to limitations in the process.

A recent wet extraction process reported is the sub-critical water (SCW) extraction process. This process does not require dry algae as feedstock, which saves considerable energy spent on the drying process. Also water acts as the solvent in this process, which reduces the energy spent for solvent recovery. Using water as the solvent for extraction makes this process ‘green’ and environmentally friendly. Most of the life cycle assessment studies reported were focused on different algal cultivation systems with solvent extraction as the downstream processing technique. The motivation of this study is to analyze the change in energy requirements and environmental impacts of recent developments in the downstream processing of algal biomass. The main objective of this study is to analyze the life cycle energy requirements and greenhouse gas emissions of algal biodiesel production from the bio-crude produced via sub-critical water extraction. This study also compares the life cycle energy requirements with the traditional solvent extractions reported in other studies.

2. Materials and Methods

2.1. Goal and scope

Life cycle assessment, often known as the cradle-to-grave analysis, is a technique used to analyze the environmental impacts associated with all stages of the production

process. A complete analysis of all the processes involved from raw material synthesis to disposal or recycling of the used product is conducted. There are several bottlenecks in the production of algal biodiesel production. One of the major hurdles is the cultivation of algae. There have been several works in the past that studied the life cycle assessment of energy and greenhouse gas emissions for various algae cultivation methods. Most studies consider solvent extraction as the extraction method in their base case. Some studies do not include the energy associated with the solvent recovery process (Khoo et al., 2011; Lardon et al., 2009; Ventura et al., 2013). In this study, subcritical water extraction is used for the extraction of algal oil. The energy costs involved with solvent recoveries is also included.

The goal of this study is to assess the life cycle energy and life cycle greenhouse gas emissions associated with the production and combustion of algal biodiesel using subcritical water extraction. This study performs a complete well-to-wheels analysis of algal biodiesel production. The life cycle inventory includes cultivation and harvesting of algae, extraction and conversion of algal oil into biodiesel, and production of methane from residual algae using anaerobic digestion. A functional unit of 1 kg of biodiesel is considered and greenhouse gas emissions of combustion of biodiesel and other co-products are also included.

2.1.1. Process description

The algal biodiesel production system considered in this study uses raceway ponds for algal biomass cultivation. The cultivated biomass is harvested using flocculation followed by centrifugation to achieve desired concentration suitable for downstream

processing. The harvested biomass is then sent into a heat exchanger to pre-heat the algae slurry. Then the pre-heated algae slurry is sent to a sub-critical water reactor and heated up to the required temperature to produce bio-crude. After the extraction the hot bio-crude from the SCW reactor sent to the heat exchanger used in the previous step to pre-heat the algae slurry. The cooled bio-crude is then filtered using hexane and the neutral lipids are separated. The separated neutral lipids are then trans-esterified using ethanol to produce algal biodiesel. The residual algae from the extraction process is anaerobically digested to produce methane, which can be used as an energy source.

2.1.2. System boundary

The system boundary considered in this study is shown in Fig. 1. The key energy inputs considered in this study are the energy associated with major processes involved in the biodiesel production, which are: cultivation of algae, harvesting, extraction of algal oil, conversion of biodiesel, and anaerobic digestion. The energy required for hexane recovery during separation of algal oil and the energy required to produce the ethanol used in the conversion process are also included. Energy associated with the nutrient production and hexane production is not included. The factors considered for the greenhouse gas emissions are: the emissions from electricity production, emissions from production of raw materials, and combustion of all the fuel products. The major CO₂ offset is from the cultivation of algae.

2.2. Life cycle inventory

2.2.1. Microalgae cultivation

Microalgae can be grown in both open raceway ponds and photobioreactors. Cultivation of microalgae in raceway ponds is more suitable for mass production than photobioreactors (Chisti, 2007). Study shows that the net energy ratio (NER) of algae cultivation in raceway ponds is higher than photobioreactors (Jorquera et al., 2010). In this study algae cultivation from raceway ponds is chosen to better study the mass production capability of algal biodiesel. The microalgae specie used in this study is *Nanochloropsis salina* 1776, which was cultivated in the Fabian Garcia Science Center at New Mexico State University. The selection of *Nanochloropsis salina* has several advantages. First, *N. salina* is a salt water species, which can be grown using sea water. High salinity growth conditions help to reduce the invasion of other species. Also, the average lipid content of *N. salina* is in the range of 21 – 36% (Gong & Jiang, 2011). A detailed analysis of the life cycle energy requirements for cultivation of *Nanochloropsis sp.* using raceway ponds, flat-plate photobioreactors, and tubular photobioreactors is presented elsewhere (Jorquera et al., 2010). The major energy cost associated with the cultivation step is from pumping of water and CO₂/air mixture into the pond. The CO₂ mixing within the pond was achieved using the turbulent flow generated from pumping.

