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Life cycle assessment on microalgal biodiesel production using a hybrid cultivation system

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HIGHLIGHTS

- Life cycle assessment was performed on a putative algal biodiesel production plant.
- Hybrid cultivation system couples airlift tubular bioreactors with raceway ponds.
- Environmental impact of algal biodiesel was considerably lower than fossil diesel.
- Algal cultivation and drying of wet biomass were the two largest energy input.
- Sustainability of algal biodiesel depends on efficient utilization of co-products.

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ABSTRACT

A life cycle assessment (LCA) was performed on a putative biodiesel production plant in which the freshwater alga *Chlorella vulgaris*, was grown using an existing system similar to a published commercial-scale hybrid cultivation. The hybrid system couples airlift tubular photobioreactors with raceway ponds in a two-stage process for high biomass growth and lipid accumulation. The results show that microalgal biodiesel production would have a significantly lower environmental impact than fossil-derived diesel. Based on the functional unit of 1 ton of biodiesel produced, the hybrid cultivation system and hypothetical downstream process (base case) would have 42% and 38% savings in global warming potential (GWP) and fossil-energy requirements (FER) when compared to fossil-derived diesel, respectively. Sensitivity analysis was performed to identify the most influential process parameters on the LCA results. The maximum reduction in GWP and FER was observed under mixotrophic growth conditions with savings of 76% and 75% when compared to conventional diesel, respectively.

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1. Introduction

Increasing global concerns on energy security and environmental deterioration owing to carbon emissions from combusting fossil fuels has led to growing research on sustainable and renewable alternatives to fossil-derived fuels. Biofuels (such as biodiesel, bioethanol, biohydrogen, biogasoline, and biogas) are considered sustainable and renewable sources of energy due to their relatively short processing time as well as the availability and continual replenishment of their feedstock (Schenk et al., 2008). Biofuels are nontoxic, biodegradable, low sulphur fuels that can reduce harmful emissions of greenhouse gases (GHGs), carbon monoxide, hydrocarbons and particulate matter (Mata et al., 2010). On a life-cycle basis, biodiesel made from soybean oil has been reported to have a 78% reduction in net carbon dioxide emissions when compared to conventional diesel fuel (Tyson, 2001). Biodiesel blended directly with fossil-derived diesel has also been shown to have a substantial improvement on engine exhaust emissions. For example, Schumacher et al. (2001) reported that the combustion of biodiesel decreases carbon monoxide emissions by 46.7%, particulate matter emissions by 66.7% and unburned hydrocarbons by 45.2%.

On the other hand, biofuels produced from first generation feedstock (rapeseed, soybean, sunflower, wheat, corn) and second generation feedstock (switch grass, forestry waste and other lignocellulosic materials) have received criticism regarding their carbon mitigation potential and limited ability to achieve commercial targets for biofuels production (Mata et al., 2010). Areas of notable debates include food vs. fuel issues, requirement for arable land

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and freshwater, increase in deforestation, damages to biodiversity and significant amount of carbon dioxide released from the soil when considering land-use changes, especially the use of previously uncultivated land (Khoo et al., 2011). As an alternative to land-based crops, biodiesel from microalgae has received significant research interest due to their potential advantages over first- and second-generation feedstock (Chisti, 2007; Schenk et al., 2008).

Microalgae do not have to compete with food crops for arable land or other scarce agricultural inputs. Many microalgal strains grow rapidly and can be cultivated in open ponds or photobioreactors. Biomass productivity on a dry cell basis has been estimated to range from $\sim$50 to 70 MT ha^{-1} year^{-1} when cultivated in high rate ponds (Sheehan et al., 1998; Carlsson et al., 2007) and $\sim$150 MT ha^{-1} year^{-1} when grown in photobioreactors (Carlsson et al., 2007). This is in contrast with productivity of terrestrial crops: $\sim$3 MT ha^{-1} year^{-1} for soybeans, $\sim$9 MT ha^{-1} year^{-1} for corn, and $\sim$10–13 MT ha^{-1} year^{-1} for switch grass (Perlack et al., 2005). Moreover, some microalgal strains are able to accumulate high lipid content (mostly between 20% and 50% per dry cell weight) which is more efficiently converted into biofuels than any other traditional biofuel-producing feedstock (Chisti, 2007). The potential yield of oil from microalgae has been estimated to be $\sim$40 tons ha^{-1} of oil on a large-scale, which is significantly greater than $\sim$1.5 tons ha^{-1} of oil from rapeseed grown in the U.K. (Rodolfi et al., 2009). Microalgal cultivation can also be integrated with wastewater treatment plants as they have the ability to utilize nutrients (e.g., nitrates and phosphates) from municipal waste water and agricultural waste (Sheehan et al., 1998). Furthermore, microalgae can utilize waste CO_2 from power plants or other industrial sources, as a carbon source for biomass production.

