Algal Research 19 (2016) 155–161

Contents lists available at ScienceDirect

Algal Research

journal homepage: www.elsevier.com/locate/algal

A simple model for algae-bacteria interaction in photo-bioreactors

Jesús Zambrano [a,*], Ivo Krustok [a], Emma Nehrenheim [a], Bengt Carlsson [b]

[a] School of Business, Society and Engineering, Mälardalen University, P.O. Box 883, 72123 Västerås, Sweden
[b] Department of Information Technology, Uppsala University, P.O. Box 336, 75105 Uppsala, Sweden

ARTICLE INFO

Article history:
Received 11 March 2016
Received in revised form 21 June 2016
Accepted 30 July 2016
Available online xxxx

Keywords:
Biomass
Photo-bioreactor
Irradiance
Modeling
Monod.

ABSTRACT

This work presents a simple model to describe the consortia of algae-bacteria in a photo-bioreactor. The model is inspired by the Activated Sludge Model (ASM) structure, which includes different process rates and stoichiometric parameters. The model comprises two main biomass populations (algae and bacteria), two dissolved substrates (ammonium and nitrate) and two dissolved gases (oxygen and carbon dioxide) in the reactor. The model was calibrated with data from batch experiments performed in two lab-scale photo-bioreactors. A sensitivity analysis was done to identify the parameters to be considered for the model calibration. Results indicate that the maximum algae and bacteria growth rate, bacteria growth yield and half-saturation constant for carbon were the most sensitive parameters. Moreover, the comparison between the experiments and the model shows good agreement in terms of predicting the ammonium, nitrate and oxygen concentrations in the photo-bioreactor.

1. Introduction

In recent years, special attention has been devoted to studying the potential benefits of using algae in biological processes for wastewater treatment [1]. Under illumination, algae consume carbon dioxide and produce oxygen. This activity can be beneficial in wastewater treatment processes, since the oxygen produced by algae can be used by aerobic bacteria to biodegrade pollutants. Additionally, algae can consume the carbon dioxide released from bacterial respiration for photosynthesis [1,2], thereby completing the photosynthetic cycle. In this way, the energy costs for both aeration and carbon dioxide generation can be reduced. However, an important factor to consider is that algae growth is light limited [3]. The review from Subashchandrabose et al. [1] show results from experiments at various scales with different reactor configurations and with different algae-bacteria genera for degrading pollutants and removing nutrients from wastewater.

Recent studies have highlighted the potential of consortia of algae-bacteria. For example, Su et al. [4] performed batch experiments showing the effect of different ratios of algae-bacteria on several process indicators, including dissolved oxygen (DO), chemical oxygen demand (COD), pH and total suspended solids (TSS). Comparisons were made with algae alone and sludge alone. Experiments show that it is possible to obtain higher rates of nitrogen and phosphorus removal when a consortium of algae-bacteria is used. Algae cultivated in photo-bioreactors have been shown to be a potential substrate for methane production [5] due to their ability to photosynthesize and their relatively high growth rate.

From the point of view of modeling, several attempts have been made to describe the algae dynamics. The basic Droop model [6], which assumes one main substrate, one biomass and one internal nitrogen cell quota, has been able to describe the main behavior of algae dynamics in line with experimental studies. Further studies have added different levels of complexity to the algae model. In addition to the variables presented in [6], Bernard [7] presented a model which includes the chlorophyll concentration in order to predict the light attenuation in the photobioreactor. The chlorophyll concentration depends on the amount of particulate nitrogen and the amount of light to which the algae is photo acclimated. The model also takes into account the difference in light intensity between the surface and bottom of the bioreactor. Bouterfas et al. [8] studied the effect of light and temperature on the growth of different algae species in batch culture experiments. The results were compared with different mathematical models for the growth rate.

