Algal Research xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Algal Research

journal homepage: www.elsevier.com/locate/algal

An analysis of energy consumption for algal biodiesel production: Comparing the literature with current estimates

Adam J. Dassey, Steven G. Hall, Chandra S. Theegala *

Department of Biological and Agricultural Engineering, Louisiana State University & LSU AgCenter, Baton Rouge, LA 70803, USA

ARTICLE INFO

Article history:
Received 3 April 2013
Received in revised form 15 December 2013
Accepted 19 December 2013
Available online xxxx

Keywords:
Algal biodiesel
Life cycle analysis
Energy balance

ABSTRACT

Algae have significant potential compared to other biomass feedstocks to supplement current transportation fossil fuel usage. To determine the acceptability of algal biodiesel as a replacement for petroleum, a life cycle analysis (LCA) with parameters of aerial productivity, culturing, CO_2 mitigation, water use, nutrient loading, biomass harvesting, lipid extraction, and energy conversion was explored on algae production in Louisiana. High and low energy estimates found in several published LCAs were compared to current realistic estimates and analyses completed by the authors. Considering a system with an aerial biomass productivity of 15 g/m^2/day and cell lipid concentration of 20%, the energy inputs exceeded the outputs from biodiesel production by 53% under the most ideal conditions. However, slight increases in biomass productivities and lipid contents are anticipated to tilt the overall energy balance more favorably. Considering the current conservative estimates (for biomass productivity and lipid content), incorporation of value added processes such as wastewater treatment and biogas production from residual biomass, could improve the sustainability of the system, allowing it to potentially achieve a 13.2% energy surplus.

1. Introduction

Increases in energy prices and national mandates to reduce the dependence on foreign oil have brought renewed interests in alternative energy. The Energy Independence and Security Act of 2007 established a mandatory Renewable Fuel Standard requiring transportation fuel sold in the U.S. to contain a minimum of 36 billion gallons of renewable fuels, including advanced and cellulosic biofuels and biomass-based diesel, by 2022 [1]. One challenge for renewable transportation fuels, however, has been the development of a suitable biomass feedstock. The aerial yields and sustainability of traditional food crops such as corn, sugarcane, and soybean have made them unlikely candidates as biofuel feedstocks [2]. Since 70–80% of the total biofuel production costs are in the raw materials, proper feedstock selection is crucial [3,4]. Microalgae has shown potential as a sustainable feedstock for reasons such as: i) predicted high per-acre productivity, ii) based on non-food resources, iii) use of otherwise non-productive, non-arable land, iv) utilization of a wide variety of water sources (fresh, brackish, saline, and wastewater), v) mitigation of greenhouse gases released into the atmosphere, and vi) production of both biofuels and valuable co-products [5].

To assess the sustainability of algal biodiesel as a replacement for petroleum, a life cycle analysis (LCA) was explored on algae production in Louisiana, which was determined to be one of the top three states for algae production by the National Renewable Energy Laboratory [6]. Louisiana's transportation sector accounted for 17.1% of its total energy usage including 52.9 million barrels of motor gasoline and 33.6 million barrels of distillate fuels [7]. The energy contained within algal biodiesel is approximately 37.8 MJ/kg [8] as compared to the 43 MJ/kg found in conventional fuels. Therefore, 87.4 million barrels of algal biofuel would be needed to replace current transportation fuels in Louisiana. The design of an algal conversion system requires the combination and optimization of several factors such as biomass culturing, growth management, transport to conversion plants, drying, product separation, recycling, waste management, transport of saleable products and marketing [2,9]. Major process engineering accounts for the partial costs associated with biomass culturing, harvesting, oil extraction and oil transesterification [10]. For the current analysis, a combination of estimates, projections and experiments (conducted at LSU) were assembled and categorized accordingly in the following sections.

