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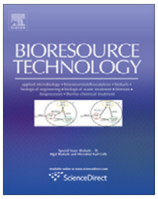

Life cycle energy and CO_2 analysis of microalgae-to-biodiesel: Preliminary results and comparisons

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ABSTRACT

Despite claims that microalgal biofuels are environmentally friendlier alternatives to conventional fuels, debate surrounding its ecological benefits or drawbacks still exists. LCA is used to analyze various biofuel production technologies from 'cradle to gate'. Energy and CO_2 balances are carried out for a hypothetical integrated PBR-raceway microalgae-to-biodiesel production in Singapore. Based on a functional unit of 1 MJ biofuel, the total energy demands are 4.44 MJ with 13% from biomass production, 85% from lipid extraction, and 2% from biodiesel production. Sensitivity analysis was carried out for adjustments in energy requirements, percentage lipid contents, and lower/higher heating product value. An 'Optimistic Case' was projected with estimates of: 45% lipid content; reduced energy needs for lipid extraction (1.3 MJ per MJ biodiesel); and heating value of biodiesel (42 MJ/kg). The life cycle energy requirements dropped significantly by about 60%. The results are compared with other published case studies from other countries.

1. Introduction

International concerns of fossil fuel depletion, energy security and CO_2 emissions are the main drivers for the search of alternative sources of energy such as biofuels. The seemingly 'green' first -generation biofuels (from palm oil, corn, and other food crops) have spawned huge disputes over their contribution to increased food prices and the neglect of accounted greenhouse gas emissions due to land use changes (Demirbas and Demirbas, 2011; Halim et al., 2011). Many authors claim that the conversion of food crops into biofuels is unsustainable, not just on the basis of threatening food supply, but also rise in deforestation rate and damages to biodiversity (Scharlemann and Laurance, 2008; Khoo et al., 2009).

Biofuels from microalgae are fast attracting international research interest because compared to those from food crops – they are the fast growing plants that do not compete for agricultural land since they can grow in ponds or vertical photobioreactors (PBRs). Microalgae have high photon conversion efficiency with the metabolic storage of carbon intensive molecules in the form of intracellular lipids, carbohydrates and triglycerides. Microalgae are reported to produce 15–300 times more feedstock for biodiesel production than conventional, terrestrial bioenergy crops on an area basis (Christi, 2007). Microalgae are the most efficient converters of sunlight and CO_2 into biomass of all plants. Coupling the photosynthetic efficiency of microalgae with biomass production therefore offers exciting prospects for the utilization of biogenic carbon for producing renewable biofuels (Greenwell et al., 2010; Scott et al., 2010).

The production of microalgae consists of four primary processes: (i) cultivation, (ii) harvesting, (iii) lipid extraction, and (iv) oil conversion to final products (e.g., biodiesel).

1.1. Microalgae cultivation

Microalgae can be grown in both fresh and saline or brackish water. Mass cultivation of microalgae should ideally rely on open culturing since the cost of the materials for a closed system and the typical mixing energy inside the closed system are prohibitory expensive (Greenwell et al., 2010). However, a very small fraction of the entire volume needs to be cultured in a closed system (photobioreactors), equipped together with artificial lighting, to supply the algal feed biomass material for the open system (Huntley and Redalje, 2007). A few design and engineering aspects need careful attention to minimize evaporation loss and contamination problems, as well as, significant water losses in open pond systems. In this article, an integrated photobioreactor-raceway pond for microalgae cultivation will be introduced.

In order to grow, microalgae need a source of water and essential nutrients, which are collectively referred to as the culture medium. Microalgae rely on several nutrients to prosper, mainly, nitrogen (N), phosphorous (P), and source of CO_2, which would ideally be supplied from a power plant flue gas. The way in which water, nutrients, land, and light are supplied and managed for cultivation will affect the amount of energy requirements and associated CO_2 emitted.

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1.2. Biomass harvesting

There are several techniques for recovering algal biomass, the implementation of each type may vary depending on the cultivation system employed. Microalgae have very small cell size (typically less than 20 μ). Therefore engineering challenges lie in reducing the energy demands of separating or isolating the microalgal cells from the culture medium. Presently, the major techniques for harvesting microalgae are centrifugation, filtration, coagulation-flocculation and flotation (Molina et al., 2003). Although a few strains (e.g., *Haematoccocus*, diatoms) settle by their own weight, such species display relatively lower growth rates, especially in the absence of mixing (Huntley and Redalje, 2007). Microalgae are cultivated in aqueous systems and removing the water content (dewatering) to produce dry algal biomass is necessary before the next stage.

1.3. Microalgal oil (lipid) extraction

In the third stage of microalgae-to-biofuel system, chemical or mechanical processes are used to isolate the oils or lipid from the microalgae biomass. There are various metabolic pathways explored in the biosynthesis of lipids. The isolation of algal oil or lipids from microalgae cells remain one of the challenges in hindering algal biodiesel production from becoming both feasible and economical (Christi, 2007; Brennan and Owende, 2010).

