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Life cycle analyses of CO_2, energy, and cost for four different routes of microalgal bioenergy conversion

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HIGHLIGHTS

- Analyzed four major routes of microalgal bioenergy system.
- Assessment was carried using data obtained from respectable references.
- Conducted extensive assessment of the energy production, CO_2 removal and economic feasibility.
- Included CO_2 mitigation and market feasibility of the microalgal bioenergy systems.
- Covered a complete scheme of microalgae propagation, bioenergy conversion, and waste disposal.

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ABSTRACT

With a target production of 1000 ton of dry algae/yr, lipid content of 30 wt.%, and productivity of 30 g/m^2-d in a 340-day annual operation, four common scenarios of microalgae bioenergy routes were assessed in terms of cost, energy, and CO_2 inputs and outputs. Scenario 1 (biodiesel production), Scenario 2 (Scenario 1 with integrated anaerobic digestion system), Scenario 3 (biogas production), and Scenario 4 (supercritical gasification) were evaluated. Scenario 4 outperformed other scenarios in terms of net energy production (1282.42 kWh/ton algae) and CO_2 removal (1.32 ton CO_2/ton algae) while Scenario 2 surpassed the other three scenarios in terms of net cost. Scenario 1 produced the lowest energy while Scenario 3 was the most expensive bioenergy system. This study evaluated critical parameters that could direct the proper design of the microalgae bioenergy system with an efficient energy production, CO_2 removal, and economic feasibility.

1. Introduction

It is widely accepted that microalgae can serve as a source of either lipid or biomass for biodiesel or other energy conversion processes while assisting CO_2 uptake by photocatalysis. Major advantages of microalgal system include higher growth rates, less land requirement, and higher oil yields than oil producing terrestrial plants (Lardon et al., 2009; Demirbas and Demirbas, 2010). However, factors related with oil content, growth rate, nutrients and water demand, climate conditions, bioreactor design, and techno-economic difficulties of downstream processes make the microalgal system yet uncompetitive for commercial scale applications (Chisti, 2007; Campbell et al., 2011; Lardon et al., 2009; Clarens et al., 2010).

Biodiesel production from microalgae has been described to outperform the bioethanol from sugarcane (Chisti, 2007). However, factors related with strain type, supply of nutrients, water and CO_2, and high energy demand of the downstream processes make it unfeasible for large-scale production. The idea of coupling the anaerobic digestion process with the biodiesel pathway or anaerobic digestion solely provides an alternative solution to decrease the high energy and cost of the algal biofuel (Collet et al., 2011). Anaerobic digestion process does not require stringent dewatering and lipid extraction, thus, significant cost and energy reduction are achievable (Collet et al., 2011). However, the anaerobic digestion rate of microalgal biomass was found to be 60–70% slower than that of the activated sludge (Ras et al., 2011).

Due to the impending problems of the biodiesel production and anaerobic digestion of microalgae, the thermochemical conversion has been suggested to offer a higher energy recovery since it can fully mineralize the feedstock (Stucki et al., 2009). The thermochemical conversions of microalgae include hydrothermal liquefaction, pyrolysis, and supercritical water gasification (SWG) (Stucki et al., 2009; Brown et al., 2010). Hydrothermal liquefaction is used to deal with a high moisture containing biomass (Stucki et al., 2009; Brown

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et al., 2010) while the pyrolysis is known to be suitable for dry feedstock (<5 wt.% moisture) (Brown et al., 2010). These two technologies use relatively lower temperature and pressure and the main products are gases and bio-oils (Brown et al., 2010). The SWG process can also be applied to a high-moisture containing biomass; however, it is operated at a higher temperature and pressure than other thermochemical processes. SWG produces mixed gas including synthesis gas (CO and H_2), methane (CH_4), hydrocarbons (e.g., C_2H_4, C_2H_6, C_3H_8), water, and ash (Stucki et al., 2009; Brown et al., 2010).

Most LCA studies only circumvented on typical scenarios of biodiesel production (Campbell et al., 2011; Lardon et al., 2009; Jorquera et al., 2010; Khoo et al., 2011; Brentner et al., 2011; Collet et al., 2011; Clarens et al., 2010; Pfromm et al., 2011; Stephenson et al., 2010; Xu et al., 2011). This study included scenarios related to bioenergy production such as anaerobic digestion with and without biodiesel production and SWG. In particular, three major aspects of microalgal system (including energy production, CO_2 removal, and economic feasibility of the four different scenarios) were systematically analyzed. The materials and energy (heat and electricity) for producing the transesterified microalgal lipid and anaerobically digested or gasified wet biomass were calculated using realistic values from actual research and reports. The final liquid (biodiesel) and gas (biogas, mixed gas) fuels were assumed to be fed into diesel and combined heat and power (CHP) engines, respectively, employing actual energy conversion efficiency in terms of heat and electricity. The CO_2 generation from the material inputs and outputs were included to determine the net CO_2 uptake of each microalgal bioenergy system. The capital costs and the operating expenses were then evaluated to determine the economic feasibility of the different microalgae bioenergy routes.