It is estimated that 876.36 kg water, 0.08 kg nitrogen, and 0.17 kg phosphate are required to produce 1 kg of biomass in raceway ponds using fresh water without recycling (Yang et al., 2011). It is estimated that 1 kg of algae fixes 1.83 kg of CO₂ (Chisti, 2007). In another report, the stoichiometric CO₂ demand for cultivation of algae is estimated as 2.02 g CO₂/g algae (Frank et al., 2013), which is agreeable with Chisti (2007). Fatty acid methyl

ester (FAME) analysis revealed that the neutral lipid content of the *Nanochloropsis salina* used in this study is 24.3%.

2.2.2. Microalgae dewatering

Dewatering the algae is one of the major energy intensive and cost inhibiting steps. Several methods are being used to dewater the algae from the culture medium. Some of them are: centrifuge, dissolved air floatation, flocculation, etc. So far the most efficient method to harvest algae is by using a centrifuge (Lardon et al., 2009). But using a centrifuge makes the process economically and energy wise an expensive one. A two-step dewatering is used to concentrate the algae. An initial flocculation followed by centrifugation is used to harvest the algae. 2 wt.% dry weight and 16 wt.% dry weight can be achieved after flocculation and centrifugation respectively (Xu et al., 2011). This concentration is more than sufficient to use the algae for subcritical water extraction.

2.2.3. Lipid extraction

The subcritical water extraction (SCW) is a novel extraction method which processes wet biomass to extract lipids from algal biomass. The water present in the algae slurry after harvesting could be used as a solvent to extract neutral lipids at selective subcritical conditions of water. When water is heated above its boiling temperature (above 100°C) under pressure, it possesses characteristics of an organic solvent (Savage, 2009). Reddy et al., demonstrated the extraction of neutral lipids from wet algal biomass *nannochloropsis salina* and identified optimal extraction conditions (Reddy et al., 2014b). All the sub-critical water extraction experiments were carried out in a PARR 4593 stainless

steel bench top reactor accompanied by a 4843 controller unit manufactured by Parr Instrument Company (Moline, Illinois, USA). Experiments were designed to study and optimize the reaction parameters; reaction temperature (156-274°C), biomass loading (3-11%) and reaction time (9-35 min.). The experiments were conducted according to the experimental plan and crude extract produced during the extraction process was separated with hexane. The algal crude extract that comes out after the subcritical water extraction contains neutral lipids along with other algae metabolites. The crude extract was then purified to produce algal oil or neutral lipids, which is ready to be converted into biodiesel.

The freshly harvested *Nanochloropsis salina* biomass has a neutral lipid content of 24.3 % by dry weight. Nearly 70% of the neutral lipids were extracted from the wet biomass at 220°C, with 7.5% solids loading and 25 min. of reaction time. So far, these results are higher than any other published extraction methods and consume much less energy. Nearly 32% by weight of dry algae is extracted as crude extract in SCW extraction and 53 wt. % of the extracted crude are neutral lipids. Thus 0.17 kg (70%) of neutral lipids present in the 1 kg biomass is successfully extracted. After the extraction process approximately 0.39 kg of water soluble compounds are dissolved in water and 0.27 kg of residual algae is obtained as bio-char. All the experimental results obtained are average of five replicate experiments. The detailed mass balance for SCW process is shown in Fig. 2.

2.2.4. Biodiesel Conversion

Algal oil possesses similar properties to vegetable oils, which consist of triglycerides. Methanol is commonly used to convert the triglycerides to form fatty acid methyl esters (FAME), which is also known as biodiesel. In our experiments, ethanol is

used in the place of methanol to perform transesterification. For every mole of algal oil, approximately 6.5 moles of ethanol are used for transesterification. It is assumed that 50% of the ethanol can be recovered and re used. Transesterification energy requirements are calculated from the study by Janulis as seen in Table 1 (Janulis, 2004). Density of algal oil and biodiesel are assumed to be 0.9 kg/liter and 0.88 kg/liter respectively. Thus, 0.22 liter of ethanol is needed for producing a kg of biodiesel. The energy demand for ethanol production is obtained from the study by Hill as seen in Table 1 (Hill et al., 2006). From our experiments, it is estimated that 950 g of algal oil is required to produce 1 kg of biodiesel. For each kg of biodiesel 0.11 kg glycerol is produced during conversion (Ventura et al., 2013).