Lipid extraction can be achieved via a number of techniques such as mechanical expulsion, solvent extraction, and supercritical fluid extraction (Demirbas and Demirbas, 2011). Various biotechnology research areas have invested interest on microalgal lipid productivity and composition as feed for aquaculture applications or from nutritional perspectives (Greenwell et al., 2010). Lately, however, interest has been on the extraction methods and corresponding energy demands of algal lipid-derived biofuels (Ehimen et al., 2010). This renewed focus has driven the direction and objectives of this article.

1.4. Oil and residue conversion

The final stage for producing biodiesel from microalgal biomass is the conversion – via thermo-chemical or other kinds of process routes – of the lipids to the final bioenergy product (Halim et al., 2011). The properties of the biodiesel product (defined as alkyl esters of fatty acid constituents of lipids), are mostly determined by the structure and composition of the microalgal lipids (Knothe, 2005).

One of the key requirements of the entire microalgae-to-biodiesel production chain is to minimize the energy demands of each process step. Preferably, the selected lipid extraction technology – along with the culture and harvesting methods – has to be energy efficient in order to make the entire system feasible. This requirement is even more necessary when the oil extraction and conversion method is applied directly to a wet feedstock (Greenwell et al., 2010). This article will include the theoretical energy requirements of biodiesel produced via trans-esterification using methanol as a catalyst to yield biodiesel and glycerol:

$$\text{Lipid} + \text{Methanol} \xrightarrow[\text{Conversion}]{} \text{biodiesel } (90\%) + \text{glycerol } (10\%)$$

2. Methods

2.1. Life cycle assessment of biodiesel production

Life cycle assessment (LCA) is a systematic environmental management tool used for quantifying the input–output inventory of a product system throughout its life cycle stages, and projecting the environmental performance based on a selected functional value (known as functional unit) of the product (Gnansounou et al., 2009; Khoo et al., 2009, 2010).

Owing to the variety of biomass feedstock for bioenergy processes, along with the debates on the final environmental benefits or drawbacks of such systems, LCA has been increasingly applied as a useful tool to analyze and compare various biofuel production technologies from a life cycle perspective (Pleanjai and Gheewala, 2009; Yee et al., 2009; Sanz Requena et al., 2011; Clarens et al., 2010). In some cases, the primary focus of the LCA investigation is on the energy demands (e.g., Jorquera et al., 2010) and CO_2 emissions of the process chain (e.g., Stephenson et al., 2010), especially when the LCA is applied for comparing bioenergy products.

The technical framework for the LCA methodology, according to the ISO 14000 series (ISO 14041-43), consists of four phases: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and(4) interpretation.

The ISO (2006) standard is adopted for all case studies investigated in this article. The case study based on a lab-scale production of microalgae from the Institute of Chemical and Engineering Sciences (ICES) in Singapore.

2.2. LCA goal and scope

The overall goal of the preliminary study is to compare life cycle energy and life cycle CO_2 of the following:

(I). ICES microalgae-to-biodiesel production:
  - from cultivation and harvesting (integrated lab-scale),
  - lipid extraction (lab scale with estimated energy requirements),
  - theoretical Conversion (from literature),
  - sensitivity analysis.

(II). Comparison of ICES microalgae-to-biodiesel system with five other case studies.

For (II), comparisons will be made against ICES 'Base Case' and a projected 'Optimistic Case'.

The twofold objectives are to highlight the main areas for improvement, as well as, benchmark ICES' bioenergy developments as compared to others. Since the various product streams from different microalgae types and technologies do not allow a justifiable LCA comparison, this article will only focus on the value of the final biofuel product. Therefore the selected functional unit for all cases is 1 MJ as the high calorific value of biodiesel.

2.2.1. Energy balance

The energy balance in a microalgae-to-biofuel system can be quantified by comparing energy inputs required in each LCA stage, and compare the total required inputs with the embodied energy of that biofuel product. Many aspects of microalgae-to-biofuel production can influence the energy balance and each stage in the production process could have far-reaching impacts on the rest of the production chain. The authors seek to highlight the main bottleneck or energy demands of the case study, which will be introduced in the next section.

2.2.2. CO_2 balance

In accounting for CO_2 balance of the system, it is critical to consider the total emissions from fossil energy and resource consumption vs. the CO_2 intake by the microalgae during cultivation. Concentrated CO_2 should ideally come from nearby power plant or other point sources. Depending on different microalgae or algae species, the resulting net greenhouse gas emissions may turn out to be CO_2 deficit (due to large amounts of CO_2 absorbed via photosynthesis) or otherwise (more CO_2 emitted than absorbed). Patil