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Microalgal biodiesel and the Renewable Fuel Standard's greenhouse gas requirement

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ABSTRACT

The Renewable Fuel Standard (RFS2) under the Energy Independence and Security Act of 2007 requires 15.2 billion gallons of domestic alternative fuels per year by 2012, of which 2 billion gallons must be from advanced biofuel and emit 50% less life-cycle greenhouse gas (GHG) emissions than petroleum-based transportation fuels. Microalgal biodiesel, one type of advanced biofuel, has the qualities and potential to meet the RFS's requirement. A comparative life cycle assessment (LCA) of four microalgal biodiesel production conditions was investigated using a process LCA model with Monte Carlo simulation to assess global warming potential (GWP), eutrophication, ozone depletion and ecotoxicity potentials. The four conditions represent minimum and maximum production efficiencies and different sources of carbon dioxide and nutrient resources, i.e. synthetic and waste resources. The GWP results of the four CO_2 microalgal biodiesel production conditions showed that none of the assumed production conditions meet the RFS's GHG requirement. The GWP results are sensitive to energy consumption in harvesting process. Other impacts such as eutrophication, ozone depletion and ecotoxicity potentials, are sensitive to percent lipid content of microalgae, service lifetime of PBRs and quantity of hexane in extraction process, respectively. Net energy ratio and other emissions should be included in future RFS for a more sustainable fuel.

1. Introduction

The Renewable Fuel Standard (RFS) under the Energy Independence and Security Act (EISA) of 2007 requires domestic alternative fuels to meet 15.2 billion gallons by 2012, of which 2 billion gallons must be from advanced biofuels. Advanced biofuels, which include cellulosic biofuel, biomass-based diesel and other advanced biofuel, are the renewable fuels other than corn ethanol (U.S. Environmental Protection Agency, 2010). In addition, life-cycle greenhouse gas (GHG) emissions from advanced biofuels must be at least 50% less than GHG emissions from petroleum-based transportation fuels distributed in 2005 (Office of Transportation and Air Quality, 2010a, b). Microalgal biodiesel, an advanced biofuel, has the potential to support the U.S. transportation fuel and meet the RFS's advanced biofuels requirement (U.S. Department of Energy, 2010). Microalgae have been investigated for the production of a number of different products including methane, ethanol, electricity and biodiesel (Batan et al., 2010; Li Q., et al., 2008; Sander and Murthy, 2010; Stephenson et al., 2010).

Microalgae as biodiesel feedstock have a high growth rate, high productivity, and high photosynthetic efficiency (Avagyan, 2008; Bruce, 2008; Lehr and Posten, 2009; Li Y., et al., 2008; U.S. Department of Energy, 2010). These characteristics comply with the needs established by the Roadmap for Bioenergy and Biobased Products in the U.S. which are that it is easy to grow, exhibits high yields, and provides good quality fuel (Avagyan, 2008; Biomass Research and Development Technical Advisory Committee and Biomass Research and Development Initiative, 2007). The quality of microalgal biodiesel meets American Society for Testing and Materials (ASTM) Biodiesel Standard D6751, thus can substitute for petroleum diesel (Bruce, 2008; Chisti, 2007). Microalgal cultivation has been shown to consume limited land and less water resources than terrestrial biofuel crops. The study by Chisti in 2007 suggested that the land for microalgal cultivation requires only 1–3% of the total agricultural area in the U.S. for the same oil-crop diesel yield (Chisti, 2007).

Microalgal cultivation considered in this study was assumed to occur in a closed photobioreactor (PBR). Compared to open ponds, the PBR has a better control of cultivation conditions such as mass transfer, water loss by evaporation, and contamination (Li Y., et al., 2008; Posten, 2009). The PBR system is suitable for sensitive strains since contamination can be controlled more easily than in an open pond. The cell mass productivity of PBRs is about three times higher than the productivity of open ponds; hence

