



Full length article

Life cycle assessment of microalgae based biodiesel production to evaluate the impact of biomass productivity and energy source



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ABSTRACT

In the present study the life cycle assessment (LCA) of three scenarios for biodiesel production from *Scenedesmus dimorphus*, a freshwater microalgae, cultivated in open raceway ponds using primary and secondary data was investigated. The main differences in the scenarios were related to biomass productivity, mode of culture mixing and type of energy source. The process steps included algal cultivation in open raceway ponds, harvesting by chemical flocculation, dewatering by mechanical drying option (MDO)/Spray Drying (SD) followed by extraction, reaction, and purification. Supplementation of the cultivation process with electricity derived from defatted algal biomass waste was also analyzed. The scenarios were evaluated for energy demand and environmental impacts amongst the boundary conditions based on a “cradle-to-gate” inventory. The results revealed that among all the scenarios, cultivation in raceway pond was ascertained to be the most energy intensive process with the mode of culture mixing and biomass productivity being the principal determinants. The impacts were found to be directly linked to energy demand and had an inverse relationship with biomass productivity. The geographic location of the energy sources affected the environmental implications of a given process. The integration of defatted algal biomass waste derived electricity with the cultivation system showed a minor reduction in the overall energy demand.

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1. Introduction

The consumption of fossil fuel and its resulting effect on the atmosphere regarding increased levels of CO₂ have been recognised as a leading cause of climate change (Anemaet et al., 2010). Finding new sources of alternative and sustainable biofuel would contribute towards reduction of CO₂ emissions (Pittman et al., 2011). Currently, bio-ethanol and biodiesel are extracted and commercialised from varied sources such as sugarcane, palm, rapeseed and agro-residue. Although the crop based biofuels are environmentally more favourable compared to fossil fuels, concern over loss of biodiversity due to competition for agricultural land between food and energy production limits their long-term sustainability (Khoo et al., 2009).

Aquatic crops, such as microalgae, are attaining substantial interest globally as a potential source of biofuel since they can achieve higher growth rates compared to terrestrial crops. Also, cultivation of microalgae does not constitute a threat to food security as they do not compete with food crops for land or water (Jonker and Faaij, 2013) since they can be cultivated in non-agricultural land and can utilise brackish and saline water minimising the usage of fresh water (Abu-Ghosh et al., 2015; Collet et al., 2015). The sustainability and economic viability of algal biofuel production can be further enhanced by utilising the nutrient rich industrial effluent and municipal wastewater for microalgal cultivation (Pittman et al., 2011). Microalgae have also been recognised for their CO₂ biomitigation potential with the possibility of feeding industrial flue gases to microalgal cultivation systems, thereby decreasing the CO₂ emissions to the environment (Demirbas, 2011).

Open raceway pond cultivation systems have been shown to be economical with a higher net energy ratio compared to closed photobioreactors (Jorquera et al., 2010) and are preferred for mass cultivation of microalgae, e.g., *Chlorella* sp., *Nannochloropsis* sp., *Dunaliella* sp., and *Spirulina* sp. The downstream processes involved

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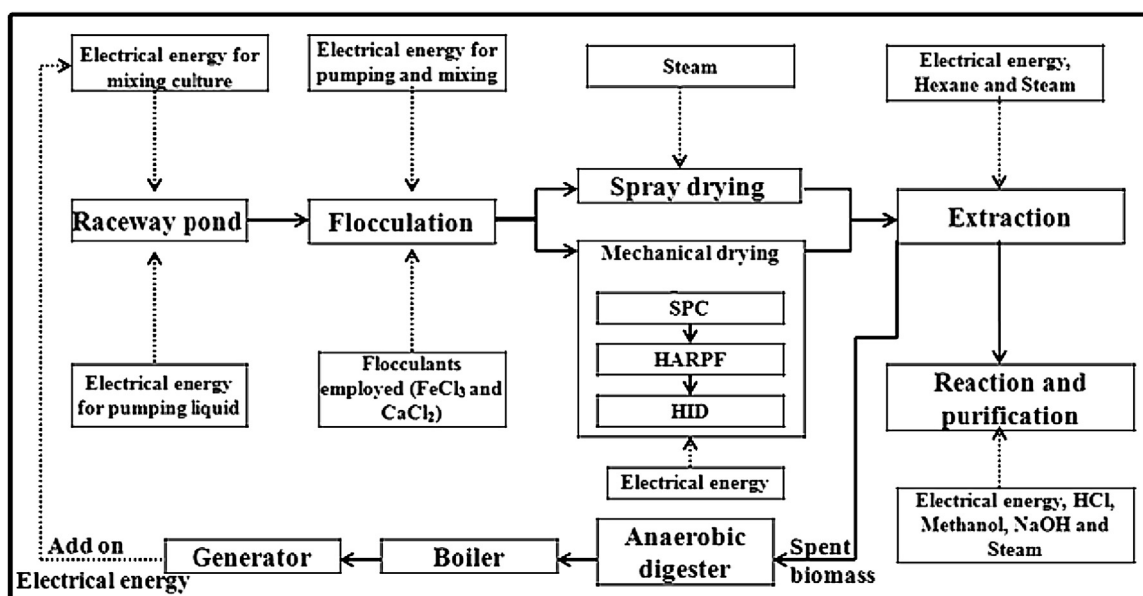


