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A financial assessment of two alternative cultivation systems and their contributions to algae biofuel economic viability☆

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ABSTRACT

The Farm-level Algae Risk Model (FARM) is used to simulate the economic feasibility and probabilistic cost of biomass and bio-crude oil production for two projected algae farms. The two farms differ in their cultivation system: an open raceway pond (ORP) and a photobioreactor (PBR). The economic analysis incorporates production, price, and financial risks the farms will likely face over a 10-year period. Current technology for both cultivation systems is assumed with an emphasis on the differences in biomass production, lipid content, culture crashes, and dewatering and extraction costs. Results of the analysis indicated that with current prices and technology neither cultivation system offers a reasonable probability of economic success. The total costs of production for crude bio-oil is 109 $ $\text{gal}^{-1} \pm 45$ $(\bar{x}, \sigma)$ for an ORP and 77 $\text{gal}^{-1} \pm 25$ $(\bar{x}, \sigma)$ for a PBR. Further analysis revealed that for every 1% increase in biomass production annual net cash income is increased 0.21% for an ORP and 0.10% for a PBR.

1. Introduction

Microalgae are being heavily researched as an alternative feedstock for renewable biofuels. In the production process there are several key steps that affect the cost of biofuel production and profitability, but the single most critical step is involved in the cultivation system and process to produce biomass feedstock [1–4]. There are two predominate cultivation systems employed in the microalgal industry, i.e., open raceway ponds (ORPs) and closed photobioreactors (PBRs) [5]. Due to their initial costs and maintenance and energy requirements, as well as their determination on final cell population density, cellular biochemical composition, and biomass productivity, the cultivation system used on a microalgae farm determines to a large extent the economic viability of microalgae-based biofuels and bioproducts.

Most available biomass productivity data have been obtained from lab-scale or outdoor small-/pilot-scale trials over a brief period of time (days or weeks), and are extrapolated to commercial-size facilities. Only a few publicly available data exist for larger size facilities or a longer time period of operation. Norsker et al. determines the production costs to be 4.95, 4.16, and 5.96 € kg^{-1} of biomass for ORPs, horizontal tubular PBRs and flat panel PBRs, respectively, for a 100 hectare facility [6]. Chisti estimates the cost per gallon of production to be $2.95 and $3.80 for PBRs and ORPs, respectively, for a facility producing 100,000 kg of biomass annually [7]. Alternatively, Davis et al. find minimum selling prices for algal lipid of 8.52 $ gal^{-1} for ORPs and 18.10 $ gal^{-1} for PBRs to achieve a 10% internal rate of return in a facility producing 10 MG yr^{-1} [3]. Richardson et al. also evaluate a production facility producing 10 MG yr^{-1} and find that ORPs have a lower cost of production at 12.74 $ gal^{-1} as compared to PBRs, which have a cost of production of 32.57 $ gal^{-1} [8]. However, in each of these studies and others [9–11], optimistic productivities were assumed that did not accurately reflect the actual productivities and the cellular lipid content currently achievable in the existing ORPs and PBRs. For example, Davis et al. [3], Richardson et al. [8], and Delrue et al. [11] assumed equal areal productivities of 25 g m^{-2} d^{-1} and 25% lipid content, for both ORPs and PBRs. However, recent studies have reported that considerably higher lipid productivities are achievable in PBRs than in ORPs. Quinn et al. reported a two-year average of 7.4 g biomass m^{-2} d^{-1} and 35% lipid content of *Nannochloropsis* sp. grown in the Solix PBR system [12]. Previously, Rodolfi et al. [13] reported average outdoor productivities of 11 g biomass m^{-2} d^{-1} and 40% lipid content for *Nannochloropsis* sp. in green wall photobioreactors [13]. Short-term productivities of *Nannochloropsis* sp. in ORPs have been 3–4 g biomass m^{-2} d^{-1} with lipid contents of 15–25% [14]; Hu et al.

Abbreviations: OPR, open pond reactor; PBR, photobioreactor; PDF, probability density function; NCI, net cash income; CAPEX, capital expenses; OPEX, operating expenses; Es, sensitivity elasticity.

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Table 1
Summary of biomass productivities, lipid contents, and biomass loss due to algal grazers assumed for the analysis based on published literature.

	Biomass productivity (g m^{-2} d^{-1})	Lipid content (%)	Harvesting biomass concentration (g L^{-1})	Grazer biomass loss (%)
ORP	6.8 ± 3.0	20 ± 5	1.5	20 ± 10
PBR	9.3 ± 2.0	40 ± 10	3.0	8 ± 3

achieved productivities of 10 g biomass m^{-2} d^{-1} and 18% average lipid content in a PBR [15].

