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Dynamic process model and economic analysis of microalgae cultivation in open raceway ponds

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ABSTRACT

Microalgae are a promising biomass feedstock for production of value-added chemicals and bioproducts. A first principle based bioreaction kinetics and bioprocess model of microalgae production was developed for an outdoor open raceway pond that takes into account year-round geospatial characteristics and variability. The primary factors that affect microalgae growth, such as solar irradiance, temperature, biological growth parameters, nutrients and carbon dioxide uptake rates, were considered in the bioreactor process model. Microalgae productivity varied between 2000 and 7200 t km^{-2} $year^{-1}$ for the different geographical regions studied. For each location, techno-economic analysis was conducted to assess microalgae production price. The capital and operating expenses for microalgae cultivation systems were quantified based on the mass and energy balances of the process. Given the geospatial locations, cost of microalgae production varied between 1074 \$ t^{-1} to 502 \$ t^{-1}. Results showed that cost of microalgae production depends heavily on the average areal productivity, price of nutrients, as well as design specifications of microalgae growth ponds.

1. Introduction

With an ever-increasing population as well as an increase in demands of energy, food and feed throughout the world, there is an imminent need to find suitable sustainable resources. Energy derived from biomass has the potential to contribute considerably to the future energy supply of the world [1]. Biomass energy not only possesses the potential to contribute to significant amounts of renewable fuels, feed, fiber and food, but also can help to decrease carbon dioxide (CO_2) from the atmosphere. The United States has set a goal of reducing CO_2 emissions by 17% by 2020. However, intensified expansion of renewable energy is required as the current trend shows only 9% reduction in CO_2 emissions relative to 2005 level [2].

Production of bioenergy is land and water intensive in nature. Microalgae are a promising bioenergy feedstock, which can grow on non-arable lands, absorb CO_2, utilize low quality water and waste water, and can accumulate substantial amount of lipids suitable for biofuel production [3]. Besides biofuel production, microalgae also has the potential to be utilized as source of food, feed, pharmaceuticals and nutraceuticals [4–6].

In the last several decades, microalgae research has focused extensively on its utilization as a renewable fuel source. The Aquatic Species Program, undertaken by the National Renewable Energy Laboratory in Colorado, USA, was an extensive research program to assess the feasibility of microalgae as energy source [7]. However, the program was discontinued as the fuel prices based on microalgae as a feedstock was more than twice the price of fossil fuels in 1996 [7], even after using aggressive assumptions. Due to very high capital costs, it has been a challenge to construct microalgae based renewable energy plants at an industrial scale. There is ongoing research on microalgae cultivation, harvesting and conversion to different products and specific challenges still exist that need to be addressed in order to make microalgae based products economically viable. There has been significant effort in addressing the techno-economic and lifecycle analyses of microalgae based biorefinery based on different assumptions [8–22]. However, the lack of detailed data regarding microalgae cultivation, harvesting, conversion and associated costs is a definite barrier in commercialization of microalgae based bioproducts.

In order to assess the current and future potential of microalgae as a bioenergy feedstock, it is very important to assess their productivity potential for a particular geographic location. Productivity is strongly dependent on geospatial location and local climatic factors like solar irradiance, air temperature, local wind velocity and relative humidity. Microalgae can be cultivated in variety of systems. Open raceway ponds are the most basic and most cost effective cultivation system for microalgae production. In comparison to other cultivation systems such as photobioreactors, microalgae productivities in open raceway ponds are low, but are often compensated by low capital and operating costs and

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high economic value of the products [3,16,23]. Several researchers have studied open raceway ponds for microalgae growth and subsequent conversion of microalgae to biofuels [24–33]. Although some researchers assumed algae biomass production greater than 11,000 t km^{-2} year^{-1} [27,34–36], however, in reality about 9100 t km^{-2} year^{-1} seems close to the upper production limit in open raceway ponds [37]. From the different literature resources, it can be inferred that there is a wide variation in microalgae productivity depending on the production location, choice of production system, algae species and local climatic condition. Productivity of *P. tricornitum* in Algeria and Netherlands in open raceway ponds are 6370 t km^{-2} year^{-1} and 4150 t km^{-2} year^{-1}, respectively [38]. This difference in productivity can be attributed mainly to the difference in solar irradiance and climatic factors. It is also important to note that productivities vary significantly for the same location and cultivation system for different species [38,39]. Researchers have obtained annual productivity of 6.1 kg panel^{-1} year^{-1} and 10.6 kg panel^{-1} year^{-1} for the two species *T. pseudonana* and *P. tricornutum* respectively, in France in flat panel photobioreactors [39]. This difference in productivity in the same location and cultivation system can mainly be attributed to the biological characteristics of the two different strains of microalgae. The difference in microalgae productivity has a strong influence on the techno-economic and life-cycle analysis of commercial scale algae based systems. It is evident from existing literature resources that there is a significant need to understand the fundamentals of the reaction kinetics and biological process of algae growth and the various factors that influence productivity and economics, especially on a year-round basis.

