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# Control of incident irradiance on a batch operated flat-plate photobioreactor

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## HIGHLIGHTS

- *Nannochloropsis oculata* was grown in a flat-plate photobioreactor (PBR) operated in batch mode.
- A model-free optimal search rapidly determined the optimum average fluence rate.
- Feed-forward inversion control continuously adjusted incident irradiance on the PBR.
- Controlling incident irradiance on PBRs enhanced productivity and reduced lag time.
- The procedure presented can be applied to any microorganism species or PBR design.

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## ABSTRACT

This study experimentally demonstrated a feed-forward inversion control scheme for maintaining an optimum incident irradiance on photobioreactors (PBRs) during batch cultivation. A data-based model-free optimization using quadratic fit was utilized to rapidly estimate the optimum average fluence rate set point value that rendered maximum microalgae growth rate. Then, the feed-forward inversion control scheme adjusted the incident irradiance with respect to the in-process measured mass concentration to maintain the optimum average fluence rate inside the PBR. Optimization of growth conditions with respect to light is of prime importance for increasing biomass and lipid productivity in microalgae cultivation. The present approach can rapidly identify the optimum average fluence rate for any given species, reduce the lag time, and increase the growth rate and productivity of microalgae. This was illustrated with *Nannochloropsis oculata* batch grown in a flat-plate PBR illuminated from both sides.


## 1. Introduction

Due to concerns over the environment and energy security, biofuels have been tipped as the next generation transportation fuel to replace gasoline and diesel derived from petroleum (IPPC, 2007). Production of first and second generation biofuels such as bioethanol from corn, soybean, sugarcane, and jatropha has been optimized and is currently profitable (Ferrell and Sarisky-Reed, 2010). However, it only accounts for 1% of the total transportation fuel production in the United States (Ferrell and Sarisky-Reed, 2010). Furthermore, it would be unsustainable if large quantities were produced (Chisti, 2007; Williams and Laurens, 2010; Ferrell and Sarisky-Reed, 2010; Chen et al., 2011a). Indeed, producing enough corn to displace 50% of the transportation fuel needs in the U.S. would require surface area eight times larger than the current U.S. arable land (Chisti, 2007; Jones and Mayfield, 2012). By contrast, estimates suggest that lipid producing microalgae would only require between 1 and 3% of the U.S. cropping area for the same outcome (Chisti, 2007). Consequently, microalgae are being considered for producing next-generation biofuels thanks to their large growth rate and large lipid content (Chisti, 2007; Williams and Laurens, 2010). However, despite its large photosynthetic efficiency, microalgae biodiesel remains approximately three times more expensive to produce than its petroleum counterpart (Jones and Mayfield, 2012). Chisti (2012) determined that the cost of production for biomass composed of 40 dry wt% lipids must be less than $0.50 for microalgal biodiesel to be economically competitive with $100 per barrel of crude oil. However, current estimates of dry biomass production costs range from $5 to $100 per kilogram (Chisti, 2012, 2013). Alternatively, Stephens et al. (2010) illustrated that biodiesel production by large-scale ($>500$ hectare), microalgae production systems may be profitable if they were also used

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for co-producing high-value products such as acid-hydrolyzed vegetable protein (HVP) or beta-carotene which can be sold for $600/kg.

Furthermore, the Energy Independence and Security Act of 2007 established the renewable fuel standards mandating 36 billion gallons of renewable biofuels to be blended with transportation fuels sold in the U.S. by year 2022 (Ferrell and Sarisky-Reed, 2010). At most 15 of the 36 billion gallons are expected to be bioethanol and the remainder is projected to come from microalgae-based biodiesel (Ferrell and Sarisky-Reed, 2010). Microalgae are also sought after for the high value chemicals and pharmaceuticals they can produce. For example, pigments such as astaxanthin and $\beta$-carotene are used as colorants or antioxidants in the food and pharmaceutical industries (Williams and Laurens, 2010). These secondary products have a much smaller market size. However, they command prices per mass three to four orders of magnitude larger than biodiesel (Williams and Laurens, 2010). In these different applications, identifying optimum growth conditions and increasing microalgae biomass productivity are essential.

