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Life cycle assessment of bio-jet fuel from hydrothermal liquefaction of microalgae

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HIGHLIGHTS

- A life cycle assessment of bio-jet fuel from wastewater algae was performed.
- We used experimental data from algae cultivation through hydrothermal liquefaction.
- We performed Monte Carlo and sensitivity analyses with ranges of parameter values.
- Transport of moderately dewatered algae increased life cycle climate change impacts.
- Collocation and heat integration reduce life cycle greenhouse gas emissions by 76%.

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ABSTRACT

Bio-jet fuel is increasingly being produced from feedstocks such as algae and tested in flight. As the industry adopts bio-jet fuels from various feedstocks and conversion processes, life cycle assessment (LCA) is necessary to determine whether these renewable fuels result in lower life cycle greenhouse gas (LC-GHG) emissions than conventional jet fuel. An LCA was performed for a functional unit of 1 GJ of bio-jet fuel produced through thermochemical conversion (hydrothermal liquefaction (HTL)) of microalgae cultivated in wastewater effluent. Two pathways were analyzed to compare the impacts of siting HTL at a wastewater treatment plant (WWTP) to those of siting HTL at a refinery. Base cases for each pathway were developed in part using primary data from algae production in wastewater effluent and HTL experiments of this algae at the University of Kansas. The LC-GHG emissions of these cases were compared to those of conventional jet fuel, and a sensitivity analysis and Monte Carlo analyses were performed. When algal conversion using HTL was modeled at a refinery versus at the WWTP site, the transportation steps of biomass and waste nutrients were major contributors to the LC-GHG emissions of algal bio-jet fuel. The LC-GHG emissions were lower for the algal bio-jet fuel pathway that performs HTL at a WWTP (35.2 kg CO_{2eq}/GJ for the base case) than for the pathway for HTL at a refinery (86.5 kg CO_{2eq}/GJ for the base case). The LCA results were particularly sensitive to the extent of heat integration, the source of the heat for HTL, and the solids content of dewatered algae. The GHG emissions of algal bio-jet fuel can be reduced by 76% compared to conventional jet fuel with feasible improvements in those sensitive parameters and siting HTL at a WWTP. Therefore, it is critical that transportation logistics, heat integration of biomass conversion processes, and nutrient supply chains be considered as investment and production of bio-jet fuels increase.

1. Introduction

Bio-jet fuel is increasingly being used in attempts to reduce the environmental impacts of aviation and to ensure energy security in the industry. The International Air Transport Association aspires to use 6% biofuel blends in aircraft by 2020 [1], which corresponds to 1.31 billion gallons of bio-jet fuel needed annually to meet the United States' demand of 21.85 billion gallons of liquid fuels in 2011 [2]. Several test flights have already been performed on blends of conventional jet fuel and bio-jet fuel from algae, camelina, and other plant-based feedstocks on commercial airlines and military aircraft [3]. In July 2011, the ASTM standard D7566 for aviation fuel

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containing synthesized hydrocarbons, including those from biological sources, was published [4]. This revised standard provides quality control guidelines for the growing commercial use of bio-jet fuel.

Microalgae has been investigated as a feedstock for biofuels due to its fast growth, its relatively high lipid content, and its ability to be harvested continuously and to be cultivated on non-arable land [5]. Bio-jet fuel derived from algae has been produced by companies such as Solazyme and tested in flight [3]. Continental Airlines conducted a commercial flight between Houston and Chicago on a 40% blend of algal bio-jet fuel, and the United States Navy demonstrated a 50% blend of algal bio-jet fuel in a military helicopter [3].

At these early stages in the production of algal bio-jet fuel, a life cycle assessment (LCA) is necessary to ensure that bio-jet fuel produced from algal feedstocks does not result in higher life-cycle greenhouse gas (LC-GHG) emissions than conventional jet fuel. Life cycle assessment can also determine which processes contribute the most to the climate change impacts of algal bio-jet fuel production and use, thus identifying the processes that require further research and development to improve the sustainability of these fuels.

This ''cradle-to-wake'' LCA proceeds from the cultivation of microalgae in municipal wastewater effluent to thermochemical conversion using hydrothermal liquefaction, upgrading to bio-jet fuel, and combustion in a jet engine. The majority of the data for the life cycle of algal bio-jet fuel upstream of upgrading processes was obtained from our pilot-scale algae cultivation experiments in wastewater effluent and subsequent lab-scale hydrothermal liquefaction reactions of the collected and dewatered algae [6–8]. Additionally, this LCA is unique among bio-jet fuel and algal biofuel LCAs due to the use of municipal wastewater effluent supplemented with recycled nutrients from hydrothermal liquefaction as the growth medium and the use of hydrothermal liquefaction in lieu of traditional algal lipid extraction methods.

