Ecological Modelling 388 (2018) 61–71

Contents lists available at ScienceDirect

Ecological Modelling

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

Biophysical modeling of microalgal cultivation in open ponds

Bunushree Behera, Nazimdhine Aly, Balasubramanian P.*

Agricultural & Environmental Biotechnology Group, Department of Biotechnology & Medical Engineering, National Institute of Technology Rourkela, 769008, India

ARTICLE INFO

Keywords:
Mathematical modeling
Microalgae
Biomass productivity
Carbon sequestration
Feasibility analysis
Photoinhibition

ABSTRACT

Microalgal biomass is currently recognized as a promising sustainable source for biofuel production and carbon dioxide (CO_2) sequestration. Utilization of biophysical models are emerging to access the real-time feasibility of microalgal technology. In this present work, a comprehensive mathematical model based on the site-specific meteorological variables is formulated using MATLAB ODE 45 s solver to estimate the microalgal productivity. The predictive model framework utilized material balance equations with basic laws of physics, known constants and conservative assumptions to evaluate the water temperature that influences the microalgal viability. The dynamic behaviour of algal ponds considering the operating variables like light intensity (including the effects of photoinhibition), water temperature, and design criteria like pond depth, microalgal concentration, was used to estimate the performance of *T. pseudonana* in open ponds. Maximum growth was projected in September accounting to the biomass and lipid productivity of 170.28 kg (dry mass) ha^{-1} d^{-1} and 39.42 l ha^{-1} d^{-1} respectively with a CO_2 capture potential of 224.77 kg (CO_2) ha^{-1} d^{-1} based on the influence of water temperature. Optimal pond depth and operational conditions to achieve the desired productivity for the specific site were estimated. The maximum annual areal productivity dropped by 19% from 62.18 tons (dry mass) ha^{-1} yr^{-1} due to photoinhibition. The simulated biophysical model as a tool could be used to evaluate the biokinetic processes affecting the algal pond performance for further facilitation of effective decision making on scaling up of microalgae cultivation.

1. Introduction

The rapid industrialization along with depleting oil reserves and increasing fuel prices in the past few decades has led to the search for alternative renewable energy sources. The rising issues of pollution and global climate change have also resulted in profound interest towards carbon neutral, renewable, third generation algal biofuels. Microalgae due to its superiority over other energy crops regarding ease of cultivation and the presence of substantial quantity of lipids (up to 60% of total biomass) have attracted the attention of global researchers recently (Chisti, 2007; Behera et al., 2018). Additionally, the concepts of integrated microalgal based industrial wastewater treatment utilizing the flue gasses to grow algae that can be processed into biodiesel could sort out the increasing demands of fuel as well tackle the issues related to environmental pollution and global climate change (Rangabhashiyam et al., 2017). Regardless of the portrayed advantages of microalgae, the realistic biomass productivity and carbon dioxide (CO_2) sequestration potential at a particular location during scale up are still questionable. Economic challenges due to the lack of appropriate data with most of the studies confined under controlled lab scale conditions hinder translating the same at the field scale. Site specific studies with biophysical predictive mathematical models as a preliminary resource can provide a comprehensive knowledge about the practical problems witnessed at the field scale. Such studies not only evaluate the economic feasibility of the process but also provide an opportunity to the researchers and policy makers to analyze the influence of a range of vital parameters on microalgal productivity.

Microalgal growth depends on several influencing factors, with solar radiation (light intensity in specific) being the most important (Behera et al., 2018). Several researchers have evaluated the effects of daily solar irradiation on microalgal productivity and CO_2 capture capacity (Weyer et al., 2010; Wigmosta et al., 2011). Sudhakar et al., (2012) and Asmare et al. (2013) predicted the microalgal production potential using simple emperical equations for the different parts of India and Ethiopia respectively. Sudhakar and Premalatha (2012), estimated the microalgal productivity in open ponds for six global sites based on the received solar insolation at study area. Sudhakar et al. (2014) predicted the microalgal biomass and oil productivity in Chennai and Una of India using the local climatic parameters like the solar insolation received and the air temperature. Slegers et al. (2011, 2013) developed a mathematical model to evaluate the spatiotemporal climatologic effects in closed photobioreactors and open ponds with *P.*

* Corresponding author.
E-mail address: biobala@nitrkl.ac.in (B. P.).

https://doi.org/10.1016/j.ecolmodel.2018.09.024
Received 14 July 2018; Received in revised form 26 September 2018; Accepted 27 September 2018

tricornutum and *T. pseudonana* as the model organism in Netherland, France, and Algeria. Marsullo et al. (2015) used a dynamic mathematical model for open pond reactor and predicted the areal biomass productivity in Sevilla (Spain) and Petrolina (Brazil). Béchet et al. (2017) developed the viability model using the temperature function for predicting the growth rate of microalgae at different locations in the Mediterranean regions. Banerjee and Ramaswamy, (2017) estimated the microalgal biomass productivities based on the year round geospatial characteristics. Very recently, Darvehei et al. (2017) separately modelled the growth of microalage as a function of daily light exposure and temperature fluctuations. Most of the above studies were restricted towards the prediction of algal growth rate and biomass productivities, based on the ideal light conditions without taking into account the effect of light attenuation and photoinhibition. Aly et al. (2017) have recently modelled the performance of microalgae in the fixed and trackable photobioreactors based on the amount of solar insolation received including the photoinhibition effects. Aly and Balasubramanian (2016, 2017) evaluated the effect of changes in microalgal productivities in open ponds of NIT Rourkela, India, and ten other locations in Equator, Tropic of Cancer and Tropic of Capricorn including the effects of photoinhibition. Most of the predictive models reported so far are based only on the effect of a single influencing variable, which is either the light intensity or temperature. However, at outdoor locations, different physiological variables like solar insolation, water temperature and the reactor design parameters like pond geometry [particularly the depth (in the absence of mixing)] and algal concentration can be tuned together to provide more reliable estimates.