2. Estimated culture parameters

2.1. Theoretical maximum estimates

Algae growth rates, like those of land based plants, are dependent on their photosynthetic efficiency. Photosynthetic efficiency (PE) is the fraction of light energy that can be fixed as chemical energy for biomass production of an algal cell. Oxidative photosynthesis, however, remains somewhat inefficient at converting solar energy to chemical energy and ultimately biomass [11]. The maximum PE that can be achieved is only 10% due to photoinhibition [12], because the light capturing antennae

---

* Corresponding author. Tel.: +1 225 578 1060; fax: +1 225 578 3492.
E-mail address: ctheegala@agcenter.lsu.edu (C.S. Theegala).

2211-9264/$ – see front matter © 2014 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.algal.2013.12.006

of algae harvest one photon every 0.5 ms, but the dark phase reaction centers can only process one photon every 5 ms.

Since average solar radiation in the state of Louisiana is $4.6\ \mathrm{kWh/m^2/day}$, the maximum theoretical radiation that can be used by algae for biomass production over the course of a year is:

$$4.6\frac{\mathrm{kWh}}{\mathrm{m^2 * day}} * \frac{3.6\ \mathrm{MJ}}{\mathrm{kWh}} * \frac{365\ \mathrm{days}}{\mathrm{year}} * 10\% = \frac{604\ \mathrm{MJ}}{\mathrm{m^2 * year}}.$$

Under phototrophic cultivation, there is a large variation in the lipid content of microalgae, ranging from 5% to 68%, depending on the type of microalgae species [13]. The most common microalgae (*Chlorella*, *Dunaillea*, *Isochrysis*, *Nannochloris*, *Nannochloropsis*, *Neochloris*, *Nitzschia*, *Phaeodactylum*, and *Porphyridium*) possess oil levels between 20 and 50% (w/w) and exhibit reasonable productivities in laboratory culture testing [14]. Assuming that a nonspecific algal species consists of 20% lipids (triglycerides (lower heating value) LHV = 37.5 MJ/kg) and the remaining 80% to be carbohydrates and proteins (LHV = 18 MJ/kg), the maximum theoretical biomass production is:

$$\frac{604\ \mathrm{MJ}}{\mathrm{m^2 * year}} * \frac{\mathrm{kg}}{21.9\ \mathrm{MJ}} * \frac{4047\ \mathrm{m^2}}{\mathrm{acre}} * \frac{\mathrm{ton}}{1000\ \mathrm{kg}} = \frac{111\ \mathrm{mt}}{\mathrm{acre * year}}.$$

Where 21.9 MJ/kg is the weighted average of LHV for lipids, carbohydrates and proteins. Assuming the algal oil density to be 864 g/L, which falls within the range determined by Kumar and coworkers [15] for various species (857–892 g/L), the oil production per acre is:

$$\frac{111\ \mathrm{mt}}{\mathrm{acre * year}} * \frac{1000\ \mathrm{kg}}{\mathrm{ton}} * 20\%\ \mathrm{lipids} * \frac{\mathrm{L}}{0.864\ \mathrm{kg}} = \frac{25{,}694\ \mathrm{L}}{\mathrm{acre * year}}.$$

This estimated value is the theoretical "upper limit" of PE, as it does not account for other factors that could decrease efficiency and conversion (e.g. photosaturation, photorespiration, and poor light absorption) [16]. Due to such impacting factors, most autotrophic organisms attain PE levels typically between 1% and 3% [17]. Therefore, assuming a PE of 2%, algal production can realistically be expected to produce 5170 L/acre/year. To supply Louisiana's energy demand of 87.4 million barrels of biofuel for transportation purposes, the state would require 710,153 acres of algal ponds. This is less than 2.2% of the total land surface area in Louisiana. In comparison of land allocation, Louisiana farms approximately 200,000 acres of crawfish ponds during the year [18].

2.2. Aerial productivity

Most commercial microalgae cultivation systems are carried out in open pond systems using solar energy as the light source, which is the cheapest light source available [12,13]. High rate ponds used in commercial algae production are typically operated at 20 to 40 cm (6 to 16 in. liquid depth, mixed with paddlewheels and up to about 0.5 ha in size [19]. For this manuscript, a hypothetical 1 acre, 40 cm deep oval raceway was assumed to culture a nonspecific algal species with 20% lipid content and an aerial productivity of 15 $\mathrm{g/m^2/day}$.

