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A techno-economic analysis of microalgae remnant catalytic pyrolysis and upgrading to fuels

Rajeeva Thilakaratne [a,c], Mark M. Wright [b,c,*], Robert C. Brown [a,b,c]

[a] Center for Sustainable Energy Technologies, 3116 Biorenewable Research Laboratory, Iowa State University, Ames, IA 50011, United States
[b] Bioeconomy Institute, 3116 Biorenewable Research Laboratory, Iowa State University, Ames, IA 50011, United States
[c] Department of Mechanical Engineering, 2078 Black Engineering, Iowa State University, Ames, IA 50011, United States

HIGHLIGHTS

- The study develops a techno-economic analysis of microalgae remnant pyrolysis biofuels.
- It compares partial mechanical drying and thermal drying scenarios with subsequent energy flow analyses.
- It finds that microalgae remnant biofuel could vary in price between \$1.49 and \$1.80 per liter.
- Sensitivity analyses show strong influence of fuel yields, feedstock prices, and capital costs.

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ABSTRACT

Microalgae have been proposed as potentially promising feedstock for the production of renewable transportation fuels. The plants are intriguing for their capacity to serve both as a source of renewable carbon fuels and as a powerful tool for carbon sequestration. Microalgae remnant, a low-cost by-product of microalgae lipid extraction, is a particularly appealing candidate for these processes. Through catalytic pyrolysis, microalgae remnant is capable of producing aromatic hydrocarbons that could be used for the production of drop-in biofuels. One of the most challenging barriers to this promising pathway is the high moisture content of harvested microalgae.

The goal of this study is to compare the economics of two catalytic pyrolysis pathways for the production of drop-in biofuels, each pathway employing its own distinct method of feedstock dewatering: thermal drying or partial mechanical dewatering. The study presents chemical process models, capital expense and operating cost estimates, and sensitivity analyses of both scenarios.

Results indicate that thermal drying prior to catalytic pyrolysis (TDCP) incurs capital costs similar to those incurred in partial mechanical dewatering prior to catalytic pyrolysis (MDCP) (\$346 million vs. \$409 million). TDCP and MDCP yield minimum fuel-selling prices (MFSPs) of \$1.80/l and \$1.49/l, respectively. Energy analysis shows that TDCP achieves 16.8% energy efficiency and MDCP achieves 26.7% efficiency.

1. Introduction

Global environmental concerns about atmospheric carbon levels have prompted interest in both reducing atmospheric CO_2 levels and increasing the use of renewable carbon fuels in the energy sector. Both objectives can be accomplished through the cultivation and conversion of microalgae biomass. In the 1970s, the U.S. Department of Energy extensively researched the growth and conversion of microalgae for transportation fuels [1]. At that time, it was determined that the costs to produce transportation fuels from microalgae rendered the process economically infeasible. Today, innovative approaches to microalgae growth and conversion have renewed interest in algae biofuels [1,2], but the question of economic feasibility remains. Despite the increase in algae-related publications, few papers effectively address this key question of the economic costs of producing algae biofuels.

The cost estimates given in the literature vary greatly in their level of detail. Some provide single value estimates and others give complete process and economic analyses. Lundquist et al. [1] published that algae biofuel costs would range from \$0.17/l to \$2.09/l.

* Corresponding author at: 3033 Black Engineering, Iowa State University, Ames, IA, 50011, USA. Tel.: +1 515 294 0913; fax: +1 515 294 8993.
E-mail address: markmw@iastate.edu (M.M. Wright).

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Abayomi et al. [2] suggested a cost range of $0.88/l to $24.60/l. There are several reasons for the wide range of prices given in the literature, but the primary driver of these wide variations is the wide difference found in the combined costs of algae cultivation, extraction, and pretreatment. Published algae biomass costs vary from $0.35/kg to $7.32/kg, depending on algae strain, cultivation and extraction methods, and facility locations [2].

Algae are microscopic in nature and account for most of the organic matter found in aquatic cultures. The surface-to-volume ratio of algae is very high, which results in rapid nutrient and CO_2 uptake and a fast growth rate [2]. Microalgae are suitable for numerous applications such as livestock and aquaculture feed [2], but their high processing costs have discouraged widespread commercialization [2].

Similarly, algal biomass is suitable for conversion to liquid fuels through various processes. Lipids extracted from algae can be transesterified to biodiesel [3] or hydroprocessed to green diesel. Whole algae or algae remnant can be hydrothermally processed [4] or dried and pyrolyzed [5] to produce bio-oil suitable for hydroprocessing to renewable gasoline or diesel. Whole algae or algae remnant can also be gasified and the resulting syngas can be catalytically synthesized to liquid fuels [6]. The technology for upgrading lipids to fuels has already been developed for vegetable oils and animal fats [4,7], but algal lipids are currently too expensive to upgrade with this method due to their high processing costs. The conversion of whole algae and algae remnant to fuels, which contain large amounts of protein and carbohydrate as well as lipids, is still under development.