Fig. 1. Overview of microalgae biodiesel production coupled with biogas generation system, process inputs (dotted lines) and energy required for each stage. (SPC-Spiral centrifuge, HARPF-Heat assisted rotary pressure filter, HID-Heat integrated dryer).

in algal biodiesel production are harvesting and drying of microalgal biomass, lipid extraction and conversion to biodiesel. The microalgae based biodiesel production is still prohibitively costly and energy intensive making it less competitive compared to the conventional fossil fuel. The sustainability of a process is primarily determined by the overall energy consumption and emissions of the key unit operations in the process (Chiaramonti et al., 2015; Keller et al., 2015). Therefore, the energy requirement of each step in the microalgae based biodiesel production process needs to be analysed to identify the process steps needing improvement. Life Cycle Assessment (LCA) is a tool to carry out such a system scale analysis to assess the overall sustainability of a process.

LCA quantifies the environmental impacts of all the associated steps over the entire life cycle, commonly incorporating a “cradle-to-gate” approach of a product or process within a defined system boundary. It helps in identifying hot spots of a process that have to be improved so that overall impacts can be minimised. As the energy use in the process produces the majority of the environmental burden, a comprehensive LCA for the energy flow through the microalgae based biofuel production process would help in determining the environmental impact of each process step (Bradley et al., 2015).

LCA has been applied by various researchers to analyse the microalgae cultivation/biodiesel production process. Lardon et al. (2009) studied the algal biofuel lifecycle estimates of greenhouse gases in Europe; Jorquera et al. (2010) compared the energy life-cycle for algal cultivation in an open raceway pond and closed photobioreactor; Collet et al. (2011) conducted LCA of algal cultivation coupled with methane production; Campbell et al. (2011) performed comparative LCA for biodiesel production from algae with canola and ULS (ultra low sulphur) diesel; Connell et al. (2012) examined the environmental LCA for downstream processing involved in algal biodiesel production process; Rickman et al. (2013) conducted life cycle and techno-economic analysis for algae utility co-location; Quinn et al. (2014) carried out LCA for multiple scenario pathways for microalgae to biodiesel production process considering the net energy ratio (NER) and Greenhouse gases (GHG). Gnansounou and Raman (2016) estimated the environmental impacts for algae based biodiesel process and byproducts (such as biogas, glycerol and succinic acid). Further, Chowdhury

and Freire (2015) estimated the primary energy requirements and green house emissions (GHG) for algal bio-energy production using dairy manure as source of nutrients by employing various process combinations. Azadi et al. (2014) studied the environmental impacts of biodiesel production from algae based feed stock in terms of greenhouse gases.

Most of these reported studies are based on secondary data and are confined to either selective upstream or downstream processes in the algal biodiesel process chain. The overall impacts of the entire process chain involved in biodiesel production under multiple scenarios have not been thoroughly explored. Also, the energy source for electricity generation differ from one region to another affecting the productivities and the lifecycle burden of the whole system (Campbell et al., 2011; Clarens et al., 2010).

The novelty of the present work was to assess the impact of biomass productivity and energy source on the overall energy demand of the microalgae based biodiesel production system. The sensitivity of low, medium and high biomass productivities concomitant with various energy sources have been considered in the present study. LCA of the microalgae based biodiesel production process covering both the upstream and downstream operations, i.e., cultivation, harvesting by flocculation, dewatering, lipid extraction and conversion to biodiesel under multiple scenarios was conducted. The indigenous microalga, *Scenedesmus* sp., was cultivated in an outdoor raceway pond for biodiesel production. Primary data were generated using a limited scale cultivation system, and the system was suitably expanded to build a notional production system under conditions prevailing in India. Three different scenarios were developed by combining the primary and secondary data of various unit operations, productivities and energy sources. The multiple scenarios were further integrated with biogas generation from defatted algal biomass. The energy requirements and environmental impacts of the scenarios were estimated and compared.

2. Materials and methods

2.1. Goal and scope

The goal of the study was to analyze the life cycle energy requirements and environmental impact of microalgae based biodiesel

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