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Review article

Growth kinetic models for microalgae cultivation: A review

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ABSTRACT

Microalgae-based biofuel has received increasing attention as one of the alternative energy sources because of its many advantages. Cultivation of microalgae is a crucial step for successful applications in the biofuel industry. Growth kinetic models are needed to provide an understanding of microalgal growth so that cultivation conditions can be optimized. This review study aims to provide an overview of the existing growth kinetic models for microalgae cultivation and identify knowledge gaps. The existing models were compiled and organized into three groups: those considering a single substrate factor, a light factor, or multiple factors including both substrate and environment. Three major knowledge gaps were identified in this review. For models considering multiple factors, the trade-off between the complexity of the model structure and the usability of the model must be managed. There is a need for appropriate incorporation of light and temperature in the growth model. This can be accomplished through developing an appropriate expression for temporally varying culture temperature and improving light expressions by considering the light attenuation and variation in sunlight intensity. Lastly, developing a generalized growth model for incorporation of species diversity is necessary for more realistic modeling of actual systems.

Contents

1. Introduction

Increasing energy demand has led to concerns about fossil fuel depletion as well as anthropogenic carbon dioxide (CO_2) emissions which have contributed to global climate change [100,111,130]. To reduce the consumption of fossil fuel and associated CO_2 emissions, sustainable and renewable energy sources, including wind, tidal, solar, and

Nomenclature

a	Fitting constant
a'	Optical cross section of chlorophyll a, $m^2\ g^{-1}$ chl
b	Fitting constant
C_n	Algal nitrogen content per unit algal dry weight, %
$C_{n,\max}$	Maximum algal nitrogen content or nitrogen content of the functional substance per unit algal dry weight, %

