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Effect of Photo-Limitation on Growth of Microalgae in Tubular Photobioreactor

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ABSTRACT

This paper presents a mathematical model for light-limited growth of microalgae in tubular photobioreactor. Here, the specific growth rate of microalgae has been evaluated by integrating the steady-state radiative transfer equation with the Monod equation. The Monod equation also considers a maintenance term featuring lost/unused light energy due to cell death and/or the presence of non-growth components in the culture. The model assumed (a) the incident light intensity to be normal to the surface of the tube, (b) uniform distribution of intensity along the length, and (c) negligible variation of light intensity over time. Overall, this study aimed to develop a predictive model which could prove useful for improving a controlling unit of industrial photobioreactors. The study revealed the maximum light intensity at the periphery of the tube and minimum light intensity at the centre of the tube. Consequently, the growth of microalgae was relatively large at the periphery of the tube and low at the centre of the tube.

Keywords - Tubular photobioreactor, Microalgae, Radiative transfer, Specific growth rate

NOMENCLATURE

A_{abs}	mass absorption cross-section (m^2/kg)
C	maintenance coefficient (h^{-1})
D	dilution rate (h^{-1})
I	light intensity (Wm^{-2} or $\mu Em^{-2}s^{-1}$)
L	length of the tube (m)
r	radius of tube (m)
S	substrate concentrate
s	distance from the peripheral surface of tube (m)
W_0	balanced biomass concentration (kg/m^3)

Greek symbols

λ	light wavelength (nm)
μ	specific growth rate (h^{-1})
γ_e	objective function

Subscripts

max	maximum
s	saturation
in	incident

1. INTRODUCTION

At present, around the world there is a heightened wakefulness for immediate transition from fossil-based fuels to renewable and sustainable energy sources. The objective is to lessen (a) the impacts of the impeding energy crisis, (b) the depletion of natural resources, and (c) the greenhouse gases that impact the environmental conditions.

Biofuels are one such alternative for minimizing the emission of the greenhouse gases. Most importantly, among many biofuel producing resources, microalgae were having a higher photosynthetic efficiency than other biofuel producing plants, and demands less land area [1]. These microalgae were also proved to be useful for carbon dioxide fixation, waste water treatment, and for production of nutrient and other health supplements [1]. They are also economically very useful. In fact, they yield number of products of commercial importance such as food, pharmaceutical, textile, and cosmetic industries.

Currently, large scale biomass productions in industries were carried out either in open ponds or in closed photobioreactors. But, closed photobioreactors were gradually replacing the open ponds due to the significant improvement in biomass productivity as a consequence of less contamination [2]. In spite of the improvement, the overall biomass productivity is fairly low in photobioreactors since the growth of microalgae in photobioreactors depends on numerous factors such as optimal light intensity, culture temperature, nutrient, dissolved oxygen, CO_2 concentration, etc [3]. Indeed, to maximize the growth of microalgae in photobioreactors an efficient controlling unit is essential to maintain these parameters at its optimal level [4]. This can only

be possible using a predictive theoretical model which serves as a foundation for a controlling unit [4].

In the last two decades, a number of theoretical models and controlling units were proposed for the growth of microalgae in tubular photobioreactor which considered factors such as the effect of light, carbon dioxide concentration, dissolved oxygen level, and temperature, separately [5-7]. However, models featuring collective effect of various parameters on the growth characteristics of microalgae in tubular photobioreactor are scarce.

Therefore, our on-going research goal is to develop and validate a theoretical model featuring growth of microalgae due to the collective effect of photo-limitation, photo-inhibition, carbon dioxide concentration, dissolved oxygen, and temperature. In view of the above, this article presents a preliminary model featuring the effect of photo-limitation on the growth characteristics of microalgae in a horizontal tubular photobioreactor.

2. METHODOLOGY

2.1. Problem definition

Figure 1 depicts a schematic diagram of horizontal tubular photobioreactor. Here, the incident light was assumed to be normal to the surface of tubes shown in Fig. 1. Thus, each tube in the photobioreactor receiving same amount of light along the length of the tube since the source is one. The above realization is feasible by installing a perfect reflector at the bottom and side walls of the photobioreactor. Further, the variation of light over time is neglected since the study assumed indoor conditions featuring constant light illumination and single growth cycle.

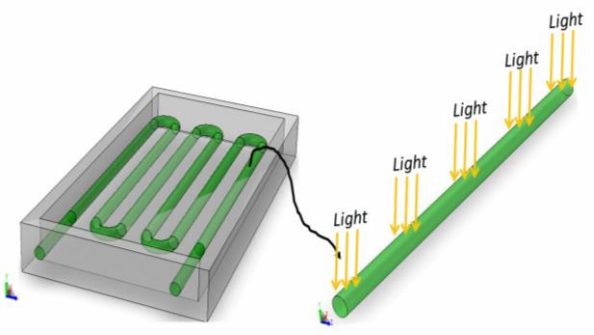

Fig. 1 Schematic of a typical horizontal tubular photobioreactor [8]

Based on the above assumptions, the problem formulates a model which predicts the light distribution and specific growth rate at a section of a tube. In fact, the overall growth of the microalgae in the photobioreactor can be easily determined by integrating the growth over the volume of the tube, i.e., cross-section multiplied by total length of the tube.

