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Effects of co-products on the life-cycle impacts of microalgal biodiesel

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HIGHLIGHTS

- This study investigated a cradle-to-gate microalgal biodiesel and its co-products.
- Ozone depletion, global warming, smog, acidification and eutrophication potentials were assessed.
- The market opportunities for each co-product were examined.
- The scenario with the least life-cycle environmental impacts has the highest net energy ratio.
- The scenario also had the highest total income indicating their co-products market potential.

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ABSTRACT

Microalgal biodiesel production has been investigated for decades, yet it is not commercially available. Part of the problem is that the production process is energy and chemical intensive due, in part, to the high portion of microalgal biomass left as residues. This study investigated cradle-to-gate life-cycle environmental impacts from six different scenarios of microalgal biodiesel and its co-products. Ozone depletion, global warming, photochemical smog formation, acidification and eutrophication potentials were assessed using the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI). Monte Carlo Analysis was conducted to investigate the processes with major contribution in each impact category. The market opportunity for each co-product was examined based on supply, demand and prices of the products that could potentially be substituted by the co-products. The results indicated that the scenario with the least life-cycle environmental impacts in all the five impact categories with the highest net energy ratio was the scenario utilizing a multitude of co-products including bioethanol from lipid-extracted microalgae (LEA), biomethane (to produce electricity and heat) from simultaneous saccharification–fermentation (SSF) residues, land-applied material from SSF residue anaerobic digestion (AD) solid digestate, recycling nutrients from SSF residue AD liquid digestate and CO_2 recovered from SSF process contributed. Decreasing the energy consumption of the centrifuge in the land-applied material production process and increasing the lipid content of microalgae can reduce environmental footprints of the co-products. The same scenario also had the highest total income indicating their potential as co-products in the market.

1. Introduction

Biodiesel from microalgae has a potential to replace petroleum diesel, the highest petroleum fuel consumed in the U.S. transportation sector (U.S. Energy Information Administration, 2013a). Microalgae as a biodiesel feedstock has several advantages over other fuel crops since the cultivation of microalgae can be located on non-arable land, and thus it does not compete with food crops (Campbell et al., 2011). However, microalgal biodiesel production is currently not economically viable compared to other biodiesels due, in part, to the energy and chemical intensive nature of current harvesting and lipid extraction methods. Moreover, there is a high portion of microalgal biomass left as residues after lipid extraction compared to the resource consumed. One of the strategies to enhance microalgal biodiesel production is by producing valuable co-products from the algae residue and the by-products of transesterification. Glycerol can be used as a heat source for other production processes or as a carbon source in microalgal cultivation systems, open ponds and photobioreactors (PBRs) (Vasudevan and Briggs, 2008). Lipid-extracted algae (LEA) results from residues

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left from the microalgal oil extraction process; LEA can be used directly as animal feeds and land application for purposes of fertilizing or as a feedstock to produce bioethanol and biomethane (Ehimen et al., 2009; Yang et al., 2010). Biomethane can be further converted to heat and electricity via Combined Heat and Power (CHP). Anaerobic digestion (AD) can be used to convert LEA to methane, while simultaneous saccharification and fermentation (SSF) and distillation are the processes to convert LEA to bioethanol (De Paoli et al., 2011; Ritslaid et al., 2010). In addition, residues from AD, which consist of both solid and liquid substrates, can be land applied as a fertilizer and nutrients can be recycled to algae photobioreactor (PBR), respectively (Park et al., 2012). Residues from bioethanol production can be categorized into distillation residue for animal feeds or land-applied materials and SSF residue for biomethane (for electricity and heat) production (Balan et al., 2009; das Neves et al., 2007; Harun et al., 2010). Another by-product from bioethanol production is carbon dioxide (CO_2), which can be recycled and fed to PBR as a carbon source for microalgae. CO_2 from the fermentation is normally recovered and cleaned for carbonation of beverages and frozen into dry-ice for food industry (Ritslaid et al., 2010; Xu et al., 2010). Approximately, only 5–7% of the total CO_2 produced from the fermentation process are captured (U.S. Environmental Protection Agency, 2010).

Life cycle assessment (LCA) is an appropriate tool to examine and compare environmental impacts from microalgal biodiesel along with its different co-product combinations. LCA is a tool to quantify environmental impacts over the entire life cycle of product, process or service (International Organization for Standardization, 2006). In this study, a cradle-to-gate LCA was used to analyze the benefits of different co-product strategies; the LCA includes the production of microalgal biodiesel from microalgal biomass to conversion process and the productions of bioethanol, biomethane (heat and electricity), animal feed, land-applied materials (from LEA, distillation residue, SSF residue AD solid digestate and LEA AD solid digestate), recycling nutrients, glycerol and CO_2 from various residues from the microalgal biodiesel production, and excludes the use and end-of-life stages of the products.