2. Methodology

2.1. Four bioenergy routes

Scenario 1 was based on biodiesel production while Scenario 2 was created from Scenario 1 with the integration of an anaerobic digestion of the residuals after lipid extraction. Scenarios 3 and 4 used the wet algae biomass omitting the drying step for the biogas and mixed gas (supercritical gasification) production. Further discussions can be found in the Supplementary data.

2.2. Calculation basis (materials)

2.2.1. Microalgae cultivation

The target production of this LCA study is 1000 dry tons of algae (*Chlorella vulgaris*) per year with a production rate of 30 g/m^2 d (Campbell et al., 2011; Darzins et al., 2010) for 340 days of yearly operation. The algal concentration for the harvesting stage is 0.6 g/L with a lipid content of 30 wt.% (Benemann and Oswald, 1996). The microalga is cultivated in a 0.3 m-deep raceway pond with 0.2 m depth (Weismann and Goebel, 1987; Benemann and Oswald, 1996) of water and the residence time of 4 days (Benemann and Oswald, 1996; Darzins et al., 2010). Nutrients in forms of urea (0.15 g/L) and diammonium phosphate (DAP, 0.01 g/L) (Darzins et al., 2010) are used as the nitrogen and phosphorous sources. CO_2 is supplied at a ratio of 2.2 ton/ton algae and assumed to be obtained from a nearby power plant with the concentration of 15 vol.% (Benemann and Tillet, 1987). Water is supplied continuously using recycled and industrial water. A complete water and nutrient recycle mostly from the harvesting and dewatering steps is assumed to avoid wastage except for the water evaporation loss of 0.3 cm/d (Benemann and Oswald, 1996; Campbell et al., 2011; Darzins et al., 2010).

2.2.2. Harvesting and dewatering step

The harvesting stage adopts the coagulation–flocculation-settling scheme. The concentration of alum coagulant is 0.74 mg/L (Molina et al., 2003) and final biomass concentration and recovery yield were assumed to be 30 g/L and 97% on mass basis, respectively (Benemann and Tillet, 1987).

For further dewatering, a self-discharged disc-stack centrifuge with the recovery yield of 85% (Heasman et al., 2000; Molina et al., 2003; Darzins et al., 2010) is used to obtain a final concentration of 150 g/L algal biomass. Finally, dried biomass with moisture content of 12 wt.% is obtained by using a thermal dryer without biomass loss.

2.2.3. Oil extraction and biodiesel synthesis

Hexane is used at the mass ratio of 0.5 (hexane/biomass) to extract lipid from microalgal biomass. The lipid recovery yield is 80% with corresponding solvent loss of 2 wt.% (Darzins et al., 2010). The recovered hexane (98 wt.%) is reused after distillation. For the esterification of the extracted lipid, an alkali catalyst (1.5 wt.% KOH) and methanol (in excess of 6 M) are used (Darzins et al., 2010). For every gram of C-18 triglyceride, approximately 1 g of biodiesel and 0.11 g of glycerol are produced. The unreacted alcohol is recovered in the distillation column at an assumed efficiency of 99.5%. For crude biodiesel clean-up, phosphoric acid (1.5 wt.% oil) and water (15 wt.% oil) are used (Darzins et al., 2010).

2.2.4. Anaerobic digestion unit

The digester unit is added after the lipid extraction process in Scenario 2 to reutilize extraction residuals for biogas production. In Scenario 3, all wet microalgal biomass is subjected to biogas production. The digester temperature is maintained at mesophilic state without temperature control. The anaerobic digester is operated for 14 days at the loading rate of 0.006 ton VS/m^3·d producing CH_4 gas at 0.2 L/g VS (volatile solids) of the microalgae (Collet et al., 2011; Ras et al., 2011). The total solid (TS) concentration of both Scenarios 2 and 3 is maintained at 93 g/L and the VS content is assumed to be 0.9 g VS/g TS (Collet et al., 2011; Ras et al., 2011). The solid digestate is recovered by centrifugation of the effluent using the same centrifugation specification and efficiency as the harvesting stage. The liquid digestate, however, is returned to the pond assuming no fertilization effect on the microalgae cultivation system.

2.2.5. Supercritical gasification unit

The supercritical gasification of microalgae is carried out after the centrifugation of the microalgal biomass. The biomass with a moisture content of 85 wt.% is gasified at 500 °C and 24 MPa with the loading rate of 7.73 g wet biomass/L h (Brown et al., 2010). A Ru/TiO_2 catalyst is added to catalyze the supercritical water gasification with a catalyst/biomass ratio of 0.7 g/g (Brown et al., 2010). No experimental data is available on the residual content after the gasification, therefore it is assumed that the ash content was the same as the chemical composition of *C. vulgaris* (7 wt.% ash) (Chanikala et al., 2010). The product gas is composed of 3.2, 0.046, 5.35, 5.904, 0.087, and 1.87 mmol/g algal biomass for H_2, CO, CH_4, CO_2, C_2H_4, and C_2H_6, respectively (Brown et al., 2010).

2.3. Calculation basis (energy)

In order to analyze net energy output or return, each scenario was evaluated in terms of their energy demand and production. The energy requirements starting from the upstream to the downstream were selected from literatures (Lardon et al., 2009; Clarens et al., 2010; Jorquera et al., 2010; Stephenson et al., 2010; Brentner et al., 2011; Campbell et al., 2011; Collet et al., 2011; Khoo et al.,