2.1. Theoretical model

The governing relation used for computing the distribution of light intensity is given by (Boguer-) Beer-Lambert law [9] as

$$I(p) = I_{in} \exp(-pA_{abs}W_0) \tag{1}$$

where I is the light intensity, I_{in} is the maximum light intensity at the surface of tube, p is the path length (m), A_{abs} is the mass absorption cross-section (m^2/kg), and W_0 is the balanced biomass concentration (kg/m^3) maintained in the photobioreactor.

Here, the path length p depends on the angle of incident of light as shown in Fig. 2. Based on geometric analysis, the path length p can be written in terms of radius r of the tube and distance s of ray from the surface of the tube as [10]

$$\begin{aligned} p(\theta, s) &= a + b \\ &= \left[(r-s)\cos\theta\right] + \left[\sqrt{r^2 - (r-s)^2 \sin\theta}\right] \end{aligned} \tag{2}$$

where, r is radius of the tube, s is distance of ray from tube surface, θ is the angle subtended by the ray.

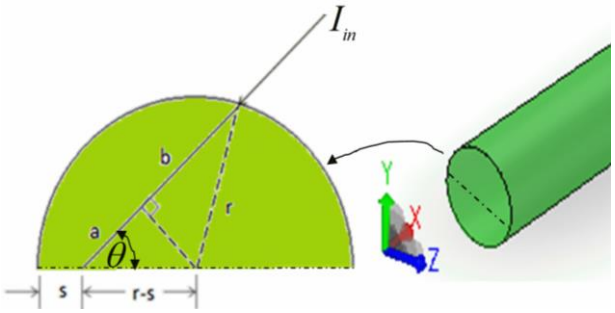

Fig. 2 Schematic representation of one-half of a cross-section through a tube.

Next, substituting the value of path length p in Eq. (1) gives us the intensity of light as a function of radial location and orientation of ray

$$I(s,\theta) = I_{in} \exp\left[-A_{abs}W_0 \left\{\begin{matrix}(r-s)\cos\theta \\ +\sqrt{r^2-(r-s)^2\sin\theta}\end{matrix}\right\}\right] \tag{3}$$

Therefore, the intensity for all points at a distance *s* is the normalized value of total intensity from all directions and is given as [11]

$$I(s) = \frac{1}{\pi}\int_0^{\pi} I(s,\theta)\,d\theta = \frac{I_{in}}{\pi}\int_0^{\pi} \exp\left[-A_{abs}W_0\left\{\begin{matrix}(r-s)\cos\theta \\ +\sqrt{r^2-(r-s)^2\sin\theta}\end{matrix}\right\}\right] d\theta \quad (4)$$

Here, the value of intensity at each point *s* is normalized over all angular space 0 to π. This value of intensity remains same for angular space π to 2π due to symmetry.

Therefore, the specific growth rate μ at each point *s* due to absorbed light intensity *I* was given by modified Monod equation as

$$\mu = \mu_{\max}\left(\frac{I(s)}{I(s)+K_s(s)}\right) - C - D \quad (5)$$

where K_s is the intensity of light at which growth saturates, μ_{max} is the maximum specific growth rate of a microalgae, *C* is the maintenance coefficient, and *D* is the dilution rate. The maintenance coefficient *C* can be referred to reduction in growth of microalgae due to lost/unused light energy because of unavoidable cell death and/or presence of non-growth components in the culture. The dilution rate *D* takes into consideration the reduction in specific growth rate due to outflow of culture at the exit and inflow of fresh culture. The input parameters used in the theoretical model were collected from the literature [11-13] and are tabulated in Table 1.

Table 1 Input parameters for estimating the specific growth rate of microalgae Chlorella in tubular photobioreactor.

Parameters	Value	References
r (m)	0.025	-
μ_{max} (h^{-1})	0.082	[11]
λ (nm)	550	[12]
K_s ($\mu Em^{-2}s^{-1}$)	15.9 (= 3.458 Wm^{-2})	[12]
I_{in} ($\mu Em^{-2}s^{-1}$)	98 (= 21.314 Wm^{-2})	[12]
C (h^{-1})	0.00385	[13]
A_{abs} (m^2/kg)	435	[12]
W_0 (kg/m^3)	0.2	[13]
D (h^{-1})	0.0224	[13]

Here, for the given input parameter the computation was performed in MATLAB.

3. RESULTS AND DISCUSSIONS

Figure 3 depicts the variation of overall intensity and per hour growth of microalgae with radius center of the tube.