2.2.5. Anaerobic Digestion

Anaerobic digestion of residual biomass is done to produce methane. It is estimated from our experiments that the residual algae accounts for 270 g for each kg of dry algae biomass processed in extraction. According to Collet (2011), a minimum of 40 days is required to achieve 75% methanisation yield (Collet et al., 2011). It is assumed that the methanisation rate, yield, and the quality of the biogas produced are the same for the fresh biomass and the residual biomass. The produced biogas has a composition of approximately 70 % CH₄ and 30 % CO₂ (Collet et al., 2011). Produced biogas is then bubbled into water under high pressure to dissolve CO₂, other gasses, and dust. A 96% methane rich biogas is produced after removing CO₂ and other trace gasses (Collet et al., 2011). All the variables used in this study with their sources of information are shown in Table 1.

3. Results and discussion

3.1. Life cycle energy analysis

In this work a basic functional unit (FU) of 1 kg of biodiesel is considered. To estimate the energy requirements for production of biodiesel, it is necessary to calculate the energy demand in all steps involved in the production. Energy required for transportation of materials is not included in this study. Based on the algae lipid content, lipid extraction efficiency, and the amount of algal oil required to produce 1 kg of biodiesel, it is estimated that 5.6 kg of algae biomass is required to produce 1 kg of biodiesel. According to Jorquera (2010), the total energy consumption per year to produce 100,000 kg of algae in open ponds with a volumetric productivity of 0.035 kg/m³.day is 378.45 GJ (Jorquera et al., 2010). Most of this energy is from the operation of the pump for CO₂ mixing and water input. Hence for producing one functional unit, 21.17 MJ of energy is required in the cultivation step alone. In the harvesting step, centrifugation (0.071 GJ/ton algae) is more energy demanding than flocculation (26.5 kWh/ ton algae). The total energy required to harvest the algae biomass with 16 wt.% concentration is 1.03 MJ/ kg biodiesel.

The algae biomass is fed into the reactor at 7.5 wt.% concentration and heated up to 220°C to perform extraction. The energy requirements for the subcritical water extraction process are calculated based on heat capacities of water and algae. The heat energy required to raise the algae slurry to the required temperature is provided at two stages. In the continuous process the output stream from the SCW reactor will be at a higher temperature and used with a heat exchanger to pre-heat the algae slurry. In Fig. 2, the output stream

from SCW reactor will have heat energy (Q_3), which is equal to sum of $m_1c_{p1}\Delta T$ (Water) and $m_2c_{p2}\Delta T$ (Algae). $Q_3 = (69.08 \text{ kg} \times 4.18 \text{ kJ/kg-K} \times 195 \text{ K}) + (5.6 \text{ kg} \times 1.31 \text{ kJ/kg-K} \times 195 \text{ K}) = 57.74 \text{ MJ}$. The specific heat capacity of algae is assumed to be 1.31 kJ/kg-K . Heat exchanger efficiencies are often assumed as high as 85% in full-scale plants and 90% in pilot-scale plants (Liu et al., 2013). In this study, we assumed a heat exchanger efficiency of 50% in our base case. Hence, 50% of the required heat energy ($Q_2=28.87 \text{ MJ}$) for the SCW process will be obtained from pre-heating and the net heat energy requirement will be $Q_1 = Q_3 - Q_2 = 28.87 \text{ MJ}$.

For each batch of 1 kg (dry algae) biomass, 4 kgs of hexane is used to separate the lipids. The hexane used in this process can be recovered using a distillation column and it is assumed that there is no hexane loss during this process. The energy required for hexane recovery is calculated using the latent heat of evaporation of hexane. The total energy demand for the extraction step including hexane recovery is 32.96 MJ/kg biodiesel. Khoo et al. (2001) estimated that the energy demand for solvent extraction using a mixture of hexane and methanol as 152 MJ/kg biodiesel, which include the energy consumption in the extraction process and energy consumption in evaporation of solvents. This is almost five times higher than SCW extraction energy demand.

