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Optimal decision curve of light intensity to maximize the biomass concentration in a batch culture

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ABSTRACT

This paper proposes a method to find an optimal decision curve to manage the incident light intensity (q_0) that is applied to microalgae cultivation to maximize biomass concentration (C_X). Microalgae are characterized by the production of high value compounds of interest to industry; the challenge is to obtain the highest biomass concentration. Optimization of the performance of microalgae culture systems is important to guarantee the viability of the economical process. The advantages of this optimization proposal are to attain to C_X maximum productivities, as well as its simplicity and its robustness against perturbations. The optimization proposal is illustrated and evaluated on a numerical simulation in a batch culture of microalga *Chlamydomonas reinhardtii*. Additionally, it was compared to a conventional constant light operation and with an optimization approach based on finding the ratio between q_0 and C_X (light-to-microalga ratio). In the analysis, the performance of the optimal decision curve was contemplated in presence of the perturbations and variation of parameters. The simulations of proposal in this paper shows an optimal behavior in terms of a maximum production C_X · In addition, this would have a better behavior in front of robustness and disturbance rejection capabilities, compared to both, constant light operation and light-to-microalga ratio.

1. Introduction

Microalgae are unicellular organisms that assimilate carbon dioxide (CO_2), nitrogen (N) and phosphorus (P) to form their biomass [1]. These organisms contain significant amounts of micronutrients, such as proteins, carbohydrates and lipids, as well as pigments, polyphenols and minerals. These metabolites can be transformed into products of interest for the energy [2,3], nutraceutical [4], cosmetic [5] and food industries [6]. Additionally, they are used in diverse applications related to environmental restoration [7,8]. This has turned microalgae into a new natural resource with great potential and high interest to industry, but with the challenge of improving efficiency to achieve an increase of the biomass concentration (C_X).

Microalgae can be cultivated in closed systems called photobioreactors (PBRs). Usually the PBR requires: nutrients, an inorganic carbon source, agitation, light supply, pH and temperature, constants. Light energy is the most important factor for microalgae growth cultures photosynthesis; it must be supplied in a continuous manner because radiative energy may not be accumulated [9,11]. Usually the problem in cultivating microalgae is related to the light intensity, the growth rate of photosynthetic microalgae depends on the light energy absorbed by cells, a low intensity causes photolimitation and higher intensity causes photoinhibition [12,13]. On the other hand, when the C_X increases, the mutual shading enhances and the photolimitation takes places, which decreases the light energy available per cell, starts playing an important role. As a result, light utilization efficiency decreased and so does the specific growth rate. Moreover, it's not possible to increase the light intensity over a certain level because a high light energy per cell

Abbreviations: C_X, biomass concentration; HNN, hybrid neural network; IPOPT, interior point optimizer; LED, light-emitting diode; PBR, photobioreactor; PMP, Pontryagin's maximum principle; q_0, incident light intensity; q_0^*, optimum value for q_0; μ, total specific growth rate; μ_p, photosynthetic growth rate; μ_{pMAX}, maximum μ_p; μ_s, respiration growth rate.

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will photoinhibit the photosynthetic cells [14]. Due to this fact, it is important that the incident light intensity (q_0) applied be optimal according to C_X during period of microalgae cultivation, the bioprocess could be optimized to impose q_0 over the PBR by C_X to be maximal at the end of cultivation time.

Conventional optimizations are performed based on deterministic mathematical models. However, most of these methods have not reached accuracy, because microalgae based processes are a nonlinear response at varying time [15]. Recently many researchers have optimized to increased C_X using exhaustive searching methods as: hybrid neural network (HNN) model [15], response surface methodology based on experiments [16], indirect methods such as Pontryagin's maximum principle (PMP) [17], and Interior Point Optimizer (IPOPT) [18]. Nevertheless, these improving methods do not have into account the influence of possible disturbances. Although, calculation of the optimum q_0 is a difficult task due to the complexity of the model and the time scale of the optimization problem. In this paper a simple form of optimization is proposed. To carry out the optimization, the model descripted in [19,20], was used. The development generated an optimal decision curve by q_0 to increase the amount of C_X and the optimization was carried out offline. The performance of the proposed optimization was evaluated by means of numerical simulations. It was compared to: 1) a conventional constant light operation and 2) an offline optimization approach based on finding the ratio between q_0 and C_X (light-to-microalga ratio) developed by [19]. This determines that the optimal decision curve has a better performance towards disturbances and variation of parameters reaching maximize C_X.

This strategy is the first phase of an investigation that looks for: 1) confidence that this proposal will give a greater biomass to be obtained against existing proposal, and 2) an appropriate experimental design based on the estimation of the amount of biomass according to the results of the simulations.