Yin-Hu [9] presented a model to describe the combined effect of phosphorus, nitrogen and light intensity on the algae growth rate based on the Steele model (used to describe the relationship between the specific growth rate of algae and the light intensity) together with the classical Monod model and the Droop model. The review presented by Béchet et al. [10] gives special attention to light intensity as a key factor in algae activity. This study divided models into three principal types. Type I models take into account the rate of photosynthesis of the entire culture being a function of the incident or average light intensity. Type II models account for the impact of light gradients on the local rate of photosynthesis. Type III models consider that the rate of

* Corresponding author.
E-mail address: jesus.zambrano@mdh.se (J. Zambrano).

http://dx.doi.org/10.1016/j.algal.2016.07.022
2211-9264/

photosynthesis is a function of the light intensity experienced by the algae over time. Decostere et al. [11] presented a basic model for algae dynamics considering the growth on inorganic carbon. The model structure was inspired by the Activated Sludge Models (ASMs), and the calibration was conducted using data from respirometric-tritimetric experiments in order to adjust kinetics parameters.

Recently, Solimeno et al. [12] presented a model for an algae treatment process based on the River Water Quality Model no. 1 (RWQM1) [13], which is part of the ASMs. The model includes carbon limiting the growth of algae, and a dynamic model for the photosynthesis previously proposed by Eilers and Peeters [14]. Dochain et al. [15] proposed a dynamic model of a waste stabilization pond which considers three microorganisms: microalgae, aerobic bacteria and sulphate-reducing anaerobic bacteria. The study includes the model calibration using data from different seasons.

The aim of the present work is to propose a simple model to describe the dynamics involved in the consortia of algae-bacteria in a photo-bioreactor by means of the most elementary process reactions and components. The work includes a sensitivity analysis of the model parameters. The results of this sensitivity analysis were used for the model calibration, which was assessed by using experimental data obtained from batch experiments in lab-scale photo-bioreactors. Part of the model is inspired by the ASM no. 1 [16] for the bacteria dynamics, and the other part is inspired by the recent work presented by [12] for the algae dynamics. In our model, several assumptions were made in order to simplify the expressions for the process rates, and to reduce the number of the model components and parameters. Based on this work, we believe that the developed model is an important step for creating a fundamental platform for dynamic studies of the consortia of algae-bacteria in a photo-bioreactor.

The paper is organized as follows. The mathematical model is presented, with a description of its components and process rates. This is followed by details of the experimental and model setup. Next, results of the model calibration are shown, followed by a discussion and conclusion.

