Journal of Process Control 37 (2016) 58–69

Contents lists available at ScienceDirect

Journal of Process Control

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

Optimization of biomass production in outdoor tubular photobioreactors

G.A. de Andrade[a,*], M. Berenguel[b], J.L. Guzmán[b], D.J. Pagano[a], F.G. Acién[c]

[a] *Universidade Federal de Santa Catarina, Departamento de Automação e Sistemas, 88040-900 Florianópolis, SC, Brazil*
[b] *Dpto. de Informática, Universidad de Almería – CIESOL, Campus de Excelencia Internacional Agroalimentario, ceiA3, Crta. Sacramento s/n, 04120 La Cañada, Spain*
[c] *Dpto. de Ingeniería, Universidad de Almería – CIESOL, Campus de Excelencia Internacional Agroalimentario, ceiA3, Crta. Sacramento s/n, 04120 La Cañada, Spain*

ARTICLE INFO

Article history:
Received 4 May 2015
Received in revised form
24 September 2015
Accepted 5 October 2015
Available online 29 November 2015

Keywords:
Biomass production
Microalgae
Nonlinear programming
Optimization
Photobioreactor

ABSTRACT

This paper is concerned with microalgal biomass production optimization in outdoor tubular photobioreactors. The main purpose of such optimization system is to calculate the culture medium flow rate in order to maximize the biomass production over a determined period of time. Two different methods are shown in this work: (i) an optimal and (ii) a near-optimal strategy. The optimal strategy belongs to the optimal control theory. In this context, a direct method is used to discretize the control problem and a nonlinear programming technique is applied into the resulting optimization problem. The near-optimal strategy calculates only the culture medium injection time, while the culture medium flow rate is maintained constant during this time. For this aim, a photobioreactor model, under real environmental and culture conditions, is used to compute the injection time. This strategy is mostly important for those photobioreactors that are not equipped with a continuous culture medium valve. Simulation and experimental results allow the user to evaluate the effectiveness of the biomass production optimization strategies proposed in this work, compared with a classical harvesting strategy.

1. Introduction

Over the last years, there has been an increasing interest in the culture of microalgae due to their potential in many industrial applications [1]. Dozens of algal species are used to produce animal feed, human nutrition, cosmetics and pharmacy industries [2,3]. Large-scale cultures also find application in environmental remediation as wastewater treatment, carbon dioxide fixation and greenhouse gas emissions reduction [4,5]. Even further, microalgal production is being used as a clean and renewable energy source, because of their high yield and low spatial requirements, if compared to terrestrial plants [1,5,6]. In this context, some authors are considering microalgae as one of the main biodiesel feedstocks for the future [7].

Microalgae are cultivated at an industrial scale in two widespread systems: (i) open-culture systems and (ii) closed-culture systems. Open-culture systems, for example open ponds and raceways, are the simplest and less expensive ones. Unfortunately, the microalgae culture can be easily contaminated and little control of the operating conditions can be made on such systems. Closed-culture systems, such as tubular photobioreactors, allow a certain control level of operating conditions and also to avoid contamination, being possible to obtain higher biomass production and high-value algal products, if compared to open-culture systems [8].

Despite their recognized utility, algal biotechnologies have progressed slowly [3]. The current worldwide production of microalgal biomass is very low, it is estimated in 15,000 t dry matter per year, with a price ranging from 30 to 300 €/kg [9]. To be competitive in the bioenergy market, the microalgal production must approximate crop prices and capacity. From an industrial scale application point of view, the problem of use microalgae to produce biomass is to justify the high costs of installation, operation and maintenance [3].

As can be seen, the technology used in microalgal cultivation systems must be scaled-up several orders of magnitude to significantly contribute to the biofuels market. Currently, extensive efforts have been reported in literature. For example, in [10–13] advanced control strategies are proposed to control the pH in order to reduce the CO_2 losses. The biomass production optimization is also other research field outstanding on photobioreactors

---

[*] Corresponding author. Tel.: +55 3721 9934.
E-mail addresses: gustavo.artur@posgrad.ufsc.br (G.A. de Andrade), beren@ual.es (M. Berenguel), joseluis.guzman@ual.es (J.L. Guzmán), daniel.pagano@ufsc.br (D.J. Pagano), facien@ual.es (F.G. Acién).

http://dx.doi.org/10.1016/j.jprocont.2015.10.001
0959-1524/

[4,14–17]. Some works have been addressed in other research fields, such as economic and environmental issues [9,18], and photobioreactor design and operation [19–21].

This work concerns with the biomass production optimization in outdoor tubular photobioreactors by acting on the culture medium injection of the system to optimize the biomass production over the period of one day. In these processes, two features are of extreme importance for the design of such optimization system. First, the natural sunlight is the only energy source available for the microalgae. The light source is therefore periodic with a light phase (day) and a dark phase (night). Second, the auto-shading effect has to be taken into account: high biomass concentrations affect the light distribution and thus the biological activity within the reactor. Therefore, the mathematical photobioreactor model used for the optimization process must consider these features in order to obtain an adequate solution.

