



Adaptive control of light attenuation for optimizing microalgae production[☆]



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ABSTRACT

The light attenuation factor, defined by the ratio between the incident light and the light at the bottom of the reactor, is a key operating parameter for light-limited phototrophic culture. Here, two nonlinear control laws have been proposed in order to regulate this ratio: a static controller, which is input-to-state stable with respect to measurement noise, and an adaptive controller. Then, we propose a set-point for the light attenuation factor in order to optimize microalgae productivity under constant illumination. Finally, numerical simulations illustrate how the adaptive controller can be used to optimize biomass productivity under realistic day–night cycles.

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1. Introduction

Microalgae are emerging as a promising solution to address a number of markets including feed, food, green chemistry, and bioenergy [1–3]. Nonetheless, the productivities recorded in outdoor conditions are often disappointing with respect to the actual potential of these fast growing microorganisms. This is mainly due to low photosynthetic yields resulting from a non optimal conversion of light into energy fuelling biomass and reserve compounds synthesis [4]. In this context, the control of phototrophic culture is a key feature to improve economic and environmental yields [5,6,4,7,8]. The use of continuous cultures¹ is of particular interest since it allows to drive the process to a desired state by manipulating adequately the dilution rate (ratio between the input flow rate and the reactor volume). Light absorption by pigments and scattering by the particles creates a light gradient in

these phototrophic cultures. For light-limited growth (assuming that all nutrients are supplemented in excess), apprehending the light distribution inside the reactor is a keystone for productivity optimization. At high biomass, dark zones where photosynthetic growth is lower than respiration appear. On the other hand, at low biomass, a large part of the photons are not be absorbed. Both phenomena lead to reduced productivity. It is therefore crucial to correctly represent light attenuation inside the reactor, and to adapt the dilution rate in order to regulate microalgae concentration.

For one-dimensional light distribution geometry (e.g. flat panel or raceways) and under constant illumination, a criteria has been proposed in order to optimize microalgae production: the steady-state biomass productivity is optimal when the light at the bottom of the culture is such that the specific growth rate equals the respiration [9]. The biomass concentration should be regulated, through the dilution rate, in order to satisfy this condition.

The optimization of biomass production under day–night cycles is more challenging. Indeed, the aforementioned criteria could not be maintained during a full day [10]. In [11], an optimal biomass concentration has been determined experimentally in order to optimize biomass productivity under natural sunlight. Given the high complexity of the problem, mathematical modelling of microalgae culture [4,12] can be helpful. Based on a dynamic model considering the effects of light, nutrient and temperature, [13] have determined numerically an optimal strategy. By

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¹ The reactor is permanently fed with an inflow of nutrients, while the same outflow keeps the culture volume constant.

following the approach of self-optimizing control, the authors have shown that near optimal productivity can be obtained through the regulation of the light attenuation factor, defined by the ratio between the incident light and the light at the bottom of the reactor. The main idea is to find a trade-off over the day/night cycle between maximizing light capture and minimizing respiration losses, by manipulating adequately the dilution rate. At first glance, this attenuation factor is proportional to the biomass concentration. Nonetheless, the pigment content of microalgae can vary because of nitrogen limitation or light change (photoacclimation), leading to a more complex relationship between light attenuation factor and biomass. This operating mode – using the dilution rate to regulate the light attenuation factor – is generally called *turbidostat* or *luminostat*.²

Our objective is to propose closed loop control laws to automatically reach near optimal biomass productivity for light-limited cultures. To this end, we design a controller which regulates the light attenuation factor. The structure of the control law, based on the work of [14,15], is of particular interest for bioprocesses since it does not require any knowledge of the growth rate kinetics. Then, we show that this controller optimizes microalgae production.

The paper is organized as follows. We first describe a model for light-limited cultures [16]. In Section 3, we present the design of the control laws which regulate the light attenuation factor. Then, we show that this controller can be used in order to optimize biomass production in light/dark cycles. Finally, we illustrate our approach with numerical simulations of a – more realistic – extended version of the model (presented in appendix).

2. Modelling light-limited growth of microalgae

This section presents a simple model for light-limited growth of microalgae, based on the research work developed by Huisman and co-workers [16–18] for competition. Originally developed for natural systems (lake, ocean, etc.), this theoretical approach can be used for microalgae culture systems (planar photobioreactor or raceways).

