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Growth Kinetic Models for Algae: Revealing a Light Factor

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Abstract- Biodiesel production from Microalgae has received collective attention as one of the alternative energy sources. Growth kinetic models are needed to provide an understanding of microalgal growth so that cultivation conditions can be optimized. This review focused on overview of the present growth kinetic models for microalgae cultivation. The existing models were compiled and considering a light factor. There is a requirement for appropriate assimilation of light and temperature in the growth model.

Keywords: kinetics, light intensity, maximum specific growth rate

I. INTRODUCTION

For photoautotrophic microalgae in nutrient saturation conditions, light is a critical factor for photosynthetic activity. Growth of microalgae limits due to insufficient light [1, 2]. Microalgae require a specific light level in order to extent the maximum growth rate, referred to as a saturated light level. If light intensity is far above the saturation level, the growth will be inhibited by light (known as photo inhibition). If light intensity is below the saturation level, the growth will be limited by light (called light limitation). For example, in outdoor mass culture systems (cultivation systems with high concentrations of microalgae), microalgae growth is limited due to light scattering by a thick top layer where increase areal productivity of microalgae occurs [3]. Algae biomass productivity is the result of photosynthesis and endogenous respiration. Expecting the rate of these mechanisms during outdoor cultivation is difficult because algae growth is affected by several factors for example temperature, light intensity, pH, dissolved oxygen concentration and nutrient availability [33].

II. RELATED WORK

The growth kinetic models considering the effect of light plays the key role for the design of photobioreactors and outdoor ponds to optimize the performance. In this paper the growth kinetic models reflecting the single factor of the light intensity are summarized. The models in this group have simple structures with two or three parameters and easy to implement [4]. These models have often been applied in lab-scale studies. The Tamiya model is an eminent theoretical model as well as the most widely applied model, which is similar to a Monod type model in describing the effect of light on microalgae growth [5]. In that model, the growth rate is interrelated to the incident light intensity with two parameters μ_{max} (maximum specific growth rate) and KI (saturation constant with respect to the light intensity). When the incident light intensity (I) is lower than KI, the growth is limited by light according to first order kinetics. When light intensity (I) is far above KI, the growth is independent of light and μ approaches to μ_{max} [6]. The Tamiya model was describing the growth of *Euglena gracilis* under laboratory conditions using fluorescent lamps (about 0-550 μ_{mol} photon m^{-2} s^{-1}) with kinetic parameters of μ_{max} as 0.06 h^{-1} and KI as 178 μ_{mol} photon $m^{-2}s^{-1}$. Under continuous illumination of fluorescent light, the growth of *Spirulina platensis* followed the Tamiya model with the KI = 0.2 klx (about 124 μmol photon m^{-2} s^{-1}) and μ_{max} = 2.0 day^{-1} [7]. Tamiya model was able to accurately explain the growth rate of *Chlorella vulgaris* in the circulating photo bioreactor under different incident light intensities [2]. Several empirical models have been developed by van Oorschot [8], Bannister [9], and Chalker [10]. Van Oorschot [8] used a Poisson function (1-e-I/KI) describing light-limitation. The Webb model is a commonly used model for predicting photosynthetic rates in literature [11]. Bannister et al. adopted the same structure of the Tamiya model with integration of a shape parameter (m) depending on the algae species [9]. Jassby and Platt investigated eight kinetic models to describe the population of marine phytoplankton and reported a hyperbolic tangent model was the best fit to their data [12]. Hyperbolic tangent function is the most popular mathematical form to explain the photosynthetic activity as a function of light intensity [10]. The relationship between the algae growth rate and incident light intensity assuming that photosynthetic activity is the only limiting mechanism of microalgae growth [13]. To determine the best expression of microalgae growth rate, several expressions including the Poisson, hyperbolic tangent and Tamiya models and established that the hyperbolic tangent function was the best mathematical expression for *Chorella littorale* growth kinetics under the incident light intensity ranging from 2.3 to 1060 μ_{mol} photon $m^{-2}s^{-1}$ [13]. On the other hand, Martinez et al. compared the Tamiya and Poisson models and concluded that the Poisson model provided a better fit to the experimental data of *Chorella pyrenoidosa* under the incident light intensity of 400-2000 lux [14]. The difference of the experimental conditions such as illumination range and algae species make it challenging to compare different studies. There is minimal self- shading by the microalgae cells. Light attenuation is generally observed in microalgae cultivation systems which typically have high algae concentrations for biofuel production. For light attenuation, an average light intensity or absorbed light intensity has been adopted. The average light intensity (or absorbed light intensity) is determined by the light path, culture density and incident light intensity. This represents the average light absorption of algae cells in the system [15]. Bechet et al. observed that average light intensity influence not be the appropriate parameter to represent light intensity because it does not account for heterogeneity of light intensity received by individual cells in the system and its effect on the overall algae growth [16]. Tamiya model was improved with the average light intensity and introduced an exponent (n) in the formula [17]. That is similar to Bannister's shape parameter. This model was often applied in the optimization of the photobioreactors for both indoor and outdoor culture [18, 19]. On the other hand, the Ogbonna model is similar to a linear formula and the model includes a cell concentration (X) and reactor volume (V) to justification for the impact of cell concentrations on the light attenuation [20]. This model uses the non-illuminated volume fraction to integrate the effect of dark zones on growth. In outdoor culture systems, however, microalgae can experience photoinhibition during the mid-day peak light period. To reduce the energy cost from artificial illumination, outdoor mass culture systems have been adopted. Some models consist of both light limitations and photo inhibition.