Recently-developed methods for extracting lipids from wet algal biomass have yielded wet algae remnant as a by-product [6]. Algae remnant can be converted to methane through anaerobic digestion or it can be sold as a protein supplement for animal feed [2]. However, its greatest value may lie in its thus-far-undeveloped potential to serve as a low cost feedstock for biofuel production. Direct liquefaction, such as that accomplished through catalytic fast pyrolysis and hydrothermal processing, is capable of thermally converting algae remnant into an intermediate oil suitable for upgrading to naphtha and diesel biofuels [5,8,9]. The major technical challenges for this approach are the high moisture and nitrogen contents of algae remnant.

Catalytic pyrolysis offers a distinct advantage for algae processing: its zeolite catalysts are capable of reducing heteronuclear nitrogen to negligible levels [8]. Unfortunately, high moisture levels impede the catalytic pyrolysis process. Hence, effective water management is a key challenge for the conversion of algae remnant, which typically contains approximately 80 wt.% moisture [3,10]. This study investigates the performance of two water removal approaches: thermal drying and partial mechanical dewatering.

The purpose of this paper is to conduct a techno-economic analysis (TEA) of the catalytic pyrolysis of microalgae remnant for the production of biofuels that provide information to compare it to alternative algae conversion pathways. The paper will accomplish these objectives through the following five steps. It will: (1) describe two base case scenarios, each employing a different dewatering technique; (2) develop chemical process models for algae-to-biofuel conversion; (3) estimate the profitability of each scenario; (4) conduct energy flow analysis; and to 5) conduct a sensitivity analysis of the process and economic models.

2. Methods

The conversion of algae remnant to biofuels requires six primary conversion steps and three auxiliary processing units. The primary conversion steps include pretreatment and drying, catalytic pyrolysis, benzene–toluene–xylene (BTX) separation, hydroprocessing, and fractionation. Pretreatment involves feedstock drying to 10 wt.% moisture content and feedstock grinding to 1 mm diameter. Catalytic pyrolysis takes place in a reactor operating at about 700 °C, atmospheric pressure, and without air or oxygen addition. Following the pyrolysis step, solid carbonaceous particles (bio-char) are separated from the effluent stream and oil recovery is accomplished through the rapid condensation of pyrolysis oils (bio-oils). BTX separation uses distillation to recover a BTX mixture from the pyrolysis oil. Finally, heavy oil catalytic upgrading is accomplished through hydroprocessing and fractionation to gasoline and diesel range blend stock fuels. Auxiliary process units include a heat recovery and steam generation (HRSG) boiler unit, steam methane reforming (SMR) unit and a cooling plant. Algae cultivation and wastewater treatment facilities are assumed to be beyond the boundaries of the processing facility. Figs. 1 and 2 show a process block diagram and simplified flow diagram of the conversion system.

This study compares two microalgae drying technologies: thermal drying and partial mechanical dewatering. Thermal drying takes place at 290 °C using hot air to reduce moisture content from 80 wt.% to 10 wt.%. This method requires significant energy input. Mechanical dewatering is an alternative technique that can reduce moisture content at a lower energy cost. The technique has been suggested as a possible alternative for thermal drying of wet lignin residue in the cellulosic ethanol pathway, but it has never been demonstrated for microalgae drying [10]. Unbound water can be

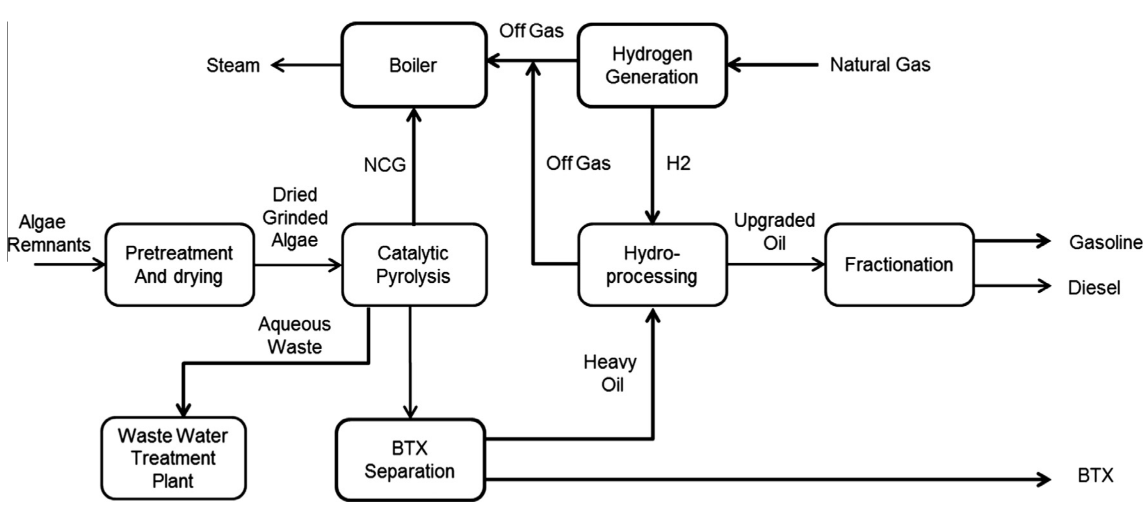

Fig. 1. Process block flow diagram for microalgae remnant catalytic pyrolysis and upgrading to drop-in transportation fuels.