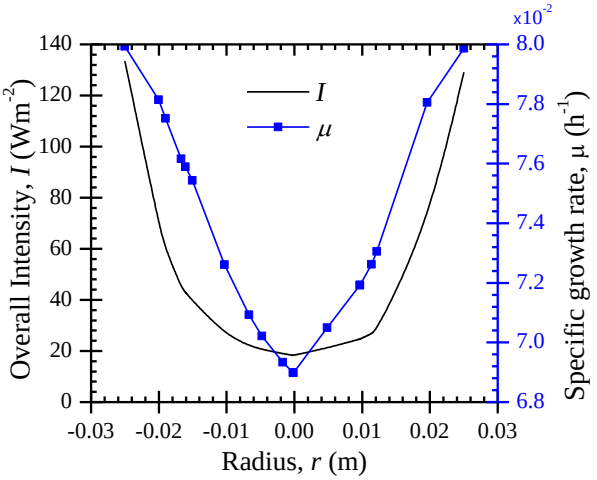

Fig. 3 Variation of light intensity and specific growth rate of microalgae with the radial distance from the center of the tube.

Figure 3 revealed maximum light intensity at the periphery of the tube and minimum light intensity at the center of tube. Consequently, per hour growth of microalgae was relatively large at the periphery of the tube and low at the center of the tube. Indeed, the above observation verifies the effect of photo-limitation/shading of light by peripheral microalgae. The above limitation can be minimized by introducing baffles or by introducing rotational flow.

One can get a clear picture of above description from the contour plots shown in Fig. 4. Figure 4(a) depicts the variation of light intensity with the radius of the tube. Similarly, Fig. 4(b) depicts the per hour growth of microalgae at a cross-section of tube. The larger growth rate at the periphery also supports the reason for bioflim formation at the inner walls of glass tube as the extracellular components often bears some sticking property. The formation of bioflim can be controlled either by introducing flow rotation using baffles or maintaining small resident time at a particular cross-section. Indeed, the present assumption of fresh supply of culture at the inlet of tube with balanced concentration after every cycle could prove advantageous. The fresh cells would reduce the production of excessive mucilage adhering substances due to microalgae's reproduction cycle and balanced concentration would maintain a constant growth rate over time. In fact, the above protocol could improve the overall concentration of biomass.

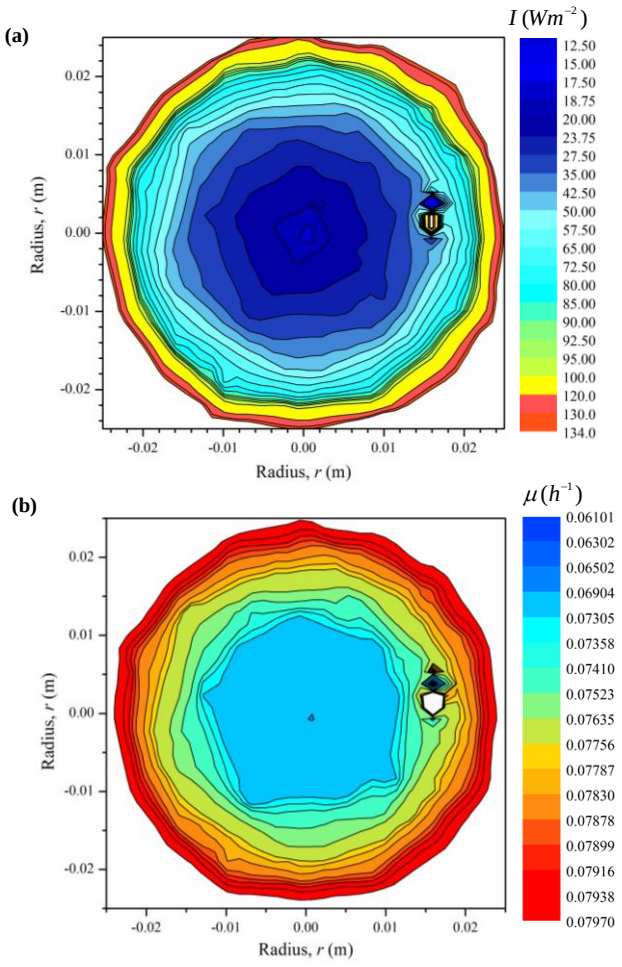

Fig. 4 Contour plots highlighting (a) the radial distribution of light intensity, and (b) the radial variation of specific growth rate of microalgae culture.

4. CONCLUSION

This paper presents a theoretical model featuring the growth of microalgae due to light-limited situation, dilution of biomass, and maintenance factors in a tubular photobioreactor. The growth of microalgae at a particular cross-section of the tube was found to be rapidly decreasing due to the attenuation of light along the radius of tube. The maximum growth was observed at the periphery and minimum growth was noted at the center of the tube. Overall, the shading effect can be minimized by maintaining a rotational flow inside the tubular photobioreactor. This will also reduce the growth of bioflim at the inner surface of the tube.

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