Microalgae can be produced in large quantities in photobioreactors (PBRs) operated in batch or continuous mode. Batch cultivation is more widely used due to its simplicity and low cost (Chen et al., 2011b). Optimization of the light available to microorganisms in PBRs is a crucial aspect of biomass production and process productivity (Ferrell and Sarisky-Reed, 2010; Pilon et al., 2011; Carvalho et al., 2011; VanVooren et al., 2012; Pruvost and Cornet, 2012). Light is the energy source that enables these photosynthetic microorganisms to metabolize. Inadequate amount of light causes a decrease in growth and photosynthesis rates due to lack of energy necessary to fixate carbon. Similarly, exposing microalgae to excessively large irradiances causes photo-oxidative damage in photosystem II units. The cells continuously perform a damage repair cycle to repair the damaged photosystem II units (Baroli and Melis, 1996; Neidhardt et al., 1998). However, when the damage rate exceeds the repair rate, photoinhibition becomes apparent and the overall cell photosynthetic efficiency decreases (Baroli and Melis, 1996; Ke, 2001). Identifying the optimum level of irradiance required for maximum microalgae growth rate and maintaining an optimum fluence rate in the PBR throughout the growth phase are necessary to increase biomass productivity.

This study aims to develop a versatile and robust scheme to control the incident irradiance on PBRs for maximizing microalgae growth rate and biomass productivity. The method should be able to rapidly identify the optimum light conditions. It should also be applicable to any species and/or PBR without prior knowledge of the culture growth kinetics.

## 2. Background

### 2.1. Radiative transfer model

In order to predict the light intensity distribution in PBRs, it is necessary to solve the steady-state radiative transfer equation (RTE) in homogeneous absorbing, scattering, but non-emitting media given by (Modest, 2003)

$$\hat{s}\cdot\nabla I_\lambda = -\kappa_\lambda I_\lambda(\hat{r},\hat{s}) - \sigma_{s,\lambda} I_\lambda(\hat{r},\hat{s}) + \frac{\sigma_{s,\lambda}}{4\pi}\int_{4\pi} I_\lambda(\hat{r},\hat{s}_i)\Phi_\lambda(\hat{s}_i,\hat{s})\, d\Omega_i \tag{1}$$

where $I_\lambda(\hat{r},\hat{s})$ is the spectral radiation intensity in direction $\hat{s}$ at location $\hat{r}$ (in W/m$^2$ nm sr) while $\kappa_\lambda$ and $\sigma_{s,\lambda}$ are the absorption and single scattering coefficients (in 1/m), respectively. The scattering phase function $\Phi_\lambda(\hat{s}_i,\hat{s})$ represents the probability that radiation traveling in the solid angle $d\Omega_i$ around direction $\hat{s}_i$ will be scattered into the solid angle $d\Omega$ around direction $\hat{s}$. The local spectral fluence rate $G_\lambda(\hat{r})$ and the fluence rate $G_{PAR}(\hat{r})$ averaged over the photosynthetically active radiation (PAR) region, defined as the spectral region between 400 and 700 nm (McCree, 1981), at location $\hat{r}$ are defined, respectively, as (Modest, 2003)

$$G_\lambda(\hat{r}) = \int_{4\pi} I_\lambda(\hat{r},\hat{s})\, d\Omega \quad \text{and} \quad G_{PAR}(\hat{r}) = \int_{PAR} G_\lambda(\hat{r})\, d\lambda \tag{2}$$

