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Modelling microalgae growth in nitrogen-limited continuous culture

Xinping Zhou [a, *], Shuo Yuan [a], Ranchi Chen [b], Bao Song [c]

[a] Department of Mechanics, Huazhong University of Science and Technology, Wuhan 430074, China
[b] School of Mechanical Engineering, Purdue University, West Lafayette, IN 47906, USA
[c] School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

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ABSTRACT

In this paper, based on the mathematical models of microalgae growth, the performance of microalgae growth in nitrogen-limited and light-limited continuous culture is investigated and the effect of important factors on the growth is examined. The dilution rate and the influent inorganic nitrogen concentration have been shown to have a significant influence on the growth of microalgae in continuous culture. In order to obtain a maximum productivity of microalgae, lower dilution rate is better for a lower influent inorganic nitrogen concentration and an optimal dilution rate can be obtained for a higher influent inorganic nitrogen concentration. There is an optimal influent inorganic nitrogen concentration corresponding to maximum microalgae productivity, and the optimal value for lower dilution rate is far higher than that for higher dilution rate. This paper will lay a foundation for the design of the operational parameters of continuous culture PBR (photobioreactor).

1. Introduction

With the continuous reduction of the fossil fuels and the acceleration of global greenhouse effect mainly due to carbon dioxide (CO_2) emissions, energy supply may be in trouble in the near future. It is urgent and significant to find reliable clean energy resources alternative to fossil fuels [1]. Microalgae may become one of the most promising new resources to supply energy and mitigate CO_2 in the future [2,3]. Compared to the first generation biofuels, microalgae have several advantages in sustainability, economics and environment. Microalgae not only have higher productivity, but also can be fed in saline/brackish water/coastal seawater on non-arable and deserted land. The concept of using microalgae for biofuels as a potential biofuel source is not new, and many researchers have done plenty of work on planktons [4–7]. Technologies for producing microalgae and using microalgae for biodiesel have been known for more than 50 years. Now the technology is much accounted of owing to the current high price of depleting fossil fuels and the global warming induced by combustion of fossil fuels.

Microalgae cultures are effective technologies to produce microalgae in artificial bioreactors. The bioreactors mainly consist of open ponds and closed PBRs (photobioreactors). The advantages of the open ponds include high surface/volume (s/v) ratio, relatively cheap, easy to clean, to utilise non-agricultural land, low energy inputs, and easy maintenance. But there are poor biomass productivity, large area of land required, limited to a few strains of algae, poor mixing, and poor utilization of light and CO_2, and cultures are easily contaminated. Open ponds are suitable for a small quantity of algal species which can tolerate extreme environmental conditions, e.g., *Chlorella*, and *Spirulina*. They belong to fast growers and can thrive in highly alkaline or saline environments. Compared to the open systems, the closed systems have a higher s/v ratio, showing a larger surface area exposed to the light source to reduce the shadow effect, and can better control the culture conditions, e.g., mass flux, contamination, temperature, pH, gaseous transfer, and nutrient distributions. A large quantity of algal species can therefore be used in PBRs. The PBR has therefore been more accounted of researchers and companies recently [8,9].

By now, how to improve the biomass or oil productivity from microalgae has been the aim of all the researchers' and companies' work. Experiment is a good method to investigate the technology. But it will take a long period of time and a lot of funds to do experiment. Modelling may be an effective method to help researchers to investigate the process of microalgae growth in

* Corresponding author. Tel.: +86 27 87543838.
E-mail address: xpzhou08@hust.edu.cn (X. Zhou).

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bioreactors. Recently, some models have been proposed to study the performance of the phytoplankton growth, among which there exist differences to some extent.

Droop [10,11] proposed a dynamic model of algae growth, which takes the dilution rate and the influent inorganic nitrogen concentration into account. The model is classical, but practical, which describes the dynamic model of the algae growth and the nitrogen uptake. Some new models were developed based on Droop's model. Geider et al. [12] proposed a new model which included growth process, nitrogen uptake, chlorophyll synthesis, temperature and respiration aspects, but ignored depth dependence. Cherif and Loreau [13] proposed a more biologically realistic use of Droop's equations to model growth under multiple nutrient limitation, and examined the effect of the dilution rate on the equilibrium densities of two species. Bougaran et al. [14] proposed a model of continuous cultures of microalgae colimited by nitrogen and phosphorus, but did not examine the effect of the dilution rate or the influent inorganic nitrogen concentration. Quinn et al. [15] proposed a model for industrial scale systems based on Ref. [12]. Packer et al. [16] developed a dynamic model to predict the growth and neutral lipid synthesis of green algae by taking into consideration the influences of the photosynthesis and the nitrogen uptake on the growth rate. In Bernard's dynamic model [17], the light-limited and nitrogen-limited factors simultaneously have effects on the growth rate. In Mairet et al.' model [18], the biomass is divided into three compartments, i.e., the function part, carbohydrates, and neutral lipids, which can be transformed mutually. Yuan et al. [19] studied several main models of microalgae growth in nitrogen-limited and light-limited culture system for estimating biomass productivity by comparing different expressions and coefficients used in these models.