Janulis (2004) reported that the electrical energy demand for ethanol transesterification from rapeseed oil as 540 MJ/tonne biodiesel (Janulis, 2004). The energy required to produce a liter of corn ethanol is estimated as 9.68 MJ/liter (Hill et al., 2006). The total energy demand for the biodiesel conversion step including the energy demand for the production of ethanol is 2.66 MJ/kg biodiesel. The main energy costs associated with

the anaerobic digestion step is the electricity consumption from mixers and centrifuges used in the process. The total electricity demand is 0.22 kWh/ kg algae biomass (Collet et al., 2011). Part of the produced biogas is used to supply the necessary heat energy required in the anaerobic digestion process. Thus, the total energy demand for the anaerobic digestion step is 1.17 MJ/ kg biodiesel.

The total energy demand for producing algal biodiesel without co-product management is 58 MJ/kg. The study by Khoo et al., (2011) estimated that the total energy demand for producing algal biodiesel using dry algae biomass is 174.74 MJ/kg without co-products management. In order to calculate the net energy requirement in the production of 1 kg of algal biodiesel energy produced from co-products should be included as energy credit. The energy content of glycerol and methane are 19 MJ/kg and 55.6 MJ/kg respectively (Cuéllar & Webber, 2008; Xu et al., 2011). Thus, the net energy demand for producing algal biodiesel using subcritical water extraction is 46.02 MJ/kg.

3.2. Life cycle greenhouse gas emissions

Biofuels are known to have less environmental impacts than fossil fuels. In order to fully understand the environmental impacts in choosing algal biodiesel, greenhouse gas emissions are estimated for the algal biodiesel production system. Global warming potentials, a relative measure of greenhouse gas emissions in the equivalent of CO₂ emitted, is used to better understand the impacts of greenhouse gasses other than CO₂. Table 2 details the greenhouse gas emission distribution among the sources associated with algal biodiesel production.

Electricity used in various steps of algal biodiesel production contributes to the maximum CO₂ emissions of 3.7 kg CO₂/kg biodiesel, raw materials contribute to 2.31 kg CO₂/ kg biodiesel, and combustion of products contributes to 3.65 kg CO₂/kg biodiesel. Cultivation of algae utilizes maximum amount of electricity, which mainly comes from the pumping costs. A significant technical advancement in algae cultivation can greatly reduce the electricity requirements, which also reduces energy demand and greenhouse gas emissions. Fig. 3 details the CO₂ emissions from different raw materials used in the algal biodiesel production process. CO₂ emissions from ethanol production contribute to 1.256 kg CO₂/kg biodiesel. It is assumed in our process that no recycling of nutrients and fresh water is used for cultivation. If waste water is used in the cultivation process, it will almost avoid the use of nutrients in the cultivation. Recycling the water after harvesting might reduce the water consumption by 60% (Yang et al., 2011).

Net greenhouse gas emissions are calculated by subtracting the CO₂ offsets from the CO₂ emissions. It is estimated that 10.25 kg CO₂/kg biodiesel is consumed during the production of algae biomass. Hence 0.6 kg of CO₂ is being sequestered for every kg of biodiesel produced.

3.3. Sensitivity analysis

Sensitivity analysis is carried out for three scenarios. Scenario 1: 10 % increase in lipid content, Scenario 2: 10 % increase in heat exchanger efficiency, and Scenario 3: 10 % increase in lipid content and 10 % increase in heat exchanger efficiency. It is reported that nitrogen starvation increases the lipid content in microalgae (Lardon et al., 2009). It is also

possible to use an alternate algal species with high lipid content. As discussed earlier, heat exchanger efficiencies are often as high as 90%. We are very conservative in choosing values for the optimized case. The values chosen for the optimized case are very much possible with developments in research. Table 3 details the energy consumption in each scenario. From Fig. 4, it is clear that increase in lipid content reduces the energy demand by 30.4%, and increase in heat exchanger efficiency also reduces the energy demand by 11.9%. The reduction in energy demand is as high as 38.7% in the optimized case.

3.4. Comparison with other studies

Life cycle energy studies on biodiesel production from algae were conducted in the past by other researchers (Hou et al., 2011; Khoo et al., 2011; Lardon et al., 2009; Stephenson et al., 2010). In order to compare the energy requirements in the algal biodiesel production processes proposed by other researchers, all the functional units are converted to 1 kg of biodiesel and co-product credits are excluded. Table 4 details the energy requirements in the algal biodiesel production systems described by Lardon (2009), Khoo (2011), Hou (2011), and Stephenson (2010). These studies used solvent extraction as the preferred extraction method to extract algal oil from algal biomass. The energy requirements vary based on their assumptions during the extraction process and the amount of algal biomass used in the extraction process. The common assumptions that are considered in the previous studies are, 1. The complete extraction of lipids is achieved during extraction, 2. Algal oil behaves like other vegetable oil. Solvent extraction using solvents like hexane is more efficient when the biomass is in dry condition. Unlike other biomass, algal biomass is not harvested in dry condition. It takes huge amount of energy to

dry the algal biomass. Those energy requirements are not completely accounted in these studies. Lipid contents in algal biomass is often assumed as high as 45% (Hou et al., 2011), which is higher than the lipid content incorporated in our optimistic case.