III. RESULTS AND DISCUSSION

The models developed by Aiba [21], Lee et al. [22], Steele [23] and Bernard and Remond [24] have a relatively less complex formula with two or three parameters. Particularly, the Steele model is widely used and is able to describe the effects of light-limitation using I / I_{opt} and photo inhibition using an exponential expression (exp $(1 - I / I_{opt})$) [25, 23, 26]. Platt et al. also used the exponential expression by expanding the Webb model to include the effects of photoinhibition at high irradiances [27]. The structure of the Aiba, Lee, Talbot, and Bernard and Remond models is similar to the Andrews model's structure, which incorporated an inhibition term (expressed as a function of light intensity) in the denominator. Different light intensities were used in these models: incident light intensity (I) in the Aiba model, average light intensity (Iav) in the Lee model, normalized incident light intensity (I / Iopt) in the Talbot model and both I and I/Iopt in the Bernard and Remond model. Several models with more complex formulas have also been proposed. Rubio et al. introduced a mechanistic model to account for photadaptation, photoinhibition and the flashing light effect [28]. This model assumes that photosynthesis occurs in the photosynthetic unit (PSU, a minimum unit leading to the generation of NADPH and ATP), and PSUs are based on a metabolic control of energy consumption through an enzyme-mediated process such as Michaelis-Menten-type kinetics. In addition, this model uses a square root dependence on irradiance to explain photoinhibition. Among other complex models, the modified Grima model [29] and Muller-Feuga model [30] are commonly applied to estimate the growth rate of algae. Grima et al. [29] and Garcia-Malea et al. [31] improved the Grima model to account for photoinhibition on the microalgae growth by modifying the parameters of microalgal affinity for light (IK) and n as a function of incident light intensity (I). These models are able to describe the effect of photoinhibition, light-limitation, and light attenuation. On the other hand, the Muller-Feuga model introduced three parameters, including the minimum light intensity for survival (I_e), optimum light intensity to achieve the maximum growth rate (I_{opt}), and average light intensity (I_{av}). This model described the effect of light-limitation using $(I_{av} / I_{opt} - I_e/I_{opt})$ in the nominator and the effect of photoinhibition using $(I_{av} / I_{opt} - I_e / I_{opt})^2$ in the denominator. Martinez et al. compared the model's prediction of García-Malea et al. [31] and Muller-Feuga [30] for the growth of Synechocystis sp. They concluded that the Muller-Feuga model was able to give a closer estimation than the Garcia-Malea model because the Garcia-Malea model could not predict the reduction in growth rate of *Synechocystis species* at high irradiance. *Chlorella pyrenoidosa* shows maximum growth rate.

Table 1. Microalgal growth kinetic models for a function of light intensity: Values of μ_{max} and KI

S. no.	**Algae species**	**Values of different parameters**		**References**
		μ_{max}	**KI**	
1	*Spirulina platensis*	2.0 d^{-1}	9.2 klx	S. Huang et al. 1986.
2	*Euglena gracilis*	0.06 h^{-1}	178.7 μ mol photon m^{-2} s^{-1}	S. Chae et al. 2006.
3	*Chlorella vulgaris*	0.040 h^{-1}	2.8 mW L^{-1}	D. Sasi et al. 2011
4	*Chlorella pyrenoidosa*	0.116 h^{-1}	1011 lx	M.E. Martínez, (1997) 93–98.
5	*Chlorococcum littorale*	0.134 h^{-1}	95.8 μmol photon m^{-2} s^{-1}	N. Kurano et al. 2005