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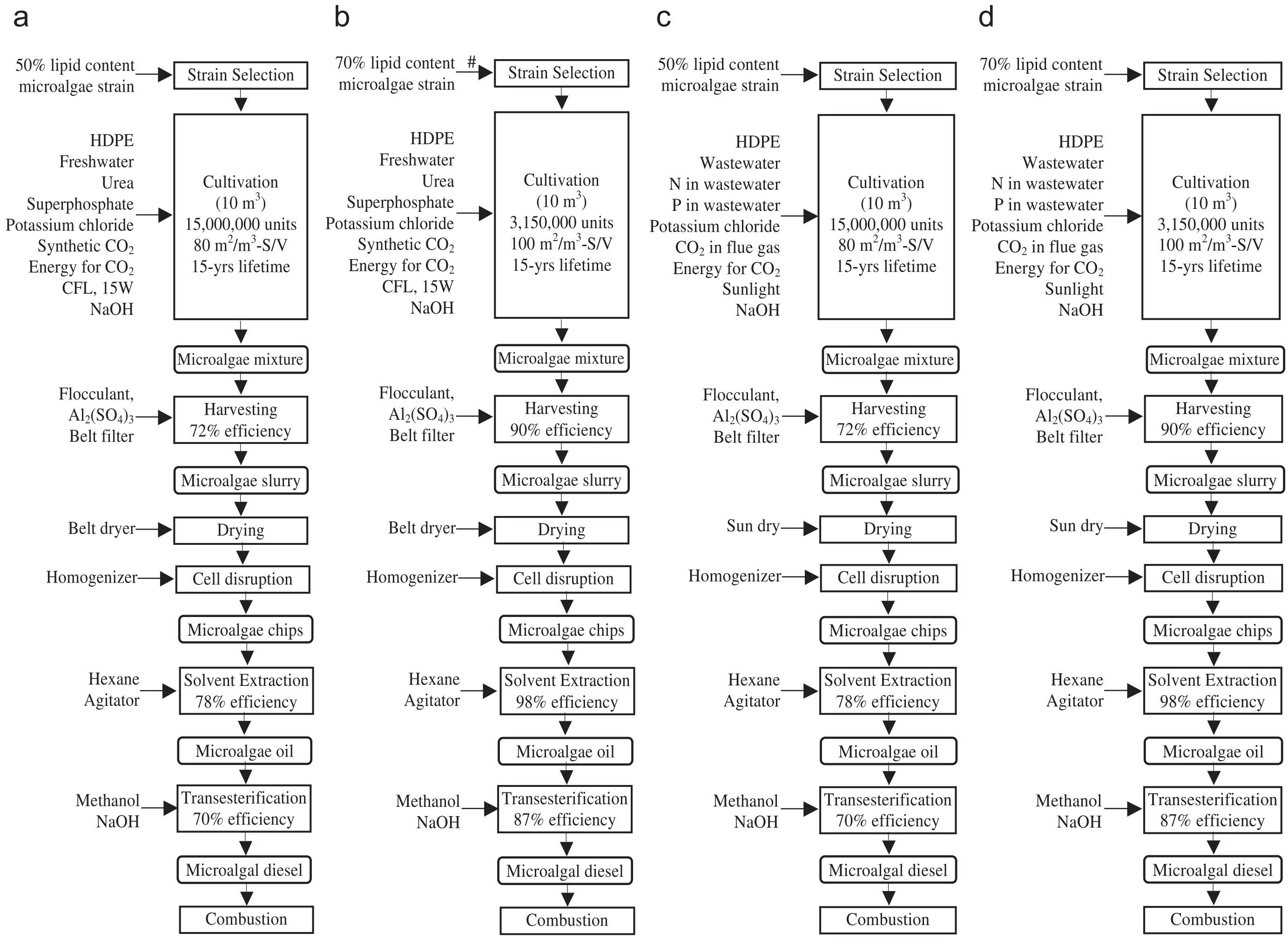

Fig. 1. *System boundaries of microalgal biodiesel production conditions.* (a) The low-efficiency production with synthetic resources; (b) the high-efficiency production with synthetic resources; (c) the low-efficiency production with waste resources; (d) the high-efficiency production with waste resources.

harvesting costs can be significantly reduced. Although the volume of industrial PBR is 5–10 m^3, some designs can be scaled to larger volume of 10–100 m^3, and the most practical method to increase the PBR volume is by adding more PBR units (Carvalho et al., 2006; Janssen et al., 2003). While the closed PBR is a viable alternative for large scale production of microalgae biomass, its operation is still more costly than open ponds (Carvalho et al., 2006; Posten, 2009).

Although various advantages support the potential of using microalgae as biodiesel feedstock, due to certain limitations, not many applications have reached the industrial scale (Carvalho et al., 2006). The limitations of cultivation techniques include the low yield from open ponds and the high cost of PBRs (Lehr and Posten, 2009). High harvesting costs have been observed due to the lighting limitations of the cultivating systems and due to the low concentration of biomass in the systems, which result from the relatively small cell-size of microalgae. Drying is also an energy-consuming process due to the large water content of the harvested biomass. In addition, microalgal cultivation facilities require higher capital cost and more operation and maintenance compared to conventional agricultural activities. However, the development of new technologies is expected to overcome these limitations (Li Y., et al., 2008).

Life cycle assessment (LCA) is a tool that can be used to examine the resource consumption and potential impacts of any product or service (International Organization for Standardization, 2006; Udo de Haes and van Rooijen, 2005). LCA consists of four main steps: (1) goal and scope definition, (2) life-cycle inventory (LCI), (3) life cycle impact assessment (LCIA) and (4) interpretation. LCA is applied to this study to quantify resource consumption and environmental and human health impacts from pond to wheel or from microalgal cultivation to microalgal biodiesel consumption.

The objective of this study was to conduct a comparative LCA on four conditions of microalgal biodiesel productions to evaluate their potential to meet the RFS2 and then to identify processes or inputs that could be targeted to minimize the overall environmental impact of microalgal biodiesel production. A common perception is that high-efficiency production with *synthetic* resources (condition HS) might consume more energy with better system control, while a production scenario utilizing *natural* and *waste* resources (i.e. conditions HW and LW) might consume more energy in preparing and cleaning resources from waste streams with unpromising yield. LCA enables researchers and policy makers to quantify the impacts of these systems and investigate tradeoffs. In addition, we use LCA results from this study to evaluate policies such as the RFS and to improve upon the production of microalgal biodiesel. Co-product allocation was not conducted due to uncertainties related to yield and quality of co-products and by-products.