2. Material and methods

The PBRs are generally exposed to constant incident light intensities provided by a LED panel or incandescent lamps or fluorescent tubes, applied on their surface during the entire culture time. The increase of biomass induces a self-shading phenomenon, generating an attenuation of light. This light attenuation reduces the photosynthetic growth which is governed by the received light. The model contemplates the batch microalgae cultures in artificially lighted PBR and in standard autotrophic conditions. The inorganic carbon source (CO_2) is supplied continuously to maintain optimum pH. The PBR has an impeller to ensure a thorough homogenization of the medium and all mineral nutrients. These nutrients (nitrogen, sulfate, phosphate, and micronutrients), required for growth, are introduced at the beginning in excess. In this case, the effective light intensity is the unique factor controlling growth, and the model treats light as such.

2.1. Culture medium and conditions

In the experiments conducted for [20,21], a type of *Chlamydomonas reinhardtii* was used, from a culture collection of the *Chlamydomonas* Genetic Center (Duke University, Durham, USA) and the French Atomic Energy Center (Cadarache, France), respectively. The culture medium used was an autotrophic minimum growth medium consisting of: $NaHCO_3$ (1.68 g L^{-1}), NH_4Cl (1.45 g L^{-1}), $MgSO_4{\cdot}7H_2O$ (0.28 g L^{-1}), $CaCl_2{\cdot}2H_2O$ (0.05 g L^{-1}), KH_2PO_4 (0.61 g L^{-1}), and Hutner's trace elements (1 mL L^{-1}). The pH (7.0–7.2) was regulated by CO_2 injection and temperature (25 °C) by ambient air blowing.

2.2. Photobioreactor

The PBR in this study is a flat rectangular panel, as referenced in [19]. It has a working volume of 1.47 L and a thickness of 4 cm. The incident light flux falls perpendicularly on one side of the PBR. For the addition of gasses (CO_2 or air) is considered that the PBR is provided with a microinjection system on the bottom and that the agitation is performed by an impeller, see Fig. 1.

2.3. Radiative model

The transfer of light, called spectral irradiance (G(z)) inside of PBR, strongly depends of the PBR geometry. When PBR is illuminated on one side, the light attenuation occurs in one direction of culture depth (z). An analytical solution of irradiance distribution was obtained by [22]:

$$G(z) = 2q_0 \frac{(1+\alpha)\, e^{\delta(L-z)} - (1-\alpha)\, e^{-\delta(L-z)}}{(1+\alpha)^2 e^{\delta L} - (1-\alpha)^2 e^{-\delta L}} \tag{1}$$

where,

$$\delta = C_X \sqrt{E_a\,(E_a + 2bE_s)} \tag{2}$$

is the two-flux extinction coefficient, and

$$\alpha = \sqrt{E_a / (E_a + 2bE_s)} \tag{3}$$

is the linear scattering modulus which quantifies the respective importance of absorption and scattering phenomena. E_a and E_s, are optical parameters and represent the mass absorption and the mass scattering coefficients ($m^2\ kg^{-1}$); b, is the backward scattering fraction (dimensionless); q_0, represents the hemispherical incident light flux (or incident light intensity); C_X, represents the biomass concentration inside the PBR ($kg\ m^3$); L, is the depth of the PBR and z, is the depth of the culture. The optical parameters depend on microorganism shape and size, as well as pigment content.

2.4. Modeling of photosynthetic growth

1) Mass Balance. Assuming that the culture broth is completely homogeneous, states that the biomass concentration dynamics in batch culture will be represented by

$$\frac{dC_X}{dt} = \mu C_X \tag{4}$$

where, μ is the total specific growth rate. Which is mainly function of cell and nutrients concentrations, pH, temperature, and incident light flux.

2) Growth Kinetics. For eukaryotic cells, growth is the result of the biomass increase by photosynthetic microorganisms and its partial degradation by respiration in mitochondria [20]. Thus, μ can be expressed as:

$$\mu = \mu_p - \mu_s \tag{5}$$

where, μ_p and μ_s are respectively the photosynthetic and respiration kinetics. Assuming that all nutrients are introduced in excess, μ_s is considered constant according to [18] and μ_p is only a function of the light received by the cell, characterized by the available light inside the culture [19]. Hereby, the model that represents the average photosynthetic responses, μ_p(G(z)), is a function of the depth of the reactor which can be obtained through the integration of the local photosynthetic responses [19,20].

$$\mu_p = \mu_0 \frac{1}{L} \int_0^L \frac{G(z)}{K_I + G(z) + \frac{G^2(z)}{K_{II}}} dz \tag{6}$$