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C_p	Algal phosphorus content per unit algal dry weight, %
C_{pro}	Cell product concentration, mg L^{-1}
$C_{pro,m}$	Maximum cell product concentration, mg L^{-1}
C_x	Microalgae cell concentration, mg L^{-1}
$C_{x,m}$	Maximum microalgae cell concentration, mg L^{-1}
c	Fitting constant
d	Fitting constant
$f(C_p / C_n)$	Saturation ratio of the pooled phosphorus in algal cells
$f(I_{av})$	A function of average light intensity
$f(T)$	A function of temperature
I	Incident light intensity, μmol photon m^{-2} s^{-1}, W m^{-2}, μE m^{-2} s^{-1}, MJ m^{-2}day^{-1}, or g cal cm^{-2} d^{-1}
I_{abs}	Total light energy absorbed in reactor, mol d^{-1}
I_{av}	Average irradiance in the culture, W m^{-2}, μmol photon m^{-2} s^{-1}, or μE m^{-2} s^{-1}
I_c	Light intensity at the center measured from one direction with light shining from both direction, W m^{-2}
I_e	Average irradiance at the energy compensation point, μE m^{-2} s^{-1} or μmol photon m^{-2} s^{-1}
I_{in}	Light intensity at the front with shining from one side, W m^{-2}
I_k	Microalgal affinity for light, μE m^{-2} s^{-1}
I_{max}	Maintenance rate, mol (kg d)$^{-1}$
I_{opt}	I at $\mu = \mu_{max}$, μmol photon m^{-2} s^{-1}, W m^{-2}, μE m^{-2} s^{-1}, MJ m^{-2} day^{-1}, or g cal cm^{-2} d^{-1}
I_{out}	Light intensity at the back with shining from one side, W m^{-2}
K	Proportionality constant which is akin in meaning to growth yield, (see Eq. (14) of Table 2), kg mol^{-1}
K_a	Attenuation constant kg m^{-3}
K_c	Curve-fitting constant, g g^{-1} Carbon, mol mol^{-1} Carbon, or mol cell^{-1}
K_I	Photo-saturation constant, μmol photon m^{-2} s^{-1}, E m^{-2} s^{-1}, W m^{-2}, klx, or KJ cm^{-2} h^{-1}
K_i	Inhibition constant, mg L^{-1}
$K_{i,CO2}$	Inhibition constant of CO_2, mg L^{-1}
$K_{i,L}$	Photoinhibition constant, klx, kJ cm^{-2} h^{-1}, or μE m^{-2} s^{-1}
$K_{i,OC}$	Sodium acetate inhibition constant of cell growth, mg L^{-1}
$K_{S,nu}$	Monod half-saturation constant of limiting nutrients, mg L^{-1}
K_S	Monod half-saturation constant, mg L^{-1}
$K_{S,CO2}$	Monod half-saturation constant of CO_2, mg L^{-1}
$K_{S,N}$	Monod half-saturation constant of nitrogen, mg L^{-1}
$K_{S,OC}$	Monod half-saturation constant of sodium acetate, mg L^{-1}
$K_{S,P}$	Monod half-saturation constant of phosphorus, mg L^{-1}
K_q	Dimensionless parameter to set the curve form, $K_q = Kc / (Q_{max} - Q_{min})$
k	Parameter
k_d	Consumption rate of photosynthesis products per unit dry weight of the functional substance, mg (mg d)$^{-1}$
m	Shape parameter
n	Exponent
p	Length of light path inside the photobioreactor, m
Pho	photosynthetic rate
Pho_{max}	Light-saturated photosynthesis rate
Q	Nutrient cell quota, g g^{-1} Carbon, mol nutrient mol^{-1} Carbon, or g cell^{-1}
Q_N	N Cell quota, g g^{-1} Carbon, mol N mol^{-1} Carbon, or g cell^{-1}
Q_{max}	Maximum nutrient cell quota for algal existence, g g^{-1} Carbon, mol nutrient mol^{-1} Carbon, or g cell^{-1}
$Q_{max,N}$	Maximum N cell quota for algal existence, g g^{-1} Carbon, mol N mol^{-1} Carbon or g cell^{-1}
$Q_{max,P}$	Maximum P cell quota for algal existence, g g^{-1} Carbon, mol P mol^{-1} Carbon or g cell^{-1}
Q_{min}	Minimum nutrient cell quota for algal existence, g g^{-1} Carbon, mol nutrient mol^{-1} Carbon, or g cell^{-1}
$Q_{min,N}$	Minimum N cell quota for algal existence, g g^{-1} Carbon, mol N mol^{-1} Carbon, or g cell^{-1}
$Q_{min,P}$	Minimum P cell quota for algal existence, g g^{-1} Carbon, mol P mol^{-1} Carbon, or g cell^{-1}
Q_P	P cell quota, g g^{-1} Carbon, mol P mol^{-1} Carbon, or g cell^{-1}
S	Nutrient concentration, mg L^{-1}
S_{CO2}	Carbon dioxide concentration in the medium, mg L^{-1}
S_N	Nitrogen concentration in the medium, mg L^{-1}
S_{nu}	Limiting nutrient concentration, mg L^{-1}
S_{OC}	Sodium acetate concentration in the medium, mg L^{-1}
S_P	Phosphorus concentration in the medium, mg L^{-1}
T	Temperature, °C
T_{ref}	Reference temperature (20 °C)
V	Liquid volume in the reactor, m^3
V_F	Illuminated volume fraction of the reactor
X	Cell concentration, kg m^{-3}
x	Carbon subsistence quota, g Carbon g^{-1} dw
x_e^*	Steady-state fraction of functional activated PSUs under continuous illumination
y_c	Yield coefficient of the functional substance from the storage substance, mg mg^{-1}
α	Initial slope of the light response curve
α'	Parameter, E m^{-2} s^{-1}
α_{Cmax}	Maximum affinity for growth at carbon dioxide limiting condition
α_{Pmax}	Maximum affinity for growth at phosphorus limiting condition
β	Sharpness coefficient (from -1 to ∞)
β'	Slope of the light response curve beyond the onset of photoinhibition
δ	Parameter, μE$^{-0.5}$ m $s^{-0.5}$
Θ	Temperature coefficients for growth
ϕ	Quantum efficiency g C mol^{-1} photons
μ	Specific growth rate, day^{-1} or h^{-1}
$\mu_{c,max}$	Maximum of synthesis rate of the storage substance per unit dry weight of the functional substance, mg (mg d)$^{-1}$
$\mu_{f,max}$	Maximum of synthesis rate of the functional substance per unit dry weight of the functional substance, mg (mg d)$^{-1}$
μ_{max}	Maximum specific growth rate, day^{-1} or h^{-1}
$\mu_{max,min}$	The most limiting nutrient's maximum growth rate, day^{-1} or h^{-1}
μ_{m1}	Maximum value for μ, day^{-1}
μ_{m2}	Specific growth rate at the absence of nutrient in the culture medium, day^{-1}
μ_{m3}	Specific growth rate at high nutrient concentration in the culture medium, day^{-1}
μ'_{max}	Hypothetical maximum growth rate at infinite Q, day^{-1}
$\mu'_{max,min}$	Hypothetical maximum growth rate at infinite Q for the most limiting nutrient, day^{-1}
μ^*_{max}	Maximum growth rate at the maximum value of Q, day^{-1}

biofuel, have received much attention [101]. Since biofuels can be stored and used directly in existing vehicle engines, they become an attractive source for transportation fuels. In particular, biofuels derived from