Biofuels have the potential to be a carbon neutral alternative to fossil fuel, because the carbon dioxide fixed by photosynthesis during feedstock growth is later released upon combustion of the fuel. However, this carbon neutrality is not achieved in reality because emissions occur throughout the life cycle of the biofuel, starting from the cultivation of biomass, harvesting, drying, through to subsequent biofuel processing, storage of finished product, transportation, distribution and use (Mandil and Shihab-Eldin, 2010). The environmental burden associated with the biofuel production process is primarily due to energy requirements such as fuel and electricity to power machinery, heating during processing, land use change, as well as embodied energy to produce raw materials (e.g., fertilizers, methanol and construction materials). The overall net savings achieved by biofuels is dependent on the particular feedstock, production and management process, and the country and location of biofuel production (DfT, 2008). It is therefore important to evaluate the environmental impacts associated with biofuel production from different feedstocks.

LCA is a methodological tool used for quantifying the environmental impact and energy requirement of a product or service, from the extraction of raw materials through to its production, usage and end-of-life treatment, recycling and final disposal of wastes (i.e. cradle to grave). One of the key benefits of LCA stems from the fact that it provides information on the total environmental performance of a process which can be used as a decision-making tool in environmental management, monitoring and policy making. LCA also helps to identify energy and emission "bottlenecks", i.e. life cycle stages of a process that are critical to the overall environmental burden and thus require further improvement (ISO, 2006a). The environmental impacts can be expressed in different categories such as global warming potential (GWP), fossil-energy requirement (FER), acidification potential, and eutrophication potential of water, which can be quantified by relating the emissions released by the process to a reference chemical. For example, GWP is expressed in terms of the equivalent mass of carbon dioxide emitted over a 100-years time horizon.

Several studies have investigated the sustainability and life cycle analysis of different aspects of the microalgae-to-fuel technology (Lardon et al., 2009; Stephenson et al., 2010; Clarens et al., 2010; Yang et al., 2011). A meta-analysis of 6 studies found that microalgal biodiesel is on par with terrestrial alternatives such as corn ethanol and soy biodiesel, and has the potential for lower GWP than fossil fuel (Liu et al., 2012). However, it was apparent that the actual outcome was heavily dependent on the modeling assumptions and system boundaries, in particular on the level of algal biomass and lipid content that could be achieved during the cultivation process. Stephenson et al. (2010) performed a comparative LCA study using either photobioreactors or raceway ponds in a two stage process, and found that while the production of microalgal-based biodiesel using raceway ponds was environmentally sustainable with a GWP $\sim$80% lower than fossil-derived diesel, that with airlift tubular photobioreactors resulted in a GWP significantly greater than the equivalent amount of fossil-derived diesel due to the high energy input for cultivation. Although the same functional unit (1 ton of biodiesel) was used in the study, the two cultivation systems investigated had different production capacities, with the raceway pond potentially harnessing the benefits of economies of scale, where a higher environmental burden is normalized by a large amount of final biodiesel product. This may not be a fair basis to conduct a comparative LCA study, and furthermore, there are many photobioreactor designs with improved energy use. The high environmental impact is probably not a useful indication of tubular photobioreactors on a large-scale and could be misleading during decision making for further consideration of microalgal biofuel production on a commercial-scale.

Interestingly, a recent comparative LCA study by Khoo et al. (2011) using a functional unit of 1 MJ biodiesel gave a different environmental impact result with the same data from Stephenson et al. (2010). The total life cycle energy demand and total life cycle net CO_2 emitted for the open raceway ponds were estimated to be $\sim$6.4 MJ/MJ biodiesel and $\sim$0.3 kg CO_2/MJ biodiesel, respectively, while the values for the tubular bioreactors were $\sim$0.9 MJ/MJ biodiesel and $\sim$0.02 kg CO_2/MJ biodiesel, respectively. These findings show that the choice of functional unit, which provides the basis for calculating inputs and outputs, can also have a profound impact on the results of LCA studies.

In the current study, an LCA is conducted on biodiesel production from microalgae based on a so-called hybrid cultivation system which couples airlift tubular photobioreactors with raceway ponds, both having relatively the same production capacity, in a two-stage process (Huntley and Redalje, 2007). The hybrid cultivation system presents a synergistic effect which would harness the advantages of both photobioreactors (PBRs) and raceway ponds, whilst minimising inherent setbacks such as high production cost associated with photobioreactors and contamination in raceway ponds. Microalgae are grown continuously in photobioreactors under nutrient sufficient conditions for high biomass production, and then a portion is transferred to nutrient-deficient raceway ponds for high lipid accumulation. The downstream processes considered include harvesting, centrifugation, drying, cell disruption, extraction and transesterification, and GWP, FER and water footprint are the impact categories investigated. Several modifications to the production process and operation parameters were examined to determine key components of the process to which the LCA result is most sensitive.

2. Methods

2.1. Process definition and overall approach

There is currently no commercial-scale production of biodiesel from microalgal feedstock, making it difficult to model a complete

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