The goal of the present study was to assess the productivity potential of microalgae for different locations considering geospatial variability. Furthermore, economic analysis was conducted to assess the minimum selling price of microalgae feedstock for the studied locations. Microalgae growth in open raceway ponds were analyzed taking into account the various geospatial effects of different locations in United States. First, a heat and mass transfer model was developed for the open raceway pond. This enabled us to assess the overall yearly temperature of microalgae growth ponds based on the different climatic parameters. Furthermore, a bioreaction kinetics based growth model was developed to determine yearly microalgae productivity potential in open raceway ponds taking into account the geospatial factors. Based on the mass and energy balances of the entire process, the capital and operating costs of the entire system were determined. Thus, the economic analyses presented in this work captured the different weather parameters and conditions and were reflected in the microalgae production price. The locations of the hypothetical microalgae production plants considered in the study were Minnesota (Twin Cities region), California (San Diego), New Mexico (Albuquerque) and Arizona (Phoenix). While assessing the feasibility of microalgae based biorefinery, previous researchers have mostly assumed microalgae productivity potential and the corresponding price of microalgae as the starting point of their analyses [9,40–42], resulting in wide variability and significant uncertainties in the techno-economic evaluation. Thus, the development of the proposed growth model and corresponding economic analysis, under varying climatic and environmental conditions, helped us to determine microalgae productivity and production price more accurately. Results from the study can help determine the best locations for construction of commercial scale microalgae production plants within the United States. The current mathematical framework was intended to serve as a guideline for entrepreneurs, scientists, engineers and policy makers for assessment of economic feasibility of microalgae as a feedstock for bioproducts.

2. Materials and methods

Open raceway ponds and photobioreactors are extensively used as microalgae cultivation systems. In the present study, open raceway ponds were considered for microalgae production. In an open pond system, microalgae grow under diurnal light and temperature conditions. During the growth phase, carbon dioxide (CO_2) and nutrients (nitrogen, phosphorus and others) are utilized and oxygen is released. Although microalgae can grow by utilizing atmospheric CO_2, however, additional CO_2 is required to boost their productivities to utilize them for biofuel production. So, the raceway ponds are often equipped with submerged aerators to provide additional CO_2. Also, to facilitate proper mixing of the microalgal culture, raceway ponds are often equipped with paddlewheels. Paddlewheels are mechanical rotating devices that are operated continuously in order to ensure that the microalgal cells are mixed properly and sedimentation is prevented. Although open raceway ponds are extensively used for microalgae growth (due to low capital and operating costs of raceway ponds in comparison to photobioreactors), there are a few disadvantages. The volumetric productivity in an open pond system is much less than that of a closed system (0.1 kg m^{-3} in comparison to 1.5 kg m^{-3}) [43]. Furthermore, being open systems, huge amount of water is lost due to evaporation from the open surface. Also, there is a possibility of contamination limiting the productivity potential as well as species sustainability [38,44].

The productivity of *Nannochloropsis* sp. in open raceway ponds was modeled using a systems approach considering the effect of different process variables influenced by geographical location. *Nannochloropsis* is a very promising microalgal species which is often touted as a suitable candidate for biofuels production [45,46]. The surface area of each raceway pond is assumed to be 8100 m^2 with a depth of 0.3 m [47]. The proposed theoretical framework of the model is depicted in Fig. 1.

To determine microalgae productivity for a location, first a combined heat and mass transfer model was developed for microalgae growth in open raceway ponds by integrating local climate factors, the reactor geometry and characteristics of the species. Then, it was integrated with biological growth kinetics to assess microalgae productivity for a given location. Once the algae productivity for a particular location was assessed, an economic analysis was conducted to determine the production price of microalgae for that location. It was assumed that the open raceway ponds were facilitated with algae harvesting and dewatering units in order to produce microalgal paste with 20% solids concentration (ash free dry weight [AFDW] basis). The economic analysis showed the significance of geospatial locations contributing to the difference in microalgae price. The entire microalgae production supply chain considered in the study is presented in Fig. 2. Details regarding process engineering aspects of microalgae growth in open raceway ponds as well as harvesting and dewatering steps to produce microalgal paste with 20% solids concentration are provided in Sections 2.1 and 2.2. The following section describes the mathematical models developed for the study in greater detail.

2.1. Model

2.1.1. Model inputs

Local Weather Data – Depending on the location of the microalgal cultivation system, the local weather information, including solar irradiation, air temperature, wind velocity, relative humidity, are required for the model, on an hourly basis. The necessary hourly weather data was obtained from the United States National Climatic Data Center [48]. Based on the weather data, which influences the thermal balance and microalgae growth rate, the heat transfer model was developed to quantify the water temperature of the open raceway ponds.

Model specific parameters – Microalgal productivity depends on the microalgal species and the varying conditions during algae growth. The different model parameters used to develop the microalgae growth model is presented in Table 1. Nutrients like phosphorus and nitrogen, in the form of Diammonium phosphate (DAP) and urea respectively, and CO_2 required for algae growth were assumed to be provided in