Algal Research xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Algal Research

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

Scenario evaluation of open pond microalgae production

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ARTICLE INFO

Article history:
Received 20 December 2012
Received in revised form 14 February 2013
Accepted 1 May 2013
Available online xxxx

Keywords:
Open ponds
Scenario analysis
Microalgae
Production estimates
Model
Decision variables

ABSTRACT

To evaluate microalgae production in large scale open ponds under different climatologic conditions, a model-based framework is used to study the effect of light conditions, water temperature and reactor design on trends in algae productivity. Scenario analyses have been done for two algae species using measured weather data of the Netherlands and Algeria. The effects of temperature control, photo-inhibition and using monthly or yearly fixed biomass concentrations are estimated by a sensitivity analysis. The calculation-based results show that climate conditions such as solar irradiation and temperature dynamics play an important role in open raceway ponds. In moderate climate zones low and high temperatures over a season suppress growth. At high latitudes this effect is important as light levels vary much during the day and between seasons. Optimal biomass concentrations in ponds depend on location, pond depth and algae species. Pond design, location and algae species interact and productivity cannot be based solely on general or assumed efficiencies. It is essential to select algae species that have a suitable growth rate, light absorption coefficient and the ability to grow over a broad temperature range. The presented approach gives a framework to validate specific cultivation systems.

1. Introduction

Currently, microalgae gain a lot of attention for their potential to produce high value products like pigments, omega-3 fatty acids and proteins, and their ability to produce lipids for the production of biofuels [1]. Microalgae employed for these applications are cultivated in a variety of cultivation systems. Open raceway ponds are the most basic cultivation systems and are used for the production of algae as food supplement and for pigments. Biomass productivities in raceway ponds are low, but are compensated by high product prices and low construction and operating costs [2].

The use of microalgae for biofuel production in open pond systems has recently been assessed [3–8]. These studies concern algae cultivation in connection with a series of processing steps to convert lipids into biofuel. General algae productivities are used to estimate algae productivity and although open ponds are straightforward systems there is a wide variation in the employed estimates. Some life cycle assessments (LCAs) assume biomass productions as high as 110 ton ha^{-1} $year^{-1}$ for open ponds [3,6,7], and even higher productivities have been mentioned before [5]. Borowitzka [9] has reported an average annual production of 91 ton ha^{-1} $year^{-1}$ in Australia, which seems to be close to the upper production limit. In contrast to these high estimates, Jorquera et al. [4] assume more modest productivities of 39 ton ha^{-1} $year^{-1}$. This estimate is close to annual areal productivities reported for experimental sites at higher latitudes. For example, productivities of 30 ton ha^{-1} $year^{-1}$ have been reported for experimental ponds in Spain [10] and an average best productivity of 20 ton ha^{-1} $year^{-1}$ for Italy [11]. According to Tredici [12] long-term productivities in commercial raceway ponds rarely exceed 47 ton ha^{-1} $year^{-1}$. In contrast to the other LCA studies, Wigmosta et al. derive potential local microalgae biodiesel productivities from fixed photosynthetic efficiencies (PE) and a factor to account for temperature effects [8]. However, such fixed PEs are not sufficient to account for the effect of location, algae species and other growth conditions [13]. It is obvious that the actual values have an important influence on the interpretation of the feasibility of microalgae cultivation systems [14,15]. As shown by Slegers et al. [16] the productivity of algae cultivation systems is strongly linked to the location of production, the layout of the production system, algae species and weather conditions. For example, a flat panel system in Algeria has different production yields than the same system in the Netherlands due to differences in solar radiation, latitude and day length. Extrapolation of available experimental and production data to other situations for LCAs is thus not straightforward, which may be one of the reasons of the wide variety of numbers found in literature.

Model simulations are a good approach to estimate the productivities to be expected under a range of conditions. Pond models are most available in waste water treatment, such as carbon dioxide modelling of algae and bacteria co-cultures under simulated diurnal cycles [17]. In micro-algae research several empirical models exist, such as the empirically derived model for the effect of light, temperature, pH and

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http://dx.doi.org/10.1016/j.algal.2013.05.001

oxygen on *Spirulina* production in Spain [10]. Also the penetration of various wavelengths of light in algae ponds has been studied in detail [18]. Algae productivities and water temperatures in ponds have been compared by James and Boriah [19], but unfortunately comparison with literature data is missing. Water temperature has been studied widely and also specifically for raceway ponds [20]. Hydrodynamics play a role for the design of pond dimensions [21] and mixing velocities [19]. Models on photo-adaptation and photo-inhibition effects including the associated timescales are very limited [22].

Models that derive algae productivities at a specific location, using various types of reactor design and algae species will provide a common basis for LCA studies. It enables consistent comparisons when studying different cases. Therefore, we have combined existing models on algae growth kinetics, light conditions and transport phenomena to predict productivities using various pond depths, weather conditions and algae species. The effect of light and temperature is analysed on estimated productivities, prior to validation. The current paper is part of a series of studies for model-based comparison of the expected productivity of various system designs at various locations. The framework is intended as a guideline for the assessment of the feasibility of alternate choices in future production scenarios, which is possible after model validation.

