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An integrated growth kinetics and computational fluid dynamics model for the analysis of algal productivity in open raceway ponds

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ABSTRACT

An integrated growth kinetic, light transfer and computational fluid dynamics (CFD) model was developed to simulate the algal growth in open raceway ponds (ORP). *C. vulgaris* was used as a model algal strain. The coefficients of the growth kinetics were experimentally determined for the prediction of the growth of *C. vulgaris* as a function of environmental factors of light intensity, temperature and pH value. Experiments were conducted to grow *C. vulgaris* in lab-scale ORPs with medium depths of 0.20, 0.25 and 0.30 m to validate the mathematical model. The final measured biomass concentration after the 3-week growth were 0.48, 0.41, and 0.35 g/L for the ORPs with the medium depths of 0.20, 0.25, and 0.30 m, respectively. The predicted algal productivities for a 3-week cultivation were 7.3, 7.4, and 7.5 g/m^2/day for depths of 0.20, 0.25, and 0.30 m, respectively, which well agreed with the measured values of 6.8, 7.2 and 7.4 g/m^2/day, respectively. The biomass productivity decreased with the increase of growth time due to the increase of cell concentration. The model was further used to analyze the effects of different harvesting strategies on the algal productivity in ORPs. The algal productivity for the 3-week cultivation in the ORP with a 0.2 m depth by harvesting 50% algae at the target 0.2 g/L cell density was 10.5 g/m^2/day, which was 43.8% higher than 7.3 g/m^2/day for the 3-week cultivation under the same condition without harvesting at a final cell density of 0.48 g/L. The average algal productivity decreased with the increase of harvesting cell density.

1. Introduction

Microalgae have received increasing attention over the last few years due to their potential for the production of high value chemical compounds, wastewater treatment and bioenergy (Rahman et al., 2015; Mehrabadi et al., 2015). Microalgae as a biomass source for the production of liquid fuels such as biodiesel, green diesel and aviation fuel have a number of advantages (James and Boriah, 2010). They are capable of extremely rapid growth and rich in oil content ranging from 20% to 50% (James and Boriah, 2010). Microalgae do not compete for arable land with food crops, and can use wastewater and directly capture CO_2 released by industries (Marsullo et al., 2015).

A wide variety of reactor designs for mass cultivation of microalgae have been tested for more than 60 years (Borowitzka, 2013). Open raceway ponds (ORP) have low construction costs and low energy consumption which is in the order of only 4 W/m^3 (Jorquera et al., 2010). Mixing in an ORP is achieved by using one or two paddlewheels to circulate water through the system (Liffman et al., 2013).

Design, optimization and operation of algal ORPs require quantitative models for radiation transport and fluid flow that are capable of predicting the spatiotemporal light exposure trajectories experienced by algal cells (Kong and Vigil, 2014). For modeling the microalgal growth in an ORP, the dynamic behavior of the algal growth should be integrated with fluid dynamics and light distribution in the ORP (Wu and Merchuk, 2002). However, the existing computational models do not consider the synergic effects of light gradient on the algal growth in an ORP. To better investigate the effects of dynamic light patterns on cell growth, CFD is a powerful low-cost tool to analyze radiation characteristics of algal cells in suspension, the effect of dynamic cell concentration on light profile, and the effect of geometry on light distribution inside an ORP. Algal productivity in ORPs are affected by harvesting cell density, medium depth and environmental factors (Amini et al., 2016). There are complicated interactions among algal growth kinetics, light transfer and hydrodynamics in ORPs (Amini

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et al., 2016).

The objective of this research was to develop an integrated mathematical model for the prediction of microalgae growth rate and productivity in an ORP. The model was validated by the experimental data that were collected on a lab scale ORP. The model was used to analyze the effects of different harvesting strategies and medium depths on the algal productivity in ORPs.

2. Materials and methods

2.1. Microalgae culture

C. vularis (UTEX 2714) was purchased from the culture collection of algae of UTEX at University of Texas at Austin. For preparing the inoculum, Bold's medium which was composed of 25 mg/L $CaCl_2{\cdot}2H_2O$, 75 mg/L $MgSO_4{\cdot}7H_2O$, 250 mg/L $NaNO_3$, 25 mg/L NaCl, 75 mg/L K_2HPO_4, 175 mg/L KH_2PO_4, 8.82 mg/L $ZnSO_4{\cdot}7H_2O$, 1.44 mg/L $MnCL_2{\cdot}4H_2O$, 0.71 mg/L MoO_3, 1.57 mg/L $CuSO_4{\cdot}5H_2O$, 0.49 mg/L Co $(NO_3)_2{\cdot}6H_2O$, 11.42 mg/L H_3BO_3, 50.0 mg/L EDTA, 31.0 mg/L KOH, 4.98 mg/L FeSO4.7H2O and 1.0 ml/l H_2SO_4, formulated using fresh water was autoclaved and used as a basal medium for cultivating the microalgae. Sample tubes were incubated in an incubator (AlgaeTron AG 130-ECO) at 20 °C to prepare preculture.