2.3. Mixing

In algal cultivation, the productivity of algal systems, cost of reactor construction and operation are dependent on the mixing system being able to maintain typical culture flow velocities of 8–14 cm/s [20], with maximum velocities of 20–25 cm/s rarely being exceeded [19]. Mixing by traditional paddlewheel is the most common method of circulation, but Collet et al. [21] indicated this to be the most energy intensive in algae cultivation, consuming 0.1 $\mathrm{kWh/m^3}$ of culture. Progresses in electricity consumption during cultivation can be achieved by decreasing the mixing costs and circulation between different production steps [9]. To accomplish this, the minimum energy required to maintain mixing velocities was determined through the headloss (h_L) experienced in the bends (h_b), straightaways (h_s) and carbonation sump (h_c) [19].

$$h_L = 2h_b + 2h_s + h_c$$

$$h_L = 2\left(\frac{K_b v^2}{2g}\right) + 2\left(v^2 n^2 \frac{L}{R^{\frac{4}{3}}}\right) + \left(\frac{K_c v^2}{2g}\right)$$

Where

K = kinetic loss coefficient
v = mean velocity (m/s)
g = acceleration of gravity (9.81 $\mathrm{m/s^2}$)
n = roughness factor (n = 0.018 for clay channels)
L = channel length (m)
R = channel hydraulic radius (m)

$$h_L = 2\left(\frac{2\left(0.25\ \frac{\mathrm{m}}{\mathrm{s}}\right)^2}{2\left(9.81\ \frac{\mathrm{m}}{\mathrm{s}^2}\right)}\right) + 2\left(\left(0.25\ \frac{\mathrm{m}}{\mathrm{s}}\right)^2 (0.018)^2 \frac{109\ \mathrm{m}}{(0.39\ \mathrm{m})^{\frac{4}{3}}}\right)$$

The power (P) to maintain a velocity of 0.25 m/s in a 1-acre raceway, is therefore:

$$P = \gamma Q h = \left(9.78\frac{\mathrm{kN}}{\mathrm{m^3}}\right)\left(1.55\frac{\mathrm{m^3}}{\mathrm{s}}\right)(.0409\ \mathrm{m}) = 0.620\ \mathrm{kW}.$$

Where

γ = specific weight of water ($\mathrm{kN/m^3}$)
Q = flowrate at velocity, v ($\mathrm{m^3/s}$)
h = headloss (m).

Assuming the efficiency of the mixing device, whether paddle wheel or air lift, to be 40% [22], the energy required to mix a 1645 $\mathrm{m^3}$ pond at 0.25 m/s for 24 h fell within the variable range of other authors (Table 1).

2.4. Carbon dioxide

Microalgae have attracted a great deal of attention for CO_2 fixation and biofuel production because they can convert CO_2 into biomass via photosynthesis at much higher rates than conventional biofuel crops [25]. Many reports on the potential and bio-economics of algal biomass to generated fuels are based on the premise that CO_2 would be utilized from fossil fuelled power stations or other industrial sources of CO_2 [9]. The specific growth rate of *Nannochloropsis* increased 58% when 15% CO_2 (typical concentration of flue gases) was used for aeration [26]. Additionally, combustion products such as NOx or SOx can be effectively used as nutrients for microalgae, simplifying flue gas scrubbing for combustions systems [27].

Algae require approximately 2 g of CO_2 for every g of biomass generated [5]. To gain a more accurate assessment of the CO_2 required to

Table 1
A comparison of the daily energy required to maintain a mixing velocity of 0.25 m/s.

Reference	[21]	[23]	[19]	[24]	Current estimates
Energy ($\mathrm{kWh/m^3\ d}$)	0.1	.006	0.016	0.089	0.023

Please cite this article as: A.J. Dassey, et al., An analysis of energy consumption for algal biodiesel production: Comparing the literature with current estimates, Algal Res. (2014), http://dx.doi.org/10.1016/j.algal.2013.12.006