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Original article

Nutrient resource requirements for large-scale microalgae biofuel production: Multi-pathway evaluation

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ABSTRACT

Growing demand for energy worldwide has increased interest in the production of renewable fuels, with microalgae representing a promising third generation feedstock. This study presents the use of a modular engineering process model, informed through literature, to evaluate the nitrogen and phosphorus resource demand of five microalgae to biofuels production systems. The baseline scenario, representative of an economically viable large-scale production system, includes sub-process models for growth, dewater, lipid extraction, anaerobic digestion, and biofuel conversion. Baseline modeling results combined with current US resource availability from fertilizer and wastewater show nitrogen and phosphorus requirements represent a potential barrier to the large-scale development of microalgae based biofuels. Baseline results show municipal wastewater sources can provide sufficient nutrients to produce 3.8 billion gallons of fuel per year, corresponding to 6% of the DOE goal of 60 billion gallons per year. Results from modeling of alternative production scenarios shows hydrothermal liquefaction to be a promising technology in terms of resource consumption. The use of lipid extracted algae as a value-added co-product is shown to be limitting due to nutrient recovery requirements for scalability. Optimistic and conservative process scenarios are simulated to bound the total resource demand and represent practical best and worst case scenarios.

Introduction

Increasing volatility in energy availability and cost, as well as the environmental impacts of fossil fuel use, has resulted in the domestic production of renewable fuels. The US Department of Energy (DOE) has quantified the level of interest in, and need for, renewable fuel through the establishment of a goal for the year 2030 that 30% of US transportation fuel or 60 billion gallons per year (BGY) will be derived from renewable sources [1]. A variety of second and third generation terrestrial based feedstock options exist, but microalgae have several advantages, including higher solar energy conversion efficiency, the ability to be grown on non-arable land, utilize impaired waters, and integration with various low value nutrient (nitrogen and phosphorus) sources including wastewater and point source carbon dioxide (CO_2) [2,3]. Furthermore, microalgae are of interest in wastewater treatment for the removal of nitrogen and phosphorus [4–6]. The many advantages make microalgae one of the more promising feedstocks for production of renewable biofuels.

Researchers have evaluated the requirements, implications, and barriers to microalgae biofuel production at the scale required for the DOE 2030 goal through techno-economic analysis (TEA), life cycle assessment (LCA), and resource assessment. The majority of the TEAs and LCAs to date have developed system models of large-scale production facilities in an effort to quantify the energy and mass requirements, with results limited to financial costs and environmental impact [7–24]. Results from TEAs have suggested that higher value co-products from the lipid extracted algae (LEA) could improve the economics of biofuel production. The impacts of selling a co-product on the nutrient requirements of the system have not been fully characterized [14,18]. Published LCAs contain results focused on energy use and carbon emissions, with minimal analysis regarding scale-up limitations based on nutrient requirements [15,23,24]. Resource assessments have evaluated in detail the impact and availability of land, water, and CO_2

Abbreviations: AD, anaerobic digestion; BGY, billion gallons per year; CO_2, carbon dioxide; C:N:P, carbon:nitrogen:phosphorus; DOE, Department of Energy; HTL, hydrothermal liquefaction; LCA, life cycle assessment; LEA, lipid-extracted algae; Mmt, million metric tons; TEA, techno-economic analysis; TGY, trillion gallons per year; TS, total solids; VS, volatile solids.

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requirements on the scalability of microalgae based biofuels, with results showing land does not currently represent a resource limitation, while water and CO_2 will be limiting resources in some regions of the US [25–32]. Pate et al. [33] performed a high-level, low-granularity evaluation of the water, land, CO_2 and nutrient requirements for large-scale production based on a mass balance assessment. Model details include only microalgae cultivation and omit all other steps of the biofuel production system. Their results provide the order of magnitude to expect for resource demand, but are inadequate due to the limited model scope. Venteris et al. [32] perform an assessment which includes land, water, CO_2 and nutrient requirements of various pathways. Modeling work is based on a system model comprised of sub-process models. However, the sub-process models for harvest, extraction (lipid extraction or HTL), and conversion to fuel are limited to individual efficiency factors. Additional nutrient assessments make claims that seawater and wastewater can potentially provide the nutrients necessary for large-scale microalgae production, but provide no justification for these claims [34,35]. The feasibility of integrating wastewater with microalgae cultivation as a source of water and nutrients for microalgae growth, as well as effective wastewater treatment has been established [2,3,36–38], but such studies have not extended results to evaluate the potential scalability at levels consistent with DOE renewable fuel goals. Despite the knowledge gained through previous TEAs, LCAs, and resource assessments, a need remains for thorough evaluation of the nutrient demand for large-scale biofuel production from microalgae.