When the capital and operational costs of PBRs and ORPs are compared in isolation, the costs of PBRs are higher than those of ORPs. When the comparison is made in the context of the entire algal biofuel production supply chain, however, it is not known which system would be more cost-effective. For example, greater stability and sustainability of microalgal mass culture, and higher biomass density and lipid content are achievable in PBRs while having considerably less water demand and associated energy consumption per kg of biomass obtained. These differences have significant economic implications for overall biomass feedstock production and subsequent harvesting, dewatering and extraction processes. However, the influence of cultivation systems and processes on the individual steps up- and down-stream has not been recognized in the previous techno-economic analyses, let alone quantitative assessments of the cultivation systems and processes on overall production cost.

As further research is done on algal cultivation systems, especially at a larger scope than lab, bench, or small outdoor-scale with a longer period of time (months or years), it needs to be analyzed to determine which technologies may be more financially feasible for use in commercial production systems. The Farm-level Algae Risk Model (FARM) developed by researchers at Texas A&M University for use in the National Alliance for Advanced Biofuels and Bio-products (NAABB) Consortium was used for this analysis [8]. Productivity data (algae growth rates, lipid contents, biomass concentrations) was based on productivities published in the literature. For PBRs, the productivities and lipid contents were based on the results of Quinn et al. [12] and Rodolfi et al. [13] while the results of Hu et al. [15] and Crowe et al. [14] were used for ORPs. These values, given in Table 1, were selected as they are representative of annual productivities observed by the authors. Product lost to algal grazers has not been well quantified, but the authors estimate that it is 5–10% for PBRs and 10–30% for ORPs. Currently, at this time there are no well documented mitigation strategies for pond predation and crashes. So, the probability of pond crashes and grazer biomass loss does not decrease over the 10 year horizon for the business.

The stochastic variables listed in Table 1 were simulated using the GRKS distribution using the Excel add-in, Simetar [16]. The GRKS[1] distribution is suited to this application because it requires minimal parameters (minimum, middle, and maximum) and provides a 2.28% probability of outliers beyond the minimum and maximum parameters. Simetar is an Excel add-in for estimating parameters of probability distributions for random variables and simulating Monte Carlo models. Simetar has been used extensively for risk analysis of business models and prospective businesses [17].

GRKS probability distributions for the following stochastic production variables were based on values in the literature: biomass productivity (g m^{-2} d^{-1}), percent lipid content, harvesting biomass concentration (g L^{-1}), percent grazer biomass loss, and number of harvests per month were specified. Combing stochastic production values listed above with total facility pond volume, the model simulates total annual biomass and lipid production.

The objective of this paper is to compare the economic feasibility of biofuel production in the two alternative cultivation systems, ORPs and PBRs, with the consideration of different algal density, cellular lipid content, biomass productivity, production loss due to grazers and parasites, and their influence on the harvesting and extraction processes. The two cultivation systems are compared as to their impacts on the revenues, expenses, and cost of production for an algae farm. While neither cultivation system is expected to result in economically feasible biofuel production at present productivities, this work will provide insight into the kinds and magnitudes of technical improvements and cost reductions required for each production step to produce economically competitive biofuels.

2. Material and methods

The data for the two algae farms with alternative cultivation systems was analyzed using the FARM to project changes in their economic viability. FARM is a Monte Carlo firm level simulation model designed to simulate the annual production and economic activities of an algae farm. The model was designed to facilitate researchers' analysis of the economic returns and costs of production for an algae farm under alternative management systems. The model can be thought of as a systems compilation of many techno-economic models for different phases of an algae farm.

2.1. FARM programming

FARM is programmed in Microsoft® Excel and depends upon the Simetar© add-in to incorporate risk. The Excel workbook model is divided up into multiple worksheets that include: Input, Model, SimData, Prices, and others.

All inputs for an algae farm are entered in the INPUT worksheet and most calculations are in the MODEL worksheet. Simetar is used to simulate the model by randomly drawing annual stochastic prices, production, and costs from known probability distributions. The parameters for price probability distributions are estimated from historical data provided as input by the researchers. Parameters for algal biomass production are estimated from actual production data for ORPs and PBRs.

The FARM model is simulated recursively for 10 years. This means that the ending cash position of the business in year 1 is the beginning cash flow position for year 2, and so on. The 10 year planning horizon is repeated 500 times (iterations) using different stochastic prices and production values for each year. By simulating the 10 year planning horizon for 500 iterations, the model is able to simulate most combinations of the stochastic variables (i.e., the best and worst cases and those in between) based on their respective probabilities of being observed. The resulting 500 values for the key output variables are estimates of the empirical probability distributions for these variables and are used to calculate probabilities of financial and economic sustainability [8].

Analysts enter all of the data to describe the scenario to be simulated for a farm. Input data include information for: the type of cultivation, final cell density, lipid content, biomass productivity, harvesting, lipid extraction, and use of co-products. A base scenario is usually defined and copied multiple times with slight variations in the many management

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[1] The GRKS distribution assumes that 50% of the observations are greater than the model value. Also, the distribution draws 2.28% of the values from above the maximum and 2.28% from below the minimum. Random values from outside the minimum and maximum values account for low frequency, rare observations, i.e., Black Swans.