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Lifecycle assessment of microalgae to biofuel: Comparison of thermochemical processing pathways ☆

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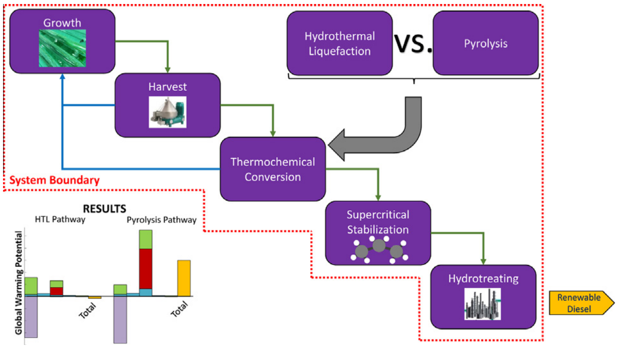
HIGHLIGHTS

- Well to pump environmental assessment of two thermochemical processing pathways.
- NER of 1.23 and GHG emissions of -11.4 g $CO_{2\text{-eq}}$ $(MJ)^{-1}$ for HTL pathway.
- HTL represents promising conversion pathway based on use of wet biomass.
- NER of 2.27 and GHG emissions of 210 g $CO_{2\text{-eq}}$ $(MJ)^{-1}$ for pyrolysis pathway.
- Pyrolysis pathway: drying microalgae feedstock dominates environmental impact.

GRAPHICAL ABSTRACT



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ABSTRACT

Microalgae is being investigated as a renewable transportation fuel feedstock based on various advantages that include high annual yields, utilization of poor quality land, does not compete with food, and can be integrated with various waste streams. This study focuses on directly assessing the environmental impact of two different thermochemical conversion technologies for the microalgae-to-biofuel process through life cycle assessment. A system boundary of "well to pump" (WTP) is defined and includes sub-process models of the growth, dewatering, thermochemical bio-oil recovery, bio-oil stabilization, conversion to renewable diesel, and transport to the pump. Models were validated with experimental and literature data and are representative of an industrial-scale microalgae-to-biofuel process. Two different thermochemical bio-oil conversion systems are modeled and compared on a systems level, hydrothermal liquefaction (HTL) and pyrolysis. The environmental impact of the two pathways were quantified on the metrics of net energy ratio (NER), defined here as energy consumed over energy produced, and greenhouse gas (GHG) emissions. Results for WTP biofuel production through the HTL pathway were determined to be 1.23 for the NER and GHG emissions of -11.4 g $CO_{2\text{-eq}}$ (MJ renewable diesel)$^{-1}$. Biofuel production through the pyrolysis pathway results in a NER of 2.27 and GHG emissions of 210 g $CO_{2\text{-eq}}$ (MJ renewable diesel)$^{-1}$. The large environmental impact associated with the pyrolysis pathway is attributed to feedstock drying requirements and combustion of co-products to improve system energetics.

Abbreviations: ($CO_{2\text{-eq}}$), carbon dioxide equivalence; (GWP), global warming potential; (GHG), greenhouse gas; (HHV), high heating value; (HTL), hydrothermal liquefaction; (NER), net energy ratio; (LCA), life cycle assessment; (WTP), well to pump.

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Discussion focuses on a detailed breakdown of the overall process energetics and GHGs, impact of modeling at laboratory-scale compared to industrial-scale, environmental impact sensitivity to systems engineering input parameters for future focused research and development, and a comparison of results to literature.

1. Introduction

The current increase in global energy demand, as well as the negative impact petroleum based energy sources are having on the environment, has led to a renewed interest in renewable energy resources. A variety of third generation feedstocks for biofuel production are being investigated as viable alternatives to traditional energy sources including microalgae based on inherent advantages, specifically characteristically high lipid yields, utilization of poor quality land and water, and integration with point source carbon dioxide sources such as coal fired power plants. Efforts to advance the commercial feasibility of microalgae based biofuels have focused on improvements to the various processing steps associated with the production of feedstock through to fuels. Life cycle assessment (LCA) has emerged as a foundational tool in evaluating alternative processing technologies with results used to highlight areas for further research and development. Various conversion technologies have been identified but the overall impact of the technologies must be understood on a systems level.