2.2. Cultivation of the microalgae for determining the growth kinetics

Cultivation of *C. vulgaris* was conducted on a bench-scale bubble column photobioreactor (PBR) setup, including eight columns, with 2.5 cm in diameter and 80 mL in volume each (Z160 MultiCultivator, Qubit systems), under different light intensities, temperatures and pH values. The Bolds medium was used in the cultivation and nutrients in the medium were measured every three days using a Lamotte Smart 3 colorimeter (LaMotte Company, Chestertown, MD, USA). The nutrients were provided continuously to prevent nutrient starvation in all experiments. The PBR was equipped with a temperature controller that can maintain the culture temperature between 5 and 50 °C. The pH value was monitored using a pH probe. CO_2 was injected to obtain a pH value below 8.0 and the HEPES buffer was used to control the pH value above 8.0. Samples at 10 mL each were taken from each culture tube to measure the cell concentration once a day. The algal culture was centrifuged at 36 g and the biomass was separated and dried at an oven at 50 °C for 24 h. The dried biomass was then weighed with an electronic balance.

2.3. Cultivation of C. vulgaris in lab-scale ORPs for validating the CFD model

Experiments were carried out in three lab-scale ORPs to validate the CFD model. The ORPs were constructed of fiber glass, with dimensions of 1.4 m length × 0.5 m depth × 0.35 m width. The paddlehweel was constructed of stainless steel, including 5 blades with 0.30 m length and 0.24 m width. The paddlehweel was connected to a two-phase motor with a variable-speed drive that can control the rotational speed of the impeller. The paddlewheel rotational speed was set at 10 rpm for all experiments. The minimum gap between the blades tip and the pond bottom was 0.01 m.

According to the literature, open raceway ponds are usually operated at a minimum depth of 0.15–0.20 m and a maximum of 0.30 m (Andersen, 2005; Chiaramonti et al., 2013). Therefore, in our study, experiments were carried out at three different medium depths of 0.20, 0.25 and 0.30 m. A total volume of 140, 175 and 210 L of preculture of *C. vulgaris* in the Bold's medium at a cell concentration of 0.05 g/L was prepared and transferred into each ORP at the beginning of the cultivation, to set the medium depths on 0.20, 0.25 and 0.30 m, respectively. The environmental parameters of light intensity, temperature and pH values in the ORP during the experiments were given in Fig. 1.

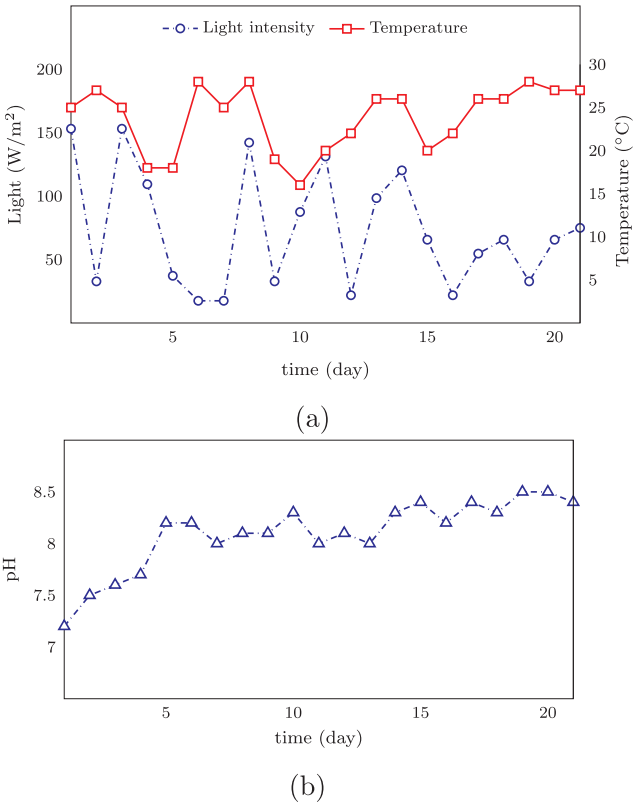

Fig. 1. Daily environmental parameters of (a) maximum light intensity (–○–) and temperature (—□—); and (b) pH value.

3. Mathematical model

3.1. Growth kinetic model and data processing

The growth of microalgae is affected by the environmental factors of light intensity, temperature and pH value. The microalgal growth kinetics can be expressed as the product of the maximum specific growth rate and individual limiting factors of environmental condition, which is given by:

$$\mu = \mu_{\max} \cdot f(I) \cdot f(T) \cdot f(pH) - Me \quad (1)$$

where μ_{max} is the maximum growth rate at the optimum environmental growth conditions in day^{-1}; $f(I)$, $f(T)$ and $f(pH)$ are the limiting growth factors of light intensity, temperature and pH value; I is light intensity in W/m^2, T is temperature in °C, pH is the pH value, and Me is the maintenance term (Wu and Merchuk, 2002).

Experimental data were used to determine the maximum specific growth rate and the limiting growth factors in Eq. (1). The optimum environmental condition for the cultivation of *C. vulgaris* were experimentally determined as the light intensity of 52.5 W/m^2, temperature of 24 °C and pH of 7.4 in our previous study (Amini et al., 2016). To determine the functions of individual limiting factors, experiments were conducted to cultivate *C. vulgaris* at various levels of a specific environmental parameter when the other environmental parameters were set at their optimum values.

3.1.1. Light function

The function of light limiting factor can be expressed as Bernard and Rmond (2012):

$$f(I) = \frac{I}{I + K\left(\frac{I}{I_{\text{opt}}} - 1\right)^2} \quad (2)$$

where I_{opt} is the optimum light intensity, K is a constant (W/m^2), and I