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Evaluation of environmental impacts from microalgae cultivation in open-air raceway ponds: Analysis of the prior literature and investigation of wide variance in predicted impacts

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ABSTRACT

It is often difficult to compare publications assessing the sustainability of algal biomass as a feedstock for biofuels, due to differences in data aggregation, life cycle boundaries, technical and life cycle assumptions, environmental metrics considered, and use of experimental, modeled or assumed data. Input data for the algae cultivation stage was collected from published studies, focusing on microalgae production in open-air raceway ponds. Input data was normalized to a consistent functional unit, 1 kg of dry algal biomass. Environmental impacts were applied consistently to the different study inputs in order to eliminate this source of variation between the studies. Greenhouse gas emissions, fossil energy demand, and consumptive freshwater use were tabulated for the algal feedstock growth stage for open pond systems, and results were categorized (energy use, macronutrient fertilizers, and everything else) to compare the different studies in general terms. Environmental impacts for the cultivation of algal biomass in the considered reports varied by over two orders of magnitude. To illustrate impacts of variability in the cultivation stage on the ultimate environmental footprint of microalgae biofuels, algal oil harvesting, extraction and conversion to Green Jet Fuel was examined using the Renewable Jet Fuel process developed by Honeywell's UOP.

1. Introduction

Sustainability issues on several scales are prompting the United States and other nations to explore alternative means of powering our infrastructure and economy. Global climate change is predicted to cause widespread damage unless our carbon dioxide emissions are reduced well below current levels [1]. Proposed reductions in atmospheric CO_2 levels will require significant decreases in our use of fossil-carbon energy sources, which add to the pool of carbon that is actively cycled between atmospheric and terrestrial pools [2]. Domestic energy production is also viewed as a means of strengthening local economies and providing employment to rural communities throughout the U.S.

In 2009, transportation fuels accounted for roughly 32% of U.S. fossil fuel usage [3]. Liquid transportation fuels from renewable feedstocks are commonly viewed as ideal replacements to current fuels due to the relative ease of integration with existing infrastructure [4] and because they have higher energy density in comparison with current batteries or hydrogen storage systems [5,6]. A variety of replacement fuels and feedstock inputs are in various stages of commercialization and research, but ideal replacement fuel candidates should come from renewable feedstocks, have a relatively high energy density, have a high ratio of embodied energy to energy required for production, and not impose a large burden on other resources, such as land use or fresh water.

Among several advanced biofuel options, unicellular microalgae are seen as a promising feedstock candidate for several reasons. Microalgae species have lipid per area production rates that are orders of magnitude higher than conventional biofuel feedstocks [7], with increases in biomass yield, lipid content and increased photosynthetic efficiency predicted through genetic modifications [8]. Different strains of microalgae and methods of processing can yield several possible end-products which can be incorporated into existing infrastructure as partial (blended) or complete replacements for

Abbreviations: GHG, greenhouse gas; LCA, life-cycle assessment; LCI, life-cycle inventory; PVC, polyvinyl chloride.

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fossil fuels. Freshwater and prime agricultural land uses can also be reduced through production methods using brackish or reclaimed water for some species while also using land that is marginally productive for other uses.

Despite all of the features that make microalgae biofuels a subject of much research and speculation, there are several technical hurdles to be overcome in order to make production economically viable. Several technical options are being proposed for each of the unit processes contributing to the feedstock supply and conversion pathways, in an effort to streamline production and reduce cost. Microalgae biofuel production is commonly viewed as requiring 5–15 years of consistent operational improvement before successful commercialization [4].

In addition to the above considerations, a thorough evaluation of the environmental sustainability of algal biofuel feedstocks is needed to demonstrate clear improvement over current fossil fuel use. Although greenhouse gas emissions and energy demand are key metrics, other environmental indicators, such as water use, should also be considered to accurately characterize the current state of knowledge surrounding algal biofuel feedstocks. Life-cycle assessments (LCAs) of algae feedstocks can also highlight areas of concern, focusing future research efforts on aspects of the supply chain that carry the largest environmental burden.

Several LCAs of algae feedstocks have appeared in the literature in recent years, displaying a marked variety in approach, assumptions, and ultimate results [9–17]. Studies have been based upon different scopes, making unique choices of processes or inputs to include in the algae value chain. A variety of assumptions have been made concerning technologies used for the various unit operations involved, algal growth and yield characteristics, or environmental burdens associated with input requirements, which may not reflect current technology and capabilities. Studies often contain a mix of assumed, modeled, or experimental data, and a lack of transparency in this regard, along with different levels of input and result data aggregation makes it difficult to compare individual aspects of the algae value chain between any two studies. Results are often not placed in a consistent context — different choices are made concerning which environmental impacts to consider, and how to consider results in regard to other fuel choices or theoretical limits.