2.1. Model development

Let us consider a phototrophic continuous culture of depth L in which microalgae grow (whose concentration is denoted x). We assume that the system is completely homogeneous, *i.e.* every concentration (microalgae, nutrients) is the same at any point. Due to light absorption and scattering by the algae, a spatial gradient of light occurs: the light intensity in the reactor decreases along the depth.

Let us assume that the light decrease in the water column can be described by the Lambert–Beer law. Thus, for a given position $z \in [0, L]$, the corresponding light intensity $I(x, z, t)$ satisfies

$$I(x, z, t) = I_{in}(t) \exp(-axz), \quad (1)$$

where $I_{in}(t)$ is the incident light, and a is the mass extinction coefficient resulting from absorption and scattering. The light at the bottom of the water column is called $I_{out}(x, t) = I(x, L, t)$.

We consider here that the growth of microalgae is only limited by light, so the specific growth rate is defined by a continuous function $\mu(I) > 0, \forall I > 0$. The total growth G of microalgae is obtained by integrating the local growth over depth:

$$G(x, t) = \frac{x}{L} \int_0^L \mu(I(x, z, t)) dz \quad (2)$$

Given Eq. (1), we obtain

$$G(x, t) = \frac{1}{aL} \int_{I_{out}(x,t)}^{I_{in}(t)} f(I) dI \quad (3)$$

with $f(I) = \mu(I)/I$.

Considering a dilution rate u and a constant basal respiration rate r ,³ the dynamic evolution of the microalgae concentration x is therefore given by

$$\dot{x} = G(x, t) - (u + r)x. \quad (4)$$

More accurate models [4] have been proposed in order to consider the effects of temperature, nutrient or photo-acclimation. Nonetheless, despite its relative simplicity, Eq. (4) has been able to represent quite accurately experimental data [19].

2.2. Model analysis in open loop

In this subsection, we consider a constant light supply I_{in} , and a constant dilution rate u .

First, note that $G(x)$ is an increasing function whose derivatives write:

$$\begin{aligned} G'(x) &= \mu(I_{out}(x)) > 0 \\ G''(x) &= -aL\mu'(I_{out}(x)) \end{aligned} \quad (5)$$

Thus, the asymptotic behavior of the model depends on the specific growth rate. In the following subsections we consider various typologies of growth functions.

2.2.1. For an increasing growth rate $\mu(I)$ [16,17]

Proposition 1. For increasing growth rate, if $(u + r) < \mu(I_{in})$, then Eq. (4) has one non-trivial equilibrium, which is globally stable.

Proof. For increasing growth rate, $G(x)$ is increasing and concave given Eq. (5) (see Fig. 1). Thus, Eq. (4) is bounded and has two equilibria if $(u + r) < \mu(I_{in}) = G'(0)$:

- a trivial equilibrium which is unstable,
- a non-trivial stable equilibrium. □

For example, assuming a kinetics of Michaelis–Menten type, the specific growth rate writes:

$$\mu(I) = \bar{\mu} \frac{I}{I + K_s}. \quad (6)$$

where $\bar{\mu}$ and K_s are respectively the maximum growth rate and the half-saturation coefficient.

The total growth G is obtained by integration along the depth:

$$G(x) = \frac{\bar{\mu}}{aL} \ln \left(\frac{I_{in} + K_s}{I_{out}(x) + K_s} \right). \quad (7)$$

The nontrivial equilibrium of Eq. (4) is obtained by solving

$$\frac{\bar{\mu}}{aL} \ln \left(\frac{I_{in} + K_s}{I_{in} \exp(-ax^\dagger L) + K_s} \right) = (u + r)x^\dagger, \quad (8)$$

where x^\dagger is the biomass concentration at steady state. This allows to define the light at the bottom of the water column at equilibrium $I_{out}^\dagger = I_{in} \exp(-ax^\dagger L)$.

² Note that the definition of these operating modes diverge between authors, in particular under day/night cycles.

³ we consider that the respiration due to the biosynthetic cost is already included in the specific growth rate $\mu(I)$

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