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Energy use and greenhouse gas emissions from an algae fractionation process for producing renewable diesel

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ABSTRACT

In one approach to algal biofuel production, lipids are extracted and converted to renewable diesel and non-lipid remnants are converted to biogas, which is used for renewable heat and power to support the process. Since biofuel economics benefit from increased fuel yield, the National Renewable Energy Laboratory analyzed an alternative pathway that extracts lipids and also makes ethanol from carbohydrates in the biomass. In this paper, we examine the environmental sustainability of this "fractionation pathway" through life-cycle analysis (LCA) of greenhouse gas emissions and energy use. When the feedstock productivity was 30 (18) g/m^2/d, this pathway emitted 31 (36) gCO$_2$e/MJ of total fuel, which is less than the emissions associated with conventional low sulfur petroleum diesel (96 gCO$_2$e/MJ). The fractionation pathway performed well in this model despite the diversion of carbon to the ethanol fuel.

1. Introduction

The profitability of a biofuel pathway depends, in part, upon the fuel yield from a given mass of feedstock. Yields from two algal biofuel pathways, algae lipid extraction and upgrading (ALU) and algae hydrothermal liquefaction (AHTL), benefit from feedstocks with large amounts of lipids [1–3]. Economic models typically favor AHTL because of its high fuel yield [2], but AHTL can direct significant levels of nitrogen to the biofuel intermediate, which must be removed later, during upgrading. If upgrading occurs remotely from the algal production facilities, then the nitrogen is recovered in produced waters that are unlikely to be returned to the algal farm [4]. ALU, on the other hand, keeps nitrogen on site and may have more (or complementary) options for high-value co-products. Thus, there is interest in revising the ALU process to increase its fuel yield from a given biomass feedstock.

The National Renewable Energy Laboratory (NREL) studied a process that fractionated algal biomass into carbohydrate, lipid, and protein-rich fractions that can be converted into fuels and co-products. The carbohydrate-rich stream, produced via acid hydrolysis of algal biomass, was fermented to ethanol. Lipids were extracted from the lipid rich fermentation stillage and were upgraded to renewable diesel (RD), which accounted for most of the produced fuel. The protein-rich residue left after lipid extraction was converted to biogas by anaerobic digestion (AD) and this biogas was used for co-generation of heat and power on-site. While this approach is a relatively new conceptual processing pathway, early research conducted at NREL has demonstrated encouraging results with high yields (>65%) for hydrolysis of algal carbohydrates to monomeric sugars, and high yields (>80%) of fermentable sugars to ethanol as well as recovery of lipids via a wet extraction process at roughly 80 wt% moisture content [5].

Davis et al. [6] performed a techno-economic analysis (TEA) of this pathway via a discounted cash flow rate of return analysis that determined the minimum fuel selling price required to achieve a zero net present value under a set of financial assumptions and based upon estimates of capital and operating expenses [6]. That study was based upon a mass- and energy-balanced Aspen Plus computer model that determined stream flows, utility demands, and material inputs, which is summarized in Fig. 1. The stream flows were used for equipment sizing and associated costs. Details are in Davis et al. [6], but in summary, this study established that the fractionation approach could achieve a selling price of $4.35 per gallon of gasoline equivalent (GGE) in 2011 dollars for a high-lipid (41 wt%) *Scenedesmus* feedstock and $5.04/GGE for a lower-lipid (27 wt%) *Scenedesmus* feedstock if projected improvements in process operating conditions and conversion yields were achieved. Although Davis et al. [6] considered ethanol production, the carbohydrate fraction could, in principle, be converted to other fuels or higher value products.

Algal biofuels are sought, in part, from the desire for fuels with fewer greenhouse gas (GHG) emissions than would be produced by conventional petroleum fuels and from the desire to reduce petroleum and fossil fuel use. Life cycle analysis (LCA) of GHG emissions and energy use computes the total GHG emissions and energy use associated with all relevant operations related to the production and use of a particular fuel [7]. Our previous LCA studies of algal biofuels [1,2,4,8–11] indicated

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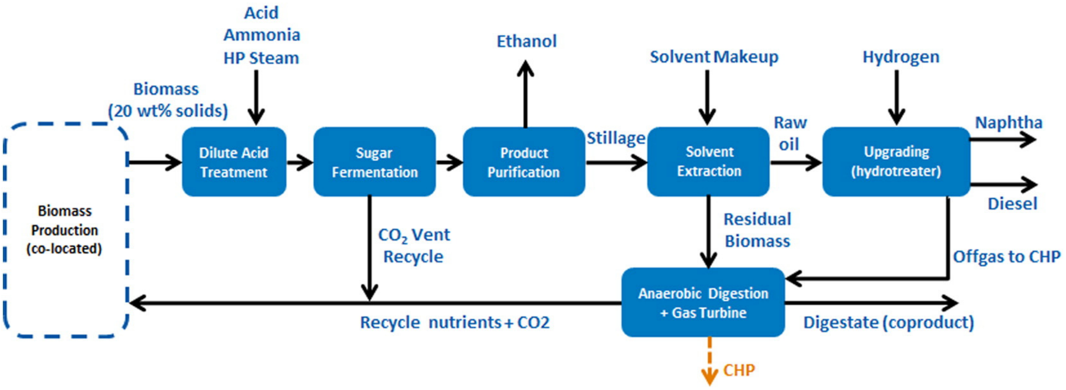