The present study aims to integrate the site specific physiological/climatologic conditions and the reactor design with the operating variables to formulate a comprehensive biophysical model for performance simulation of open algal ponds. The primary aim is to use the solar irradiance data along with other influencing metereological variables to evaluate the water temperature in order to theoretically predict the average microalgal growth rate, biomass productivity, which was thereby used to evaluate the lipid productivity and CO_2 sequestration potential. Further, design criteria like the pond depth and microalgal concentration on overall productivity has also been taken into account. The model also includes the realistic light attenuation and photoinhibition effects over the annual areal biomass productivity, providing more holistic estimates. Advantages of the proposed study could be highlighted from the fact that a simple, yet, comprehensive mathematical model has been formulated to analyze the biokinetic processes in the open algal ponds. As the parameters used in the biophysical model are measurable characteristics of algae, the model could be easily extended for any other locations as well translated for different algal species. The outcome of the study could act as a benchmark for policymakers seeking to implement the large-scale cultivation of algae at realistic proportions.

2. Methodology

2.1. Site selection

National Institute of Technology (NIT), Rourkela (22.25 °N and 84.92 °E) is located in Sundergarh district of Odisha, India with 219 m above the mean sea level. The solar radiation and the temperature of the campus are quite variable with a huge range of temperature difference between summer and winter season. This site was chosen as the study location since it harbors 7.7 ha of an open pond and receives the secondary treated wastewater from the institute (Supplementary Fig. 1), which could assist the policymakers to realize the wastewater treatment and CO_2 sequestration potential in view of environmental protection through microalgal biomass production as the source of the third generation biofuel.

2.2. Model definition and description

The metabolic rate and viability of microalgae are being affected by several physiochemical factors with most critical ones being light intensity and water temperature (Slegers et al., 2013). Photosynthetically active radiation (PAR) as a part of solar energy plays an essential role in several applications like influencing the algal pond temperature and thereby the algal productivity (Sudhakar et al., 2013a). For instance, the net incident solar radiation in the form of light energy is partly absorbed, apart from being reflected and refracted due to the scattering effect of algal broth. The absorbed solar insolation increases the heat energy that fluctuates the water temperature in open ponds (Béchet et al., 2017). These two interrelated factors governed by multiple sets of complex empirical equations, affects the overall biomass productivities, especially in open pond systems where the reactor geometry particularly the depth (in the absence of proper mixing) plays an essential role.

Since the PAR is dependent on the location, the time of the year and the atmospheric conditions (Sudhakar et al., 2013a), the topographic and spatial information of the specified location were used to retrieve the meteorological data sets (solar insolation data, air, dew and soil temperature) from NASA databases (Stackhouse, 2015). These datasets were used as inputs for the dynamic water-energy balance model to quantify the net effect of the input and output energy fluxes via evaluation of net light absorption, evaporation, conduction, convection, radiation and condensation processes that influences the water temperature. This model was further used to calculate the microalgal growth rate, biomass productivities, that in turn influences lipid productivities and CO_2 sequestration. The overall methodology has been depicted as flowchart in Fig. 1.

The shading effect of solar radiation due to nearby objects has not been taken into account. The volume of water in the open pond is assumed to be constant due to continuous inflow and outflow of water, not affecting the energy balance. The details of the dynamic model have been described in the subsequent sections.

2.2.1. Solar energy balance model

The amount of sunlight incident on the horizontal pond surface is given by $Q_{irradiance}$ (W) and is expressed as in Eq. (1).

$$Q_{irradiance} = A_W \cdot I_{surface}(t) \quad (1)$$

A_W (m^2) denotes the total area of the pond covered with water. Eq. (2) represents the amount of energy, reaching unit area of water surface per unit time, including the light distribution and reflection from water surface ($I_{surface}(t)$ (J m^{-2} s^{-1})).

$$I_{surface}(t) = Full\ spectrum \cdot \eta_{light\ distribution} \cdot \eta_{land\ use} \quad (2)$$

Full spectrum (J m^{-2} s^{-1}) denotes the light energy at a specific angle to the pond surface. $\eta_{light\ distribution}$ (Dimensionless) represents the efficiency of light distribution accounting to the reflective losses. The efficiency of light distributed due to land use/total area of the pond is given by $\eta_{land\ use}$ (Dimensionless). Solar energy is converted into biomass via growth, and a part of this energy is used for cell maintenance. The fraction of solar irradiance used for growth of microalgae is given in Eq. (3).

$$Q_{algae\ growth} = h_{comb} \cdot \mu_{growth} \cdot C_{algae} \cdot V_W \quad (3)$$

Where $Q_{algae\ growth}$ (W) is the total energy needed for the growth of algae, h_{comb} (J kg^{-1}) is the combustion energy of biomass, μ_{growth} (s^{-1}) represents optimal growth rate of microalgae, C_{algae} is the concentration of microalgae in the pond (kg m^{-3}) and V_W is the volume of water in the pond (m^3). Heat of combustion (h_{comb}) of microalgae is given in Eq. (4).

$$h_{comb} = E_P \cdot f_P + E_C \cdot f_C + E_L \cdot f_L \quad (4)$$

E_P, E_C and E_L (J kg^{-1}) are energy content of proteins, carbohydrates and lipids respectively, while f_P, f_C and f_L (Dimensionless) represents the