Nomenclature

b_{alg}	Algae decay [1/d]
b_{bac}	Bacteria decay [1/d]
$f^{\mathrm{C}}_{\mathrm{bac}}$	CO_2 produced per bacteria [g CO_2/g COD]
$f^{\mathrm{C}}_{\mathrm{alg}}$	Fraction of CO_2 in algae [g CO_2/g COD]
$f^{\mathrm{N}}_{\mathrm{alg}}$	Fraction of N in algae [g N/g COD]
I	Irradiance [μmol/m^{2}s]
$i_{X_{\mathrm{bac}}}$	N used during growth of bacteria [g N/g COD]
$K_L a_{\mathrm{o2}}$	Mass transfer coefficient of O_2 [1/d]
K_{co2}	Algae half-saturation constant for C [g C/m^3]
K_{I}	Algae half-saturation constant for I [μmol/m^{2}s]
$K_{\mathrm{n,alg}}$	Algae half-saturation constant for N [g N/m^3]
$K_{\mathrm{n,bac}}$	Bacteria half-saturation constant for N [g N/m^3]
K_{o2}	Bacteria half-saturation constant for O [g N/m^3]
p	Reference parameter value
S_{co2}	Dissolved CO_2 gas concentration [g CO_2/m^3]
S_{nh4}	Dissolved NH_4-N concentration [g N/m^3]
S_{no3}	Dissolved NO_3-N concentration [g N/m^3]
S_{o2}	Dissolved O_2 gas concentration [g O_2/m^3]
$S^{\mathrm{sat}}_{\mathrm{o2}}$	Saturation concentration for O_2 in water [g O_2/m^3]
t	Time domain [d]
T_s	Simulation time [d]
X_{alg}	Algae biomass concentration [g COD/m^3]
X_{bac}	Bacteria biomass concentration [g COD/m^3]
Y_{bac}	Bacteria growth yield [g COD/g N]
$Y^{\mathrm{C}}_{\mathrm{alg,nh4}}$	Algae CO_2 yield on NH_4 [g COD/g CO_2]
$Y^{\mathrm{N}}_{\mathrm{alg,nh4}}$	Algae N yield on NH_4 [g COD/g N]
$Y^{\mathrm{O}}_{\mathrm{alg,nh4}}$	Algae oxygen production yield on NH_4 [g O_2/g COD]
$Y^{\mathrm{C}}_{\mathrm{alg,no3}}$	Algae CO_2 yield on NO_3 [g COD/g CO_2]
$Y^{\mathrm{N}}_{\mathrm{alg,no3}}$	Algae N yield on NO_3 [g COD/g N]
$Y^{\mathrm{O}}_{\mathrm{alg,no3}}$	Algae O_2 production yield on NO_3 [g O_2/g COD]
y	Vector of experimental values
y	Vector of model values
Δp	Change in parameter value p
μ_{alg}	Algae specific growth rate [1/d]
μ_{bac}	Bacteria specific growth rate [1/d]
ρ	Process rate [g/m^{3}d]
$\sigma^{\Delta p}_{y}$	Sensitivity coefficient [−]

Abbreviations

ASM	Activated Sludge Model
COD	Chemical Oxygen Demand [g/m^3]
DO	Dissolved Oxygen [g/m^3]
DOC	Dissolved Organic Carbon [g/m^3]
FIT	Degree of fit between model and experiment values [−]
LHS	Latin hypercube sampling
LW	Lake water
TOC	Total Organic Carbon [g/m^3]
TSS	Total Suspended Solids [g/m^3]
WW	Wastewater
WWTP	Wastewater treatment plant

2. The model

We consider a biological process where the interaction between algae and bacteria takes place in a culture volume, see Fig. 1.

The algae grow with light, consume substrate containing either carbon or nitrogen and produce dissolved oxygen (O_2). The carbon component in the substrate is modeled as dissolved carbon dioxide (CO_2), and the nitrogen is modeled as dissolved ammonium (NH_4) and nitrate (NO_3), whereas the bacteria grow with O_2 and NH_4 and produce NO_3 and CO_2.

2.1. Model assumptions

The proposed model for this biological process is based on the following set of general assumptions:

- Only one class of bacteria and one class of algae are considered.
- The bacteria are assumed to be autotrophic.
- The algae growth on dissolved ammonium and nitrate, where the stoichiometry relationships presented in [17] are assumed.
- Due to the small size of the reactor, the irradiance of light is considered homogeneous throughout the photo-bioreactor.
- Since the experiments were carried out with controlled liquid temperature, the dependence of stoichiometric and biokinetics parameters on temperature was not included.
- Inhibition of algae cause by either the excess of light or excess of carbon dioxide was not considered.

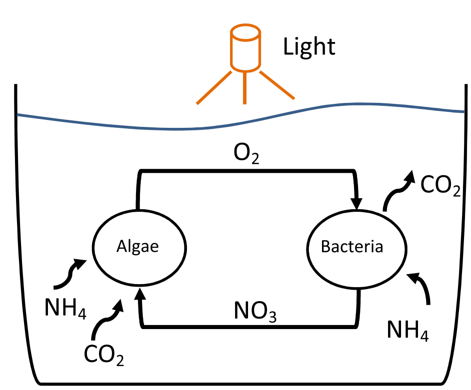

Fig. 1. Schema representing the algae-bacteria interaction in a culture volume.