Fig. 1. Fractionation process flow diagram. Biomass production is in open ponds, harvested via settling, and dewatered via dissolved air flotation and centrifugation as described in [1,2].

that energy use on-site is high, e.g., power demand for culture mixing, dewatering, and cell disruption. In the ALU and AHTL pathway models that we studied previously, significant fractions of the biomass were left as remnants, which were converted to renewable heat and power that supported the process. The GHG reduction and the reduction of fossil fuel consumption depended upon this renewable power.

The fractionation pathway is attractive economically, but it redirects biomass away from on-site renewable heat and power generation, so it is possible that GHG and energy use performance may be impaired. Performance is often assessed via a metric of emissions or energy use per unit of produced fuel. The question addressed by this paper is whether the fuel yield increase in the fractionation process compensates for the decrease in on-site heat and power production and compensates for the increase in process energy demand, e.g., for ethanol distillation.

This study presents an LCA of energy use and greenhouse gas emissions for algal biofuels produced via the fractionation process as modeled by Davis et al. [6]. The LCA considered all operations in the fuel pathway, including upstream material and energy provisioning operations, cultivation, and final fuel use. See Fig. 2. The purpose of this analysis is to examine the sustainability of the fractionation process when energy use and GHG emissions are used as metrics. This work extends the literature by considering the sustainability implications of redirecting carbon away from waste streams that provide process energy towards streams that produce additional fuel and high-value co-products. It must be recognized from the outset that there are uncertainties in the algae pathway at the current time because several operations have only been evaluated at small scale. Even if the present study cannot achieve final, definitive emissions and energy use numbers, the study has value as a sensitivity study that can increase our understanding of the consequences of using fixed carbon in the biomass for co-products rather than using it for energy to support the process.

2. Methods

The LCA study was carried out using the Greenhouse Gases Regulated Emissions and Energy Use in Transportation (GREET) model [12]. The analysis computes greenhouse gas (GHG) emissions as the sum of the two stages, namely the well to pump (WTP) stage and the pump to wheel (PTW) stage. The WTP stage computes the energy use and GHG emissions from feedstock and fuel production, including transportation to distribution to fueling stations. This stage includes the material and energy demands for nutrient manufacturing, growth, biomass dewatering, biomass to fuel conversion, and transportation of fuel to a pumping station. The PTW stage examines the energy use and GHG emissions associated with vehicle operation (fuel combustion). The sum of the WTP and PTW stages is the Well to Wheel (WTW) result and is the net result for the pathway.

GREET computes GHG emissions associated with methane, nitrous oxide, and carbon dioxide by considering their global warming potentials, expressed in equivalent grams of CO_2 (gCO_2e). The total GHG emissions are reported as grams of CO_2 equivalent (gCO_2e) per megajoule (MJ) of renewable diesel (RD) based on the lower heating value (LHV) of the RD.

2.1. System boundary and functional unit (RD_e)

The Aspen model of the fractionation process in [6] considered only the conversion of 20 wt% dewatered algae biomass to fuel intermediates plus upgrading the lipids to RD blendstock. The model included all recycle loops, co-generation, heat integration, and waste treatment and calculated net mass and energy inputs. The energy inputs computed by the Aspen model were broken down into individual fuels (electricity and natural gas) for input into the GREET LCA model. Within GREET, the

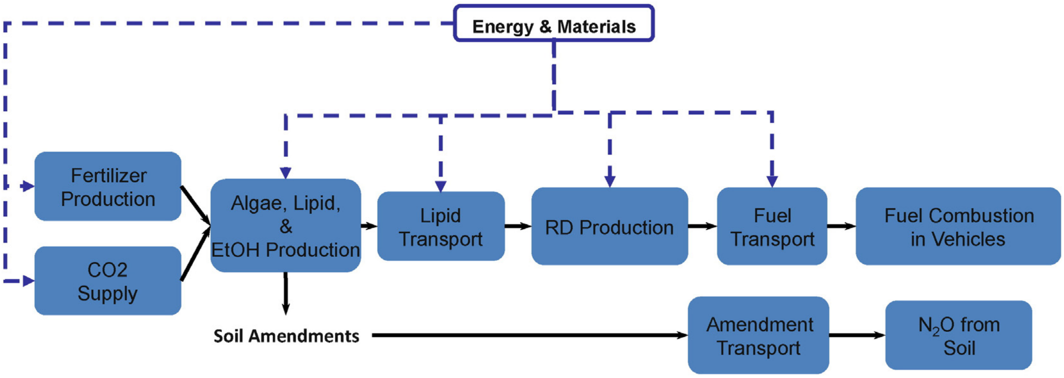

Fig. 2. Boundary of the system considered in the life cycle analysis. The soil amendment co-product is the digestate (solids) from the anaerobic digestion step.