2. Method

Open pond cultivation of algae is mostly performed in so-called raceway ponds. Algae grow under daily light conditions and during growth carbon dioxide is taken up while produced oxygen is released from the pond. Additional carbon dioxide is injected at relevant positions in the system to enhance growth. Although algae ponds do not need arable land, they do require large amounts of water when cultivated on a commercial scale. Therefore, using marine algae species and salt water is beneficial and more sustainable. A paddle wheel moves the water in the system to obtain sufficient mixing in the system. The mixing effect is important and if well-designed it is effective for the whole "raceway cycle" [21]. Direct and diffuse light penetrate the liquid. Algae absorb the light and therefore, the light intensity decreases towards the bottom of the raceway pond.

2.1. Calculation overview

This work compares algae productivity in raceway ponds under a range of decision variables such as location, algae species and system design using a model-based framework. In this paper we consider open pond productivity in various scenarios. The open pond calculations consist of three elements: calculating light input, calculating water temperature and assessing algae productivity as function of light and temperature. The calculation structure is given in Fig. 1. Prediction of algae productivities is based on measured weather conditions, i.e., direct and diffuse light, temperature, wind velocity, relative humidity and air pressure.

2.1.1. Determining light input of ponds

The light model of Slegers et al. [16] for flat panel photobioreactors is used as basis and was adapted to the conditions and design for raceway ponds. Thereby, the effect of shading on the light input due to objects in the surroundings was excluded. The first step in the procedure is to calculate the amount of received sunlight on the horizontal water surface [16]. Local solar irradiation measurements are used to include a dynamic light pattern during the day and the year. The loss of light by reflection from the water surface is taken into account as a function of sun elevation and season. The light gradient due to extinction and absorption of light by the algae is described by the law of Lambert–Beer and results in local light intensities. The light path is taken perpendicular to the water surface. This is justified as algae solutions are strongly scattering media with particles in an order of magnitude larger than the wave length, meaning that scattered light is mainly reflected [23].

2.1.2. Calculating raceway pond water temperature

The raceway pond energy balance was applied to determine the dynamic temperature of the pond water. A recently developed approach uses dimensionless numbers for heat transfer and evaporation phenomena [20], while the classical approach is based on well-established empirical relationships. In this paper the last approach is used. The energy flows due to solar irradiation, light absorption by algae, convection, evaporation, condensation, conduction and longwave radiation are considered (see Fig. 2). Changes in water volume due to evaporation or precipitation are assumed to be balanced by an overflow/inflow system that does not

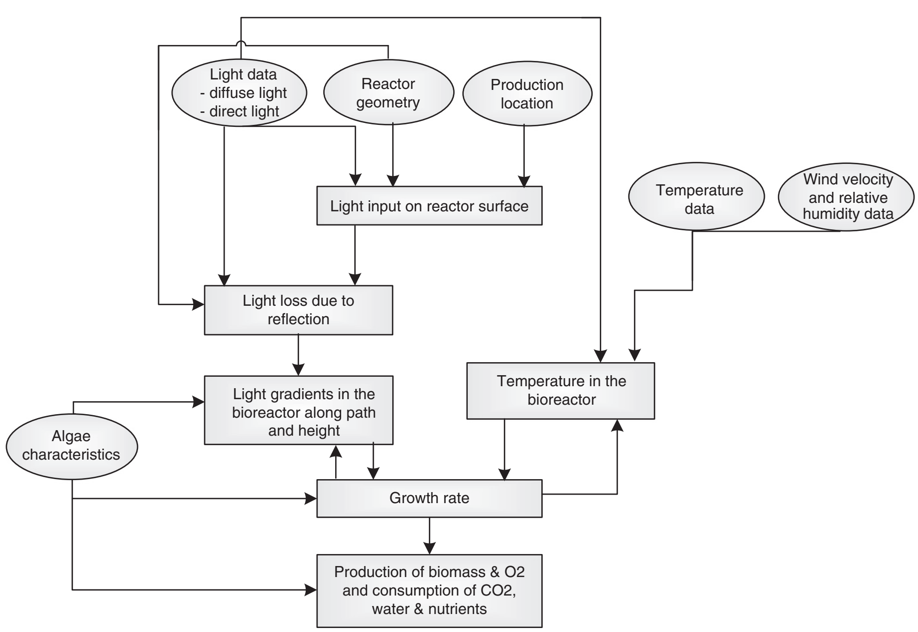

Fig. 1. Calculation scheme for evaluating algae productivity in open raceway ponds. ▭ = Calculation, ⬭ = Model inputs like data and design parameters.

Please cite this article as: P.M. Slegers, et al., Scenario evaluation of open pond microalgae production, Algal Research (2013), http://dx.doi.org/10.1016/j.algal.2013.05.001