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A novel mathematical model to simulate the size-structured growth of microalgae strains dividing by multiple fission

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HIGHLIGHTS

- A model to describe the growth of microalgae dividing by multiple fission is proposed.
- The model is also capable to simulate the evolution of the size structure of microalgae population.
- Model results are successfully compared with literature experimental data.
- Numerical experiments are performed to show the improvements arising from this model.
- Inferences are formulated about the effects of multiple fission on the bioreactors productivity.

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ABSTRACT

Several microalgae strains are capable to divide by multiple fission, namely they can give rise to variable number of daughter cells after cytokinesis. Such behavior may have implications on the overall growth and productivities of microalgal cultures that are difficult to infer intuitively. Consequently, a novel mathematical model to simulate the dynamics of the size-structured growth of microalgal strains characterized by multiple fission, is proposed in this work. The model relies on the use of population balance equations (PBEs) to describe the evolution of the size distribution of microalgae cells during growth and permits to decouple the single cell growth phase, which is known to take place in the light, from the division one, that on the contrary is assumed to occur under dark conditions according to well corroborated experimental observations. Moreover, the effect of light intensity, photoperiod and nutrients concentration on the continuous growth of the cells, are suitably accounted for by the model. Furthermore, in order to describe the partition of newborn cells after division, a new approach, which relies on suitable experimental observations, is developed to formulate a novel birth term related to PBEs which takes into account the possibility of multiple fission to take place. Model results and literature experimental data pertaining a strain capable to divide by multiple fission, are successfully compared in terms of biomass concentration evolution, thus highlighting a good predictive capability of the model. Subsequently, specific numerical experiments are performed in order to examine the potential improvements arising from this model with respect to the ones currently available in the literature. Finally, suitable simulation-based inferences are formulated about the potential implications of multiple fission on photobioreactor's productivity.

1. Introduction

It is well recognized that microalgae represent today one of the most promising renewable feedstocks for the production of a wide range of consumer goods such as biofuels, nutraceuticals, pharmaceuticals, bioplastics, functional food, lubricants and food for aquaculture systems. When compared to land plant crops, microalgae are characterized by higher growth rates that result in the need of less extended lands for their cultivation. Furthermore, microalgae production does not require agricultural lands and prevents the typical competitiveness concerns with the agro-food market that, on the contrary, arise from the use of land plants for producing non-food goods. These aspects, coupled with the fact that microalgae can be grown and processed in a bio-refinery

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Notations

$b(m,m')$	daughter distribution function (ng^{-1})
$B(m)$	birth rate of cells of mass m ($ng^{-1}\,mm^{-3}\,h^{-1}$)
C_j	concentration of j^{th} nutrient in the medium ($j=1 \Rightarrow NO_3^-$; $j=2 \Rightarrow H_2PO_4^-$) ($g\,m^{-3}$)
d	equivalent diameter of the cell (μm)
d_c	critical diameter at which the cell is committed to divide (μm)
$D(m)$	disappearance rate of cells of mass m ($ng^{-1}\,mm^{-3}\,h^{-1}$)
F_i	distribution in terms of frequency for the mass or diameter class i (/)
$g(I_{av})$	light dependent kinetics of continuous cell growth (/)
$G(m)$	continuous growth rate of cells of mass m ($ng^{-1}\,mm^{-3}\,h^{-1}$)
h_i	distribution in terms of frequency for the mass class I for unit mass (ng^{-1})
$H(I_{av})$	function accounting that cell division occurs only in the dark (/)
I_{av}	average photosynthetically active radiation within the culture ($\mu E\,m^{-2}\,h^{-1}$)
I_0	incident photosynthetically active radiation ($\mu E\,m^{-2}\,h^{-1}$)
K_{I1}	half saturation constant in the light-dependent term of the growth kinetics ($\mu E\,m^{-2}\,h^{-1}$)
K_{I2}	inhibition constant in the light-dependent term of the growth kinetics ($\mu E\,m^{-2}\,h^{-1}$)
m	single cell mass (ng)
m_c	critical mass at which the cell is committed to divide (ng)
m'	mass of the generic mother cell (ng)
N or n	number of cells (/)
$p_i(m,m')$	unequal partitioning function for the case of division into i^{th} daughter cells (ng^{-1})
R	radius of the cylindrical photobioreactors (m)
t	time (min)
V	photobioreactor volume (m^3)
X	biomass concentration ($g\,m^{-3}$)
$y_{X/j}$	ratio of weight of dry biomass produced to weight of j^{th} nutrient consumed (/)