This LCA quantifies the environmental impacts and analyzes the tradeoffs from different microalgal biodiesel co-products pathways and identifies opportunities for production process improvements. Following the ISO 14040 series framework for conducting an LCA, this study compares six different microalgal biodiesel co-product pathways, examines tradeoffs among the different pathways, investigates the process with the major contribution in each environmental impact category and indicates opportunity of the co-products in the market.

2. Methods

A comparative LCA of six microalgal biodiesel co-product scenarios were conducted to quantify their environmental impacts and net energy ratio (NER). The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI 2 version 4), which is a life cycle impact assessment (LCIA) tool developed by U.S. Environmental Protection Agency particularly for the U.S., was used to quantify five environmental impact categories (Bare et al., 2003). The environmental impacts considered were ozone depletion potential (ODP), global warming potential (GWP), smog formation potential (SFP), acidification potential (AP) and eutrophication potential (EP). The results were further investigated for production processes with major contribution to each impact category using Monte Carlo Analysis (MCA). Sensitivity analysis results from other scenarios considered in this study are available in the Supplementary Information (SI). Production and consumption quantities and prices of each microalgal biodiesel co-product were plotted and compared to other existing products in the same category to present the economical perspective of this study and inform the industry on the market opportunity.

2.1. LCA of microalgal biodiesel and its co-products

Microalgal biodiesel and its by-product, glycerol, were included in all scenarios. The six co-product scenarios are summarized in Fig. 1 and include (1) land-applied material from LEA, (2) animal feed from LEA, (3) bioethanol from LEA with land-applied material from distillation residues and CO_2 recovered from SSF process, (4) bioethanol from LEA with animal feeds from distillation residues and CO_2 recovered from SSF process, (5) bioethanol from LEA with biomethane (to produce electricity and heat) from SSF residues, land-applied material from SSF residue AD solid digestate and recycling nutrients from SSF residue AD liquid digestate and CO_2 recovered from SSF process and (6) biomethane from LEA with land-applied material from LEA AD solid digestate and recycling nutrients from LEA AD liquid digestate. A system expansion was conducted to include all the co-products of each scenario in the system boundaries. System boundaries of the microalgal biodiesel co-products scenarios are presented in Fig. 1. Functional unit of this study is 2 million gallons of microalgal biodiesel per year, which is the biodiesel production capacity of Arizona, U.S. in 2013, equals to 2.68×10^8 MJ of microalgal biodiesel (U.S. Energy Information Administration, 2013b). The production capacity in MJ was calculated based on the energy content and the density of microalgal biodiesel, which are 41 MJ/kg of microalgal biodiesel and 86.4 kg/m^3, respectively (Huang et al., 2010). The functional unit was chosen since Arizona is located in the Southwest U.S. where climate, land and water availability are suitable for microalgal biomass production (Sheehan et al., 1998).

2.1.1. System boundaries and life cycle inventory

Microalgal strain *Chlorella vulgaris* was cultivated in 36,000 units of 10 m^3-flat-plate PBR. The compositions of microalgae are 30% of lipid, 37% of carbohydrate and 33% of protein (Lardon et al., 2009). Microalgae were cultivated under sunlight and in municipal wastewater for water and nutrients, such as nitrogen and phosphorus. Flue gas with 14% of CO_2 gas by weight was fed to PBR as a carbon source. Microalgal biomass was harvested by 95% efficiency flocculation process for microalgal cake, which was dried by air-dry method for microalgal chip. A homogenizer cell disruption technique was applied to improve conventional solvent extraction efficiency (Shelef et al., 1984). Then microalgal chip was extracted by 91% efficient hexane solvent extraction process for microalgal oil. Finally, microalgal oil was converted to microalgal biodiesel via transesterification process utilized a conventional homogeneous alkaline catalyst (NaOH). Biodiesel and glycerol, which is a by-product of the biodiesel production process, were produced in 1:1 ratio. Glycerol can be co-liquefied with manure to improve bio-oil production yield; however this study included glycerol based on its average energy content of 14.6 MJ/kg of glycerol (Yang et al., 2012). LEA from lipid extraction process was used as land-applied material or animal feeds or as a raw material to produce bioethanol through SSF process or as a raw material to produce biomethane through AD process.

Bioethanol production produced CO_2 as a co-product, which was captured and recycled to the PBR cultivation system. The bioethanol production also produced two residues, which were SSF residues from SSF process and distillation residues from distillation process. SSF residues were used as a feedstock to produce biomethane, while distillation residues can be used as land-applied material and animal feeds. To produce land-applied material, distillation residues were processed through centrifugation, whereas