As shown in [15], this optimization problem can be solved by means of the Pontryagin's maximum principle and optimal control theory. In this way, a control policy to reach an optimal production over a finite time horizon can be used. However, these authors assume several simplifications to provide a simple model suitable for applying the Pontryagin's maximum principle. The distance between their proposed optimal strategy and the optimal production for a real system is therefore difficult to assess.

In order to solve such problem, a direct numerical optimization method is proposed in this work. Direct optimization methods have proved to be powerful tools for solving optimal control problems with accuracy [22–25]. The idea of direct optimization methods is to discretize the optimal control problem and apply nonlinear programming (NLP) techniques that use only control and state variables as optimization variables to the resulting finite-dimensional optimization problem.

The numerical algorithms used to solve such NLP problem, for example sequential quadratic programming (SQP), are usually developed on the basis of the Karush–Kuhn–Tucker (KKT) conditions, i.e., the first-order necessary optimality conditions. However, second-order sufficient conditions must also be checked to ensure optimality of solutions. This is easily tested by linear algebra techniques for optimization problems [22]. Part of the results presented in this paper are contained in a preliminary form in [26], with only simulation results and without describing the whole optimization problem.

Aside the direct numerical optimization technique, a near-optimal strategy is also presented in this work. Roughly speaking, this strategy simulates a complex partial differential equation (PDE) photobioreactor model, under real environmental conditions, to calculate the time injection of a constant value of the culture medium. From a practical point of view, this strategy is mainly important for those photobioreactors that are not equipped with a continuous medium valve or for those cases where the culture medium valve cannot set the flow rate values obtained from the optimal strategy proposed in this paper.

The paper is organized as follows: Section 2 presents a brief description of the plant and the mathematical model of the photobioreactor. Section 3 outlines the nonlinear programming problem to optimize the biomass production. The near-optimal strategy is shown in Section 4. Simulation and experimental results obtained with the proposed optimization strategies are shown in Section 5. Main conclusions are presented in Section 6.

Fig. 1. A real view of 10 tubular photobioreactors at “Las Palmerillas” experimental station, Almería (Spain), showing the bubble column and the solar loop.

2. The tubular photobioreactor

The tubular photobioreactor used in this work is located at the Palmerillas Experimental Station, property of CAJAMAR foundation (Almería, Spain), located inside a greenhouse (see Fig. 1), where the *Scenedesmus almeriensis* microalgae is cultivated. This microalgae is characterized by a high growth rate, withstanding temperature up to 45 °C and pH values up to 10 [27]. The experiments performed in this work consider microalgae grown photoautotrophically with continuous aeration to remove the dissolved oxygen, and with pH and temperature adequately controlled. Moreover, the culture medium composition used in the experiments is shown in Table 1. The culture is operated in nutrient-sufficient conditions: nutrients are ever at concentrations not limiting the growth.

A general scheme of the plant is depicted in Fig. 2, showing the main components: (i) the solar receiver and (ii) the bubble column.

The solar receiver is made of transparent tubes with 0.09 m diameter and joined into a loop configuration to obtain a total horizontal length of 400 m, with a capacity of 2200 L. Its structure was optimally designed to maximize the interception of solar irradiance, minimize resistance to flow and occupy minimum area to reduce the demand for land. The objective of the solar receiver is to increase the surface exposed to the sun for the microalgae capture a larger quantity of irradiance and perform the photosynthesis. Moreover, the pH of the culture is controlled by injection of pure CO_2 in this part of the process.

The bubble column is 3.25 m high and 0.5 m in diameter, with a capacity of 400 L, and several functions are performed on it. On one hand, it is used to realize the mixing of the culture and desorption of O_2 by a constant air flow rate of 140 L/min. On the other hand, it is used to add the nutrients by means of culture medium injections (see Table 1 for details about the composition of the culture medium), to harvest the produced biomass, and to control the culture temperature through an internal heat exchanger. The culture is continuously recirculated between the loop and the column at 1 m/s using a centrifugal pump located at the bottom of the column (see Fig. 2).

The pH, temperature, and dissolved oxygen are measured with Crison probes at several points of the solar receiver of the

Table 1
Composition of the culture medium used in the tubular photobioreactor.

Component	Concentration [mmol/L]
$Ca(NO_3)_2$	7.92
KH_2PO_3	2.45
$MgSO_4$	2.71
Fe-EDTA	4.8190×10^{-3}
Zn-EDTA	6.566×10^{-4}
Mn-EDTA	3.8647×10^{-3}
Cu-EDTA	2.829×10^{-4}
Mo	6.949×10^{-4}
B	2.15850×10^{-2}