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Study on modelling microalgae growth in nitrogen-limited culture system for estimating biomass productivity

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ABSTRACT

Microalgae are considered as a promising biofuel resource to fix carbon dioxide (CO_2) in the future. Modelling microalgae growth is an effective method of studying the performance of microalgae growth manifested by the parameters including light distribution, pigment dynamics, nitrogen uptake, growth rate, respiration rate, temperature dependence, and depth dependence, and helping to control the culture of microalgae in artificial bioreactors. In this paper, the models of microalgae growth in nitrogen-limited and light-limited culture system for estimating biomass productivity are investigated by comparing different expressions and coefficients used in several main models. The results show that there are some differences among the results of numerical modelling due to different expressions and coefficients. This paper will lay a foundation for the selective use of microalgae growth models for researchers.

Contents

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1. Introduction

1.1. Characteristics of microalgae

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]. Technologies for producing microalgae and using microalgae for biodiesel have been known for more than 50 years. Up to now, many researchers have done plenty of work on planktons [4–7]. 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. However, there are some shortcomings of microalgae for use as biofuels. For example, the dry solids content of the microalgae and water mixture can be as low as 0.05% dry solids content. The energy balance associated with segregating the water from the microalgae dry solids to allow a bio-esterification process to be undertaken is very high [8]. Literature [9] also indicated that some unstable biodiesel with many polyunsaturates will be derived in the process of producing biodiesels from algae oil.

1.2. Microalgae models

Some models have been established by various researchers to predict different aspects of microalgae growth process, such as mass growth, light distribution, pigment dynamics, nitrogen uptake, depth dependence, temperature dependence and respiration rate, etc. [10–13]. The biological model of microalgae comes from the population model proposed by Malthus [14]. The concept of the population model such as growth rate is used in later microalgae growth models. Droop [15,16] proposed a dynamic model which takes the dilution rate and influent inorganic nitrogen concentration into account to describe the growth of microalgae. The model is classical, but practical, which describes the kinetic model of the algae growth and the nitrogen uptake. Recently, several new models were proposed based on Droop's model. Geider et al. [17] proposed a new model which included growth process, nitrogen uptake, chlorophyll synthesis, temperature and respiration aspects, but depth dependence was ignored. Quinn et al. [18] proposed a model for industrial scale systems based on Geider et al.'s model [17]. A dynamic model was proposed by Packer et al. [19] to predict the growth and neutral lipid synthesis of green algae by using a new method. This method considered the influences of two factors (i.e., the photosynthesis, and the nitrogen uptake) on the growth rate, which was defined as a piecewise function of the two factors. Bernard [20] proposed a different kinetic model which was verified by experimental data [21]. Different from Packer et al.'s model [19], the light-limited and nitrogen-limited factors will simultaneously have effects on the growth rate in the model. Mairet et al. [22] further developed the previous models by dividing the biomass into three compartments including the function part, carbohydrates, and neutral lipids. The transformations and balances between the three parts were discussed in their model.

In the above models, various expressions and coefficients have been used. Investigation on the differences between them is needed so that it is easier for later researchers to select more proper expressions and coefficients to model, predict and control the microalgae growth. By now, little work on the comparison of different microalgae sub-models (that is, the expressions or coefficients, for example, the sub-model of nitrogen uptake) has been reported. In this paper, based on the valid Bernard's dynamic model [20] acting as the basic model (not the standard model) made up of several sub-models, various expressions and coefficients in several main models [17–19] will be compared by comparing the basic model and a new model. The new model is produced when one sub-model of the basic model is replaced by the corresponding sub-model used in another model. In the second and the third parts, the influence of other aspects such as the depth of culture and the ambient temperature is also discussed.

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, and temperature dependence. In this part, we will describe Bernard's model, and the various expressions of parameters for various models [17–20] are also discussed.

2.1. Bernard's model

The model [20] describes four variables in the ordinary differential equations: $s(t)$, which denotes the concentration of dissolved inorganic nitrogen, the nitrate or ammonium ($g\,N\,m^{-3}$), $q(t)$, which is internal nitrogen cell quota ($g\,N\,(g\,C)^{-1}$), $x(t)$ which is algae biomass concentration ($g\,C\,m^{-3}$), and $I^*(t)$ which is not the real radiation but a conceptual variable denoted radiation. The unit of $I^*(t)$ is $mol\,m^{-2}\,s^{-1}$, 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:

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

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

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

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

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

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