3. 5. Co-products management

Development of valuable co-products is the key to the sustainable biofuel production using algae. One such co-product is eicosapentaenoic acid (EPA). This is an omega-3 fatty acid. It is used in the treatment of certain coronary heart diseases, blood platelet aggregation, and abnormal cholesterol levels (Karmali, 1996). During the SCW extraction EPA is extracted in the form of free fatty acid along with the neutral lipids. A suitable separation process can be deployed to separate the EPA before converting the lipids into biofuels. We discussed the one possible use of residual algae that is produced after extraction. The residual algae have a high heating value (HHV) of 24.7 MJ/kg. Because of this HHV, residual algae can be used along with coal to generate power. Protein analysis showed that the residual algae have 45.6% of crude protein, which makes it a potential animal feed. The proteins can also be extracted to use with commercial food items for human consumption.

3.6. Further discussions

The operating conditions for the SCW extraction process are strain specific. Irrespective of the strain selection, the major energy consumptions in the algal biodiesel production are from cultivation step and extraction step. Though the operating conditions of the sub-critical water extraction process changes with the biomass selection, it is possible to recover the thermal energy used in the process. In this study, we used transesterification

method to produce biodiesel from algal oil. As seen from the sensitivity analysis, neutral lipid content in the algae biomass greatly affects the yield on biodiesel, which in turn affects the energy demand and greenhouse gas emissions.

Energy requirements estimated for our base case and optimized case suggests that more than 50% of the energy demand is from the extraction process. Most of the energy demand is in the form of heat, which is supplied to the heat the algae slurry. If the reactor can be designed to use the solar energy to heat the algae slurry, the energy demand can be significantly reduced. Two main factors that contribute to greenhouse gas emissions are electricity and ethanol. Water, nitrogen, and phosphate accounts to 1.1 kg CO₂ per 1 kg biodiesel. In this work recycling of water and nutrients are not considered. If the water and nutrients are recycled successfully, the greenhouse gas emissions from water and nutrients can be reduced significantly. Khoo et al., (2011) estimated the net CO₂ emissions to be approximately 0.3 kg CO₂ per MJ of biodiesel, which translates into 11.4 kg CO₂ per kg biodiesel (Energy density of biodiesel = 38 MJ/kg). From our estimates, SCW process has a CO₂ offset 0.6 kg CO₂ for every kg of biodiesel produced, which is better than the 11.4 kg CO₂ emissions reported using solvent extraction.

Alternatively, the bio-crude that is obtained from the SCW extraction step can also be used to produce green diesel in the existing petroleum refineries with few or no modifications to the process (Huber & Corma, 2007). Since this process does not require separation of algal oil from bio-crude, the extraction conditions like temperature and time can be optimized for maximum bio-crude yield. Limitations of this study include: the assumption of energy demand for cultivation of algae biomass is same for different species

of microalgae and transportations of materials are not included in calculations of energy demand and greenhouse gas emissions.

4. Conclusions

Extraction of oils from algae biomass is the most energy intensive step in algal biofuels production, making it the “Achilles heel” of the algal biofuel production. For every kg of biodiesel produced, it is estimated that 0.6 kg of CO₂ is sequestered. The SCW extraction process is energy efficient as wet algae are used as feedstock. It reduces the energy demand in the extraction step by 5 times when compared to traditional solvent extraction. The total energy demand for producing biodiesel is 46.02 MJ/kg in the base case and 28.23 MJ/kg in the optimized case. This study shows that algal biodiesel production system using subcritical water extraction possess a potential alternative to traditional solvent extraction.