In an effort to reliably compare studies and present the range of processing possibilities and potential environmental impacts, we present a detailed examination of microalgae LCAs that have appeared recently in the peer-reviewed literature and reports. Our initial LCA comparison will focus on the growth of algae feedstock, and we will only examine papers that discuss microalgae grown outdoors in open-air, constantly circulated (raceway) ponds, as this general system is cheaper and uses less energy than photobioreactors [7–9,13,18], meaning it is likely to operate at commercial scales in the future. Details on our approach to this comparison of current LCAs can be found in the research methods/literature analyses section below.

As a method of examining how the variability in processing choices during microalgae cultivation relates to the overall algae biofuel impacts, we apply one advanced biofuel production scenario to each algae growth scenario. An example of an advanced hydroprocessing technology is the UOP Renewable Jet Fuel process, which produces a hydrocarbon-based transportation fuel. Renewable distillate fuels derived from lipids by catalytic hydroprocessing have become a commercial reality with more than 800 million gallons per year of announced capacity [19].

2. Research methods/literature analyses

2.1. Goal/scope of LCA comparison

The goal of this LCA work is to provide a consistent comparison of the various technical options for producing microalgae for processing into a range of products, including transportation fuels. We are assuming that algae oil is the main component of algae to be used in subsequent processing steps, and other biomass components may be utilized as on-site process inputs, sold as co-products, or transformed into additional energy, all outside the goals of this work. The scope of our LCA comparison will be limited in the sense that we do not intend to track the algae value chain to ultimate end-use steps in each separate case. We are focusing our efforts on the initial step in the algae production process, the large-scale cultivation of algae biomass, prior to subsequent harvesting and processing steps. We will present one example case study of a complete fuel conversion life cycle via UOP's Renewable Jet Fuel process, in order to illustrate the relative impacts of algal cultivation compared to other important stages of the algal biofuels' life cycle.

Chemical and energy usage at the site of algae growth will be included, as well as impacts resulting from the production and upstream processing of these inputs. Inputs for algal pond design will be included if they were included in the articles being reviewed, but the impacts from these inputs are expected to be small when normalized over the anticipated lifetime of their production phases [17]. No credit for removing CO_2 from the atmosphere (either ambient atmosphere or by scrubbing from an exhaust gas of another process) has been taken, and no emissions from ultimate combustion of algae biofuels were considered (biofuel combustion returns CO_2 to atmosphere with no net change in emission). Energetic costs of separating CO_2 from some source flue gasses are potentially large [10,20], and additional CO_2 preparation and delivery inputs will be included if these values were reported in the studies under review. Processes associated with supplying the inoculum algae to the main growth and cultivation stage are considered to be outside the scope of this work. Algal harvesting and extraction techniques, followed by conversion of lipids/oils into eventual transportation fuels will be briefly addressed in this review, but will be a subject of a future review comparing relevant publications in a fashion similar to this work. The variations present in this growth phase are significant enough to warrant detailed inspection of this scope separate from the complicating effects of adding layers of processing options to the algae value chain, although the comparison and evaluation of different algae processing strategies are quite important and worthy of future investigation.

Fig. 1 shows just one example of the boundary choices, inputs for materials and energy, and the scope of an LCA publication [16] on algal biofuel production that is included in our comparison. Figures for each of the other studies appear in the Supplementary data. Table 1 shows a description of the boundaries of the prior studies.

2.2. Functional unit

The functional unit for this comparison will be 1 kg of dry algae biomass. In some instances, a significant amount of effort was required to convert data present in algae LCA papers to this common unit. Wherever assumptions were made to facilitate this conversion, those assumptions have been noted and are presented in detailed fashion in the accompanying Supplementary Data. We also include figures similar to Fig. 1 for all papers reviewed in this work to highlight the differences in scope and boundaries considered by the different LCA studies. This paper next discusses the typical configuration of open pond algal cultivation facilities.

2.3. Review of microalgae cultivation design and inputs

2.3.1. Microalgae growth system design

The main growing options for algae on commercial scales are open-air “raceway” ponds or enclosed systems, often called “photobioreactors”. There are also hybrid configurations that include a mix of the two growth options. Raceway ponds generally consist of an oval shaped man-made shallow pond lined with PVC, cement, or