6	*Chlorella pyrenoidosa*	0.076 h^{-1}	708 lx	M.E. Martínez et al 1997
7	*Chlorococcum littorale*	0.116 h^{-1}	114 μmol photon m^{-2} s^{-1}	N. Kurano et al. 2005.
8	*Chlorella pyrenoidosa (at 25 °C)*	2.48 d^{-1}	5.7 μE m^{-2} d^{-1}	N. Kurano et al. 2005
9	*Chlorococcum littorale*	0.115 h^{-1}	150 μmol photon m^{-2} s^{-1}	N. Kurano et al. 2005
13	*Chlorococcum littorale*	0.134 h^{-1}	Iopt = 505 μmol photon m^{-2} s^{-1}	N. Kurano et al. 2005
14	*Cryptomonas 976/67*	1.37 d^{-1} at 26 °C	**NA**	A. Ojala (1993)
15	*Cryptomonas 976/62*	0.72 d^{-1} at 21 °C	Iopt b 100 μmol photon m^{-2} s^{-1}	A. Ojala, (1993)

Table 2. Microalgal growth kinetic models for a function of light intensity: Values of different parameters

S. no.	**Algae sp.**	**μ_{max}**	**Values of different parameters**	**References**
1	*Spirulina platensis*	2.06×10^{-5} s^{-1}	Ik = 160 μE m^{-2} s^{-1} n = 1.49	A. Concas 2013
2	*Phaeodactylum tricornutum*	0.075 h^{-1}	Ik = 120 μE m^{-2} s^{-1} n = 2.02	R.L.L. Ribeiro et al. 2009
3	*Chlorella pyrenoidosa*	**NA**	K = 0.8 kg mol^{-1} X = 0.01905 kg m^{-3} V = 0.00075 m3 I_{max} = 0.13 mol kg^{-1} d^{-1}	N. Kurano et al. 2005
4	*Spirulina platensis*	5.4849 h^{-1}	KI = 959.2 W m^{-2} Ki,L = 0.5817 m^2 W^{-1}	H.Y. Lee et al. 1987
5	*Spirulina platensis*	**NA**	KI = 177.9 m2 W^{-1} h^{-1} KiL = 0.1083 m^2 W^{-1} h^{-1}	H.Y. Lee et al. 1987
6	*Porphyridium cruentum* (at 30 °C)	1.06 d^{-1}	Iopt = 350 μmol photon m^{-2} s^{-1} β = 2.06	D. Dermoun 1992.
7	*Chlorella pyrenoidosa*	2.0 d^{-1}	Iopt = 275 μE m^{-2} s^{-1} α = 0.05	D. Dermoun 1992.
8	*Phaeodactylum tricornutum*	0.063 h^{-1}	Ik = 94.3 μE m−2 s−1 Ki,L = 768.4 μE m^{-2} s^{-1} a = 3.04 b = 1.209 c = 514.6	F.G. Acién-Fernández, 1998.
9	*Phaeodactylum tricornutum*	0.063 h^{-1}	Ik = 94.3 μE m^{-2} s^{-1} Ki,L = 3426 μE m^{-2} s^{-1} a = 3.04 b = 1.209 c = 514.6	E.M. Grima et al. 1999
10	*Phaeodactylum tricornutum*	0.00385 h^{-1}	Ik = 94.3 μE m^{-2} s^{-1} Ki,L = 2000 μE m^{-2} s^{-1} a = 3.04 b = 1.209 c = 514.5	R.L.L. Ribeiro, A.B. Mariano, (2008)
11	*Haematococcus pluvialis*	0.11 h^{-1}	a = 2.32 b = −0.00008 μE m^{-2} s^{-1} c = 98.7 μE m^{-2} s^{-1} d = 0.034	R.L.L. Ribeiro, A.B. Mariano, (2008)
12	*Porphyridium cruentum*	1.415 d^{-1}	Iopt = 385 μE m^{-2} s^{-1} Ie = 3.5 μE m^{-2} s^{-1}	A. Muller-Feuga et al. 2003
13	*Chorella sp.* (light limitation)	0.12 h^{-1}	α′ =91 μE m^{-2} s^{-1} k = 0.24	A. Muller-Feuga et al. 2003

IV. CONCLUSION AND FUTURE SCOPE

Growth of microalgae is affected by various factors. Several growth kinetic models have been developed to describe the rate of microalgae growth. In this paper, light factor model was considered. Appropriate concern of co-limiting factors, suitable mixing of light and temperature, incorporation of species diversity in the growth model. There are numerous models considering multiple factors. The uses of the models considering multiple factors are limited due to their complex mathematical forms. This paper identified several challenges in the development of algae growth models. Following conclusions have been drawn:

- Forthcoming research should focus on developing a constraint for model selection based on the understanding of microalgae growth under different environmental conditions.
- The light intensity and temperature expressions do not consider temporal variations in sunlight intensity and culture temperature. These elements play a crucial role in outdoor mass cultivation.
- Future research must provide a better mathematical expression of light by considering light attenuation and temporal variation of light intensity if natural light is used.

