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

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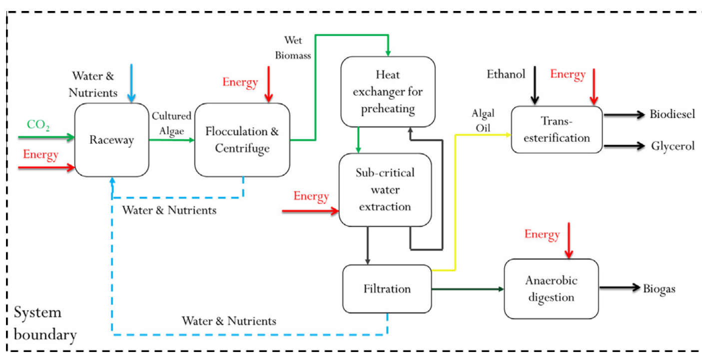
HIGHLIGHTS

- Life cycle assessment of algal biodiesel production from bio-crude oil.
- Estimation of energy consumption and greenhouse gas emissions.
- Subcritical water extraction consumes 3–5 times less energy than solvent extraction.
- Production of 1 kg of algal biodiesel could consume as low as 28.23 MJ of energy.
- 1 kg of algal biodiesel fixes about 0.6 kg of CO_2.

GRAPHICAL ABSTRACT



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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 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 CO_2. 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.

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 CO_2 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

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industry; it also contributes to increase in deforestation (Scharlemann and Laurance, 2008).

Biodiesel from microalgae is a promising solution for the alternative fuel requirements. Microalgae are microscopic organisms which require sunlight and CO_2 for their growth. The biomass content in the microalgae will increase up to two times in less than 24 h (Zamalloa et al., 2011). One of the main advantages of microalgae is that 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 steps 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 CO_2 extraction, and extraction using expeller press (Aresta et al., 2005; Brennan and 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. 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 are 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 are 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 CO_2 offset is from the cultivation of algae.