Several methods of solution for the RTE exist (Pilon et al., 2011; Dauchet et al., 2013; Lee et al., 2014; Kong and Vigil, 2014). Pottier et al. (2005) derived an analytical solution to the one-dimensional RTE using the Schuster–Schwarzschild two-flux approximation in order to model light transfer through a well-mixed algal cultures in vertical flat-plate PBRs. The local spectral fluence rate $G_\lambda(z)$ in such PBRs with (i) normally incident light at $z=0$ and (ii) perfectly transmitting back wall at $z=L$ was given by Pottier et al. (2005) as

$$\frac{G_\lambda(z)}{G_{in,\lambda}} = 2\frac{(1+\alpha_\lambda)e^{\delta_\lambda X(L-z)} - (1-\alpha_\lambda)e^{-\delta_\lambda X(L-z)}}{(1+\alpha_\lambda)^2 e^{\delta_\lambda XL} - (1-\alpha_\lambda)^2 e^{-\delta_\lambda XL}} \tag{3}$$

where $G_{in,\lambda}$ is the spectral irradiance incident on the surface of the PBR. Here, $X$ is the dry mass concentration of microalgae (in kg/m$^3$) and $L$ is the PBR thickness (in m). The coefficients $\alpha_\lambda$ and $\delta_\lambda$ are expressed as (Pottier et al., 2005)

$$\alpha_\lambda = \sqrt{\frac{\overline{A}_{abs,\lambda}}{\overline{A}_{abs,\lambda} + 2b_\lambda \overline{S}_{sca,\lambda}}} \quad \text{and} \quad \delta_\lambda = \sqrt{\overline{A}_{abs,\lambda}(\overline{A}_{abs,\lambda} + 2b_\lambda \overline{S}_{sca,\lambda})} \tag{4}$$

where $\overline{A}_{abs,\lambda}$ and $\overline{S}_{sca,\lambda}$ (in m$^2$/kg) are the average mass absorption and scattering cross-sections of the microalgae suspension, respectively. They are related to the absorption and scattering coefficients by (Pilon et al., 2011)

$$\kappa_\lambda = \overline{A}_{abs,\lambda} X \quad \text{and} \quad \sigma_{s,\lambda} = \overline{S}_{sca,\lambda} X \tag{5}$$

In addition, $b_\lambda$ is the backward scattering fraction defined, for axisymmetric scattering, as (Cornet and Albiol, 2000; Pottier et al., 2005)

$$b_\lambda = \frac{1}{2}\int_{\pi/2}^{\pi} \Phi_\lambda(\theta)\sin\theta\, d\theta \tag{6}$$

where $\theta$ is the scattering angle between directions $\hat{s}_i$ and $\hat{s}$.

Similarly, the volume-averaged fluence rate $G_{ave}$ in a one-dimensional PBR of thickness $L$ over the PAR region can be estimated from the local spectral fluence rate as (Molina Grima et al., 1996; Acien Fernandez et al., 1997)

$$G_{ave} = \frac{1}{L}\int_0^L G_{PAR}(z)\, dz \tag{7}$$

### 2.2. Growth model

The time rate of change of the microorganism mass concentration $X(t)$ can be predicted by the exponential growth equation:

$$\frac{dX}{dt} = \mu X \tag{8}$$

where $\mu$ is the specific growth rate expressed in h$^{-1}$. Despite the presence of fluence rate gradient in the PBR, growth kinetics models often use the average fluence rate $G_{ave}$ (Sukenik et al., 1991; Molina Grima et al., 1996; Acien Fernandez et al., 1997; Chen et al., 2011b). This approach is valid for optically thin PBRs where the fluence rate does not significantly vary within the PBR (Fernandes et al., 2010; Lee et al., 2014; Kong and Vigil, 2014). A more general approach is to relate the growth rate $\mu(z)$ to the local fluence rate $G_{PAR}(z)$ and average it over the volume of the PBR (Cornet and Dussap, 2009; Murphy and Berberoğlu, 2011; Takache et al., 2012; Lee et al., 2014).

Finally, the daily volumetric productivity $P_v$ (in kg/m$^3$ day) and the daily areal productivity $P_A$ (in kg/m$^2$ day) of a PBR, defined as the average biomass produced daily per unit volume and per unit