Greek letters

α_i	parameter of the Hill-Ng distribution for the case of division into i cells (/)
$\beta(\alpha_i, \delta_i)$	beta function for the case of division into i daughter cells (/)
δ_i	parameter of the Hill-Ng distribution for the case of division into i cells (/)
Γ	division intensity function (h^{-1})
$\vartheta(m,m')$	self-similar daughter distribution function (/)
Θ_i	probability of forming a number of daughter cells equal to (i) per mitotic event (/)
λ_i	distribution in terms of frequency for the mass class i for unit mass (ng^{-1})
μ_{av}	average growth rate (h^{-1})
μ_{max}	maximum specific rate of single cell growth ($ng^{1/3}\,h^{-1}$)
μ_c	mass loss rate of single cell (h^{-1})
v_m	time rate of change of cell mass m ($ng\,h^{-1}$)
ϱ	specific weight of cells ($g\,m^{-3}$)
σ_c	standard deviation of the division probability density function (ng)
τ_a	optical extinction coefficient for biomass ($m^2\,g^{-1}$)
ψ	density distribution function of the cell population ($ng^{-1}\,mm^{-3}$)
ω	Angle of incidence of light (rad)

Superscripts

0	initial conditions (/)
exp	experimental value
f	final conditions (/)

Subscripts

av	average value (/)
i	number of daughter cells or generic counter (/)
j	number of nutrients or generic counter (/)
stat	steady state value (/)

framework which might involve the capture of CO_2 from flue gases and wastewater remediation, make such technology particularly attractive both from the economic and environmental point of view. For this reason, there is today a growing interest in developing microalgae based systems for a number of applications in sectors ranging from the biotechnological to the energy one [1].

In spite of such interest, the existing microalgae-based technology is still not widespread since it is affected by economic and technical constraints that might have limited the development of industrial scale production system. Therefore, in order to be implemented at the industrial scale, the current microalgae-based technology should be properly optimized in terms of abatement of the operating costs associated to the different unit steps of the process, i.e. cultivation, harvesting and lipid extraction. In particular, the scale-up of the cultivation systems represents one of the major issues to be solved. In fact, the encouraging experimental results so far obtained at the laboratory scale have been hardly reproduced when trying to transpose the cultivation systems to the large scale.

In this regard, both the scale-up of the cultivation systems and the optimization of key operating parameters might be accomplished by exploiting suitable process engineering techniques which, in turn, rely on the use of mathematical models that are capable to predict the system behavior when changing the operating conditions. For this reason, several mathematical models of microalgae growth within different cultivation systems have been proposed in the literature in the last ten years. So far, the basic characteristics of algal kinetics have been taken into account. In particular, most mathematical models available in the literature are capable to describe quantitatively the evolution of biomass concentration as a function of light density, nutrient availability and photobioreactors operating mode. Other modeling efforts have been devoted to quantitatively describe the production of photosynthetic oxygen and the corresponding consumption of dissolved carbon dioxide within the culture as well as the pH evolution, the mass transfer phenomena and the influence of hydrodynamic regime on light availability for microalgae. In the last years, due to the growing interest in the use of microalgae for producing biofuels, the mathematical models have been focused on the quantitative description of the influence of operating conditions on the lipid biosynthesis of microalgae with particular regard to the simulation of the effect of nitrogen starvation on the accumulation of fatty acids within the cells [2–5]. Moreover, due to the interest in using microalgae as a mean to capture CO_2, mathematical model have been recently developed with the aim of quantitatively assessing the capability of microalgal cultivation to capture and convert CO_2 into useful biomass [1,6–8].

Albeit the number, the complexity and the reliability of mathematical models proposed today in the literature is still growing,