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Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Table 1

Process	Value	Unit	Reference	Energy demand/produced with 1 kg biodiesel (MJ) ⁺
<i>Cultivation</i>				21.17
Annual biomass production	100,000	kg/yr	(Jorquera et al., 2010)	
Energy consumption for 1 year	378.45	GJ		
Hours of operation (Pumping)	10	hrs/day		
<i>Harvesting</i>				
Flocculation	0.071	GJ/ton algae biomass	(Xu et al., 2011)	0.44
Biomass concentration	2	%		
Centrifugation	26.5	kWh/ton algae biomass		0.59
Biomass concentration	16	%		
<i>Conversion</i>				
Electricity for transesterification	540	MJ/tonne biodiesel	(Janulis, 2004)	0.54
Ethanol production energy demand	9.68	MJ/liter	(Hill et al., 2006)	2.12
<i>Co-product</i>				2.09
Amount of glycerol produced	0.11	kg glycerol/kg biodiesel	(Ventura et al., 2013)	
HHV of glycerol	19	MJ/kg	(Xu et al., 2011)	
<i>Anaerobic digestion</i>				10.89
Methane, 96 vol%	0.201	m ³ /kg algae biomass	(Collet et al., 2011)	
Total electricity consumption	0.2162	kWh/kg algae biomass		
Energy from combustion	2	kWh/kg algae biomass		

⁺ 5.6 kg of dry algae required to produce 1 kg biodiesel

Table 2

Material	Amount	Unit	Global-warming potential (GWP)				For 1 kg biodiesel ⁺
			Material	Emission factor	Unit	Reference	
Consumption							
CO ₂ fixed *	1.83	g CO ₂ /g algae	CO ₂	1	kg CO ₂ /kg	Korea LCI	10.25
Emissions							
<i>Electricity</i>			Electricity	0.495	kg CO ₂ /kWh	Korea LCI	3.69
Cultivation	1.063	kWh/kg algae					
Harvesting	0.0265	kWh/kg algae					
Conversion	0.0268	kwh/kg algae					
Anaerobic digestion	0.2162	kwh/kg algae					
<i>Raw materials</i>							
Water [±]	876.36	kg/kg algae	Water (Industrial)	0.000102	kg CO ₂ /kg	Korea LCI	0.501
Nitrogen [±]	0.078	kg/kg algae	Urea	0.913	kg CO ₂ / kg N	(Wood & Cowie, 2004)	0.397
Phosphate [±]	0.167	kg/kg algae	Phosphate	0.1651	kg CO ₂ /kg	(Wood & Cowie, 2004)	0.154
Ethanol	0.173	kg/ kg biodiesel	Ethanol	7.28	kg CO ₂ /kg	Korea LCI	1.256
<i>Combustion</i>							
Biodiesel	1	kg	Biodiesel	2.94	kg CO ₂ /kg	(Ventura et al., 2013)	2.94
Glycerol	0.11	kg/kg biodiesel	Glycerol	1.43	kg CO ₂ /kg	(Ventura et al., 2013)	0.157
Residual algae	0.27	kg/kg algae	Biogas	0.1836	kg CO ₂ /kWh	(Ventura et al., 2013)	0.555

⁺ 5.6 kg of dry algae required to produce 1 kg biodiesel

* CO₂ demand from (Chisti, 2007)

[±] Water and nutrient requirements calculated from (Yang et al., 2011)

Table 3

	Base Case	10 % increase in lipid	10 % increase in heat exchanger efficiency	Optimized Case
<i>Energy consumed</i>				
Cultivation	21.17	14.66	21.17	14.66
Harvesting	1.03	0.71	1.03	0.71
Extraction	32.96	22.82	27.47	19.01
Conversion	2.66	2.66	2.66	2.66
Anaerobic digestion	1.18	0.81	1.18	0.81
<i>Energy credit</i>				
Glycerol	2.09	2.09	2.09	2.09
Biogas	10.89	7.54	10.89	7.54
Total MJ per kg of biodiesel	46.02	32.03	40.52	28.23
Total MJ per MJ biodiesel*	1.21	0.84	1.07	0.74

* HHV of biodiesel assumed to be 38 MJ/kg

Table 4

	Base Case	Optimistic Case	Lardon (Dry)	Lardon (Wet)	Khoo	Hou	Stephenson
Cultivation (MJ)	21.17	14.66	7.50	10.60	18.03	1.79	7.20
Harvesting (MJ)	1.03	0.71	90.32		1.51		4.20
Extraction (MJ)	32.96	19.01	8.60	30.80	152.00	2.91	2.60
Conversion (MJ)	2.66	2.66	0.90	0.90	3.20	1.71	1.80
Total MJ per kg of biodiesel	57.82	37.04	107.32	42.30	174.74	6.42	15.80

Graphical abstract