Large-scale engineering system models are needed to quantify the nutrient requirements in the microalgae to biofuel process and evaluate the potential for various nutrient sources such as fertilizer and wastewater to meet the corresponding resource needs. This study assesses the large-scale resource requirements of multiple pathways of the microalgae to biofuel production processes. The work utilizes a modular engineering process model of the microalgae to biofuel production system to evaluate the nutrient requirements for baseline, optimistic, conservative, LEA co-product, and hydrothermal liquefaction (HTL) conversion process scenarios. The engineering system model, representative of a near-term large-scale system, includes growth, dewater, lipid extraction, anaerobic digestion (AD), and biofuel conversion processes for a system boundary that is consistent with the "well to pump" of LCA modeling. Optimistic and conservative scenarios were developed to encompass the variability of process efficiencies within the baseline system, account for advancements in processing technology, and provide bounds for the resource requirements. Alternative production processes were modeled which include a system based on the production of fuel with LEA co-products and the utilization of an alternative conversion and nutrient recycling process, HTL. Total nutrient requirements were determined for an annual fuel production level of 10 billion gallons. Discussion focuses on the results for resource requirements for the five production scenarios, system scalability within the US, a comparison of results to previous resource assessments, and sensitivity of resource results to model inputs to inform future research areas for decreasing nutrient requirements.

Methods

A modular engineering system model, designed to track mass flow, was developed in order to quantify the resource requirements of a large-scale microalgae to biofuel production system while incorporating the ability to evaluate alternative process technologies. Modeling work was performed at a plant production level of 10 million gallons of gasoline equivalent per year [39,40]. The process model, shown in Fig. 1, includes 24 inputs used to characterize the production system with process losses and efficiencies in each step included. Five production scenarios were modeled, with the following sections outlining the input values and justification for each system parameter. A summary of the fundamental system parameters and assumptions for each of the five microalgae to biofuel production scenarios used in this study is summarized in Table 1 with additional details presented in the supplementary material.

Baseline, optimistic, and conservative scenarios

The baseline scenario is intended to represent a near-term, large-scale microalgae to biofuel production system [7,8,10,11,15,22,23,41–48]. The baseline scenario is based on mature technologies and for example includes a lipid extraction system as this technology has been demonstrated at commercial scale for other oil based feedstocks [49–51]. The model includes growth, dewater, lipid extraction, biofuel conversion, and resource recycling through AD as the process steps [14,15,22,52]. In order to establish bounds on resource demand, optimistic and conservative scenarios are modeled. The optimistic scenario is comprised of the most efficient values reported in literature for each process, typically at bench or lab-scale, and represents the biofuel production system with the lowest nutrient demand. The optimistic scenario requires advancements in each of the processing technologies to be viable at large-scale. The conservative scenario represents technologies that have been demonstrated on a commercial scale, and results in the high-

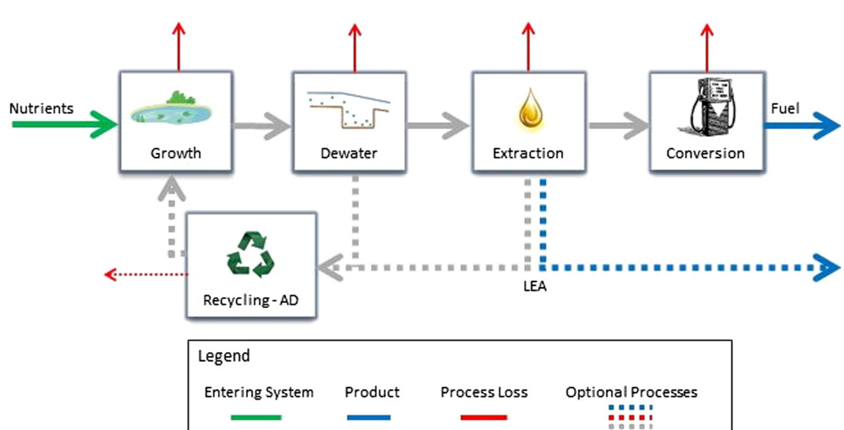

Fig. 1. Engineering process model of the microalgae to biofuel production system used to model five production scenarios. Detailed system models for each scenario are presented in supplementary material.