In the microalgae to biofuels system there are a variety of conversion technologies being explored in an effort to move toward commercialization. Various technologies have emerged as viable options for the extraction and conversion of biomass to biocrude including but not limited to pyrolysis, hydrothermal liquefaction (HTL), and lipid extraction. Two thermochemical technologies, HTL and pyrolysis, have both been experimentally demonstrated to be viable processes for the conversion of microalgae to bio-oil. Both technologies having the benefit of thermochemically converting non-lipid microalgae constituents into a bio-oil. The HTL conversion process has been demonstrated with a microalgae slurry (microalgae and water mixture), which has the benefit of decreasing the energy requirements for water removal [1–20]. Bio-oil recovery through pyrolysis has proven to an effective technology with feedstocks such as woody biomass with limited work on microalgae [2,21–24]. A challenge that arises with a microalgae feedstock is pyrolysis requires a relatively dry feedstock, 15–20% moisture [25,26]. Removal of water to this moisture content requires substantial energy for a microalgae feedstock. Both HTL and pyrolysis have been demonstrated to be feasible with limited assessment on the industrial-scale feasibility of the technologies based on environmental impact [27,28].

LCA has become a premier tool in assessing process energetics and environmental impacts of biofuels production systems. LCAs reported for the microalgae to biofuels process incorporating various conversion technologies have been performed with results varying dramatically due to simplistic process models, differences in production pathways, and incomplete system boundaries [1,3,27–58]. The majority of the studies have focused on tradition lipid extraction systems [30,32,33,39,42,43,46,50–53,55–57,59]. A limited number of studies have evaluated thermochemical conversion technologies on the metrics of net energy and greenhouse gas (GHG) emissions [1,27,28,34,60]. Frank et al. [34] examined the environmental impact of an HTL process with a well to pump (WTP) system boundary, but includes an additional processing of HTL byproducts to biogas. de Boer et al. [1] evaluates HTL as a conversion system but fails to include microalgae growth, downstream processing of bio-oil, and HTL byproducts in the analysis. An alternative thermochemical processing technology, pyrolysis, has received minimal evaluation [27]. A LCA was carried out by Grierson et al. [27] for a WTP system boundary with the growth system based on a photobioreactor architecture and spray drying for water removal. These processes are accepted in industry, but are not representative of optimized industrial function. A direct comparison of the energetics of microalgae bio-oil recovery through pyrolysis and HTL has been performed but exclusion of upstream and downstream processing limits the use of results for the comparison to other production pathways [2,27]. For assessing the thermochemical conversion of microalgae biomass through pyrolysis or HTL and directly comparing results to other technologies a LCA that accounts for all energy and GHG contributions in a WTP system boundary is required.

Based on the current state of the field there exists a need for the evaluation and comparison of the environmental impact of thermochemical processing technologies applied to the microalgae to biofuels process on a systems level. A modular systems engineering model was constructed including growth, dewatering, bio-oil recovery through HTL or pyrolysis, bio-oil stabilization, bio-oil conversion to renewable diesel, and transport and distribution to consumer pumps to define a system boundary of WTP and validated with experimental and literature data. Two system models were developed: (1) a small-scale model representative of the operation of the experimental systems and (2) an industrial-scale model, validated through experimental and literature data, to assess facility function at commercial scale. All-sub process models were validated with experimental data and integrated into a system model representative of the microalgae to biofuel production process. Literature data was limited to promising growth and dewatering techniques and bio-oil upgrading in the industrial-scale system with experimental data used for HTL and pyrolysis performance. Environmental impact results are presented on the metrics of net energy ratio (NER) and GHG emissions with sub-processing resolution. Discussion focuses on the impact of modeling at industrial-scale, sensitivity to process parameters, and a comparison of results to other conversion technologies based on published literature.

2. Methods

A modular systems engineering model, which serves as the foundation of the LCAs, is presented in Fig. 1. The systems engineering model includes sub-process models of the growth, dewater, bio-oil recovery through either pyrolysis or HTL, bio-oil stabilization, conversion to renewable diesel, and transport and distribution to the pump. System modeling and validation was performed at two scales: (1) small-scale: which leveraged laboratory based production data and (2) industrial-scale which utilized literature and laboratory data for model validation and is intended to represent industrial function. Industrial-scale modeling work focused on accurately capturing the function of a large-scale facility while incorporating experimental yield and product characterization data from thermochemical conversion experimentation. Compared to the small-scale effort, industrial-scale modeling

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