V. NOMENCLATURE

a	Fitting constant
b	Fitting constant
c	Fitting constant
d	Fitting constant
C_n	Algae nitrogen content per unit algal dry weight
Cn_{max}	Maximum algal nitrogen content or nitrogen content of the functional substance per unit algal dry weight
Cp	Algal phosphorus content per unit algal dry weight
$f(I_{av})$	A function of average light intensity
f(T)	A function of temperature
I	Incident light intensity
I_{av}	Average irradiance in the culture
I_c	Light intensity at the center measured from one direction with light shining from both direction
I_e	Average irradiance at the energy compensation point
I_{in}	Light intensity at the front with shining from one side
I_k	Microalgal affinity for light
I_{max}	Maintenance rate
I_{opt}	I at $\mu = \mu max$
I_{out}	Light intensity at the back with shining from one side
K	Proportionality constant which is similar in meaning to growth yield
K_a	Attenuation constant
K_c	Curve fitting constant
KI	Photo saturation constant
K_i	Inhibition constant
$K_{i, CO2}$	Inhibition constant of CO_2
$K_{i,L}$	Photoinhibition constant
$K_{i,OC}$	Sodium acetate inhibition constant of cell growth
$K_{S,nu}$	Monod half-saturation constant of limiting nutrients
K_S	Monod half-saturation constant
$K_{S, CO2}$	Monod half-saturation constant of CO_2
$K_{S, N}$	Monod half-saturation constant of nitrogen
$K_{S,OC}$	Monod half-saturation constant of sodium acetate
$K_{S,P}$	Monod half-saturation constant of phosphorus
k	Parameter
k_d	Consumption rate of photosynthesis products per unit dry weight of the functional substance
m	Shape parameter
n	Exponent
p	Length of light path inside the photobioreactor
Pho	photosynthetic rate
Pho_{max}	Light saturated photosynthesis rate
Q	Nutrient cell quota

Q_N	N Cell quota
Q_{max}	Maximum nutrient cell quota for algal existence
$Q_{max,N}$	Maximum N cell quota for algal existence
$Q_{max,P}$	Maximum P cell quota for algal existence
Q_{min}	Minimum nutrient cell quota for algal existence
$Q_{min,N}$	Minimum N cell quota for algal existence
$Q_{min,P}$	Minimum P cell quota for algal existence
QP	P cell quota
S	Nutrient concentration
S_{CO2}	Carbon dioxide concentration in the medium
SN	Nitrogen concentration in the medium
S_{nu}	Limiting nutrient concentration
S_{OC}	Sodium acetate concentration
S_P	Phosphorus concentration in the medium
T	Temperature
T_{ref}	Reference temperature (20°C)
V	Liquid volume in the reactor
VF	Illuminated volume fraction of the reactor
X	Cell concentration
x	Carbon subsistence quota
xe*	Steady state fraction of functional activated PSUs under continuous illumination
vc	Yield coefficient of the functional substance from the storage substance
α	Initial slope of the light response curve
α'	Parameter
αC_{max}	Maximum affinity for growth at carbon dioxide limiting condition
αP_{max}	Maximum affinity for growth at phosphorus limiting condition
Θ	Temperature coefficients for growth
ϕ	Quantum efficiency
μ	Specific growth rate
$\mu c_{,max}$	Maximum of synthesis rate of the storage substance per unit dry weight of the functional substance
μ_{max}	Maximum specific growth rate
$\mu_{max, min}$	The most limiting nutrient's maximum growth rate
μ_{m1}	Maximum value for μ
μ_{m2}	Specific growth rate at the absence of nutrient in the culture medium
μ_{m3}	Specific growth rate at high nutrient concentration in the culture medium
μ'_{max}	Hypothetical maximum growth rate at infinite Q
$\mu'_{max, min}$	Hypothetical maximum growth rate at infinite Q for the most limiting nutrient
μ^*_{max}	Maximum growth rate at the maximum value of Q

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