By now, little work has been done to analyze the effects of both dilution rate and influent inorganic nitrogen concentration on the microalgae growth in continuous culture. In this paper, based on the Bernard's dynamic model [17], the effects of the important factors including the dilution rate and the influent inorganic nitrogen concentration on the microalgae growth in nitrogen-limited and light-limited continuous culture are studied. The performance of the microalgae growth manifested by the two important parameters is investigated. Optimal values of culture parameters are discussed for maximum microalgae productivity.

2. Model description

Many models have been proposed up to now, which used various expressions to calculate the parameters e.g. light distribution, pigment dynamics, nitrogen uptake, growth rate, respiration rate, temperature dependence, dilution rate, and influent inorganic nitrogen concentration. In this paper, we will use Bernard's model to model microalgae growth in nitrogen-limited PBR [17]. The model is introduced below.

The model [17] describes four variables in the ordinary differential equations: $s(t)$, which denotes the concentration of dissolved inorganic nitrogen, the nitrate or ammonium, $q(t)$, which is internal nitrogen cell quota, $x(t)$ which is algae biomass concentration, and $I^*(t)$ which is not the real radiation but a conceptual variable denoted radiation. The unit of $I^*(t)$ is mmol m^{-2} s^{-1}, which means the number of photons absorbed per unit area per unit time. The expression of calculating variable I^* will be discussed later. The four ordinary differential equations were expressed as:

$$\dot{s} = Ds_{\text{in}} - \overline{\rho}\frac{s}{s+K_s}\left(1-\frac{q}{Q_1}\right)x - Ds \tag{1}$$

$$\dot{q} = \overline{\rho}\frac{s}{s+K_s}\left(1-\frac{q}{Q_1}\right) - \overline{\overline{\mu}}(I_0, I^*, x, q)(q-Q_0) \tag{2}$$

$$\dot{x} = \overline{\overline{\mu}}(I_0, I^*, x, q)\left(1-\frac{Q_0}{q}\right)x - Dx - Rx \tag{3}$$

$$\dot{I}^* = \overline{\overline{\mu}}(I_0, I^*, x, q)\left(1-\frac{Q_0}{q}\right)(\bar{I}-I^*) \tag{4}$$

where D denotes the dilution rate, $\overline{\rho}$ is the maximum nitrogen uptake rate, s_{in} is influent inorganic nitrogen concentration, R is the inspiration rate, $\bar{I}$ is the average radiation along culture volume, Q_0 is the minimum nitrogen quota, Q_1 is the maximum nitrogen quota, and $\overline{\overline{\mu}}$ denotes the average growth rate, which is calculated by:

$$\overline{\overline{\mu}}(I_0,\xi) = \tilde{\mu}\frac{2K_{il}}{\lambda\sqrt{\Delta}}\arctan\left(\frac{I_0(1-e^{-\lambda})\sqrt{\Delta}}{2I_0^2e^{-\lambda}+I_0(1+e^{-\lambda})K_{il}+2I_{\text{opt}}^2\left(\theta_0^C\right)}\right) \tag{5}$$

where I_0 represents the light intensity at the bioreactor surface, and $\tilde{\mu}$ is the maximum growth rate. The average radiation along culture volume $\bar{I}$ is given by:

$$\bar{I} = \frac{I_0}{\lambda}\left(1-e^{-\lambda}\right) \tag{6}$$

where the optical depth, λ, is the product of the depth of the culture L multiplied by light attenuation rate ξ:

$$\lambda = \xi L \tag{7}$$

The light attenuation rate ξ can be calculated by:

$$\xi = a\text{Chl} + bx + c \tag{8}$$

where, a, b, and c are the constants, and the chlorophyll concentration Chl can be calculated by:

$$\text{Chl} = \gamma(I^*)xq \tag{9}$$

The proportion of chlorophyll concentration to nitrogen concentration $\gamma(I^*)$ can be given by:

$$\gamma(I^*) = \gamma_{\max}\frac{k_{I^*}}{I^*+k_{I^*}} \tag{10}$$

where $\gamma_{\max}$ is the maximum value of $\gamma(I^*)$.

The parameters Δ and I_{opt} which denote the radiation providing maximum rate of photosynthesis in Eq. (5) are calculated by:

$$\Delta = 4I_{\text{opt}}^2\left(\theta_0^C\right) - K_{il}^2 \tag{11}$$

$$I_{\text{opt}} = \sqrt{K_{sI}K_{iI}} \tag{12}$$

where K_{sI} is:

$$K_{sI} = \frac{K_{sI}^*}{\theta_0^C} \tag{13}$$

The initial value of Chl/x is denoted by a parameter θ_0^C:

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