Municipal wastewater effluent can be utilized as a growth medium for algae because it contains nitrogen and phosphorus among other necessary nutrients, which would otherwise be discharged to a receiving water body. Several published LCAs discuss that lower LC-GHG emissions could potentially be achieved by using wastewater to grow algae instead of freshwater supplemented with commercial fertilizers [9–13], and a few LCAs have analyzed cases which use wastewater in algae cultivation either as a main growth media or as a supplement [13–16]. However, the potential algal biomass production at municipal wastewater treatment plants (WWTPs) is typically limited by the nutrient quantities available when a conventional lipid extraction process is used in the conversion of algae to biofuels [17]. Additionally, wastewater-fed cultures of microalgae have relatively lower lipid contents than under controlled nitrogen-limited growth conditions [5,6,18], which limits the amount of fuel that can be produced through upgrading extracted algal lipids.

Hydrothermal liquefaction (HTL) is a technology that has the potential to overcome the limitations for commercial-scale algal biofuel production imposed by the nutrient quantities available in wastewater effluent and the low lipid content typically observed in wastewater-grown microalgae. Hydrothermal liquefaction uses subcritical water to convert biomass to a carbon-rich biocrude [19,20]. The entire algal biomass can be processed through HTL because other cellular components beyond lipids are converted into biocrude [19–22]. The biocrude yields from HTL are 5–30% higher than the initial algal lipid content [21,23–31], and thus HTL is particularly appropriate for low-lipid microalgae. Hydrothermal liquefaction also generates an aqueous co-product (ACP), which contains elements (C, N, P) embodied in the original algal biomass [32,33]. The ACP could potentially be supplemented to algal pond reactors to recycle these nutrients into additional algal biomass [32–34]. The combination of nutrient recycling and HTL could greatly increase the biofuel yields possible from cultivating algae in wastewater effluent, avoiding the need for freshwater and fertilizers.

An algal biofuel production process that includes HTL may also be more sustainable than one that employs conventional lipid extraction. Unlike lipid extraction, HTL can be performed on biomass with low solids content (5–30% solids). This reduces the need for complete dewatering and drying, which are energy-intensive processes that can account for up to 69% of the energy needed for an algae-to-biofuel pathway [14]. Previously published life cycle assessments have determined that dewatering processes and/or fertilizer production are among the most energy-intensive steps in algal biofuel production [9,11–15,35–41]. Additionally, because HTL uses the entire algal biomass, less biomass must be converted to useful co-products or discarded as waste. The proposed system addresses several of the sustainability concerns identified by the United States National Research Council's ''Sustainable Development of Algal Biofuels Report'' [8,42], including the sources of water and nutrients and the fate of waste products from processing algae to fuels. However, the LC-GHG emissions of producing algal biofuels using HTL as a conversion process and utilizing waste sources of water and nutrients for algal growth need to be fully assessed for commercial-scale applications. For example, the greenhouse gas emissions from transporting larger volumes of water along with algal biomass may lead to prominent climate change impacts in the life cycle of algal bio-jet fuel, and thus transportation steps are included in this LCA.

The goals of this life cycle assessment are:

- To utilize primary data collected from algae production and hydrothermal liquefaction experiments at the University of Kansas to build a life cycle inventory for algal bio-jet fuel production.
- To compare the LC-GHG emissions of algal bio-jet fuel produced through hydrothermal liquefaction pathways to those of conventional jet fuel.
- To identify the processes that are associated with the highest greenhouse gas emissions in the production of bio-jet fuel from algal feedstocks, and
- To perform a sensitivity analysis and Monte Carlo analyses for this algal bio-jet fuel LCA based on feasible ranges of input parameters.

2. Methods

2.1. Algal bio-jet fuel LCA

This LCA was performed well-to-wake using SimaPro 7.3.3 software. The functional unit was 1 gigajoule (GJ) of fuel produced, which was converted to mass and volume units using an average energy density and specific energy for synthetic paraffinic kerosene [43]. Labor, construction, and infrastructure impacts were not included within the system boundary. The system boundary also did not include the benefit of biological nutrient removal imparted by algal cultivation in municipal wastewater in order to conservatively compare the LC-GHG emissions of algal bio-jet fuel to conventional jet fuel without incorporating impacts related to wastewater treatment. When available, our experimental data at the University of Kansas was utilized as life cycle inventory inputs. At the University of Kansas, microalgae is cultivated in four 2500-gallon open pond reactors fed with municipal wastewater effluent, collected in gravity sedimentation tanks, dewatered with an Evodos type 10 pilot centrifuge (Evodos B.V., Breda, The Netherlands), and processed in lab-scale batch HTL reactions [6,8].