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Parametric sensitivity analysis for temperature control in outdoor photobioreactors

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HIGHLIGHTS

- The impact on the broth temperature due the diffuse solar radiation received is low.
- The reactor distance between plates has a strong relation to the broth temperature.
- The reactor wall transmittance and shading have major influence on the temperature.

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ABSTRACT

In this study a critical analysis of input parameters on a model to describe the broth temperature in flat plate photobioreactors throughout the day is carried out in order to assess the effect of these parameters on the model. Using the design of experiment approach, variation of selected parameters was introduced and the influence of each parameter on the broth temperature was evaluated by a parametric sensitivity analysis. The results show that the major influence on the broth temperature is that from the reactor wall and the shading factor, both related to the direct and reflected solar irradiation. Other parameter which play an important role on the temperature is the distance between plates. This study provides information to improve the design and establish the most appropriate operating conditions for the cultivation of microalgae in outdoor systems.

1. Introduction

In order to achieve economic feasibility and sustainability in outdoor full scale production of microalgae, significant physiological and technological drawbacks must be overcome. Currently, commercial microalgal biomass production makes use of open outdoor systems such as an open pond mainly because of the lower cost of maintenance and construction. However, productivity can be greatly affected by high pH, salinity, weather changes (rains and intense solar irradiation), temperature and contamination in open pond systems (Brennan and Owende, 2010; Grima et al., 1999; Gutierrez et al., 2008), which results in low productivity in terms of kilograms of biomass per day. A suitable alternative for controlling these parameters and achieving higher productivity is enclosed photobioreactors (Chen et al., 2011; Jorquera et al., 2010). The main challenges for scaling-up biomass production in enclosed photobioreactors are not only limited to cost. In addition, the microalgae photosynthetic efficiency depends on the balance between light exposure and temperature, thus enclosed photobioreactors require maintenance of the culture medium within an optimal range of light exposure and temperature where biomass concentration can increase during the day.

Different enclosed photobioreactor designs have been developed. The main designs are vertical column, horizontal tubular and flat-plate. Every reactor design has advantages and disadvantages. Flat plate photobioreactors present higher biomass productivity and lower energy consumption compared to the other cultivation systems (Carvalho et al., 2006; Posten, 2009; Jorquera et al., 2010). For this reason the flat plate photobioreactor was chosen in this study.

It is necessary to model the heat balance to predict correctly the effects of temperature and irradiance in a scale-up of a photobioreactor. The first mechanistic model to describe the static behavior of the broth temperature was presented by Bechet et al., (2010). This model was developed for column photobioreactors and expresses the broth temperature as a function of location, ground surface, reactor geometry, light irradiance, air temperature and wind velocity parameters (Bechet et al., 2010). In process engineer-

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ing modeling, the evaluation of a model quality is often based on qualitative comparisons between simulation results and observed data. Although such an evaluation is useful, it does not provide an objective assessment of the individual effect of each parameter on the response of the model, which in this case the response is the broth temperature. It is known that the broth temperature in photobioreactors varies according the irradiation intensity and time of exposure that is converted into heat (Bechet et al., 2010; Zhang et al., 1999; Masojidek et al., 2003, 2009; Gutierrez et al., 2008), however, which parameters are the most effective in Bechet et al., (2010) mechanistic model with focus on temperature control must be evaluated.

Based on an adaptation of the mechanistic model proposed by Bechet et al., (2010) for flat plate bioreactors, the present work aims to investigate the interaction effect between the input parameters and the broth temperature by using a parametric sensitivity analysis.

2. Methods

The geometry of the photobioreactor on the mechanistic model proposed by Bechet et al., (2010) was changed from a column to a flat plate photobioreactor, however, the working volume was kept constant. The environmental conditions tested in the original model for validation, such as air temperature, wind velocity and sun irradiation also remained unchanged.

The parametric analysis of each parameters on the mechanistic model for broth temperature were performed according to the following steps: (1) test all input parameters presented in the model, (2) plan a factorial design to test the parameters, (3) run the model with different values for each parameter and collect the broth temperature data, (4) evaluate the effect of each parameter on the model response by statistical analysis, and (5) repeat the previous steps with the most influential parameters.

The equation that describes the heating balance in a photobioreactor yields (Bechet et al., 2010):

$$\rho_w V_r C p_w dT_r/dt = Q_A + Q_B + Q_C + Q_D + Q_E + Q_F + Q_G + Q_H + Q_J + Q_K + Q_L \quad (1)$$

where T_r is the reactor broth temperature (K); ρ_w and C_{pw} are the density (kg/m^3) and the specific heat capacity (J/kg/K) of water, respectively; V_r is the volume of the broth or reactor working volume (m^3); Q_A is the rate of heat transfer due the radiation from the reactor itself (W); Q_B is the rate of heat transfer due the direct solar radiation (W); Q_C is the rate of heat transfer due to diffuse solar radiation (W); Q_D is the rate of heat transfer due solar radiation reflected from the ground (W); Q_E is the rate of heat transfer due to radiation from the air surrounding the reactor (W); Q_F is the rate of heat transfer due to air radiation reflected from the ground (W); Q_G is the rate of heat transfer due to radiation from the ground (W); Q_H is the convective flux (W); Q_J is the rate of heat transfer due to the evaporation flux inside the reactor (W); Q_K is the rate of heat transfer from the air bubbles to the broth (W); and Q_L is the conductive flux with the ground surface at the base surface of the reactor (W). In this balance, the heat capacity of the reactor wall (in J/K) was considered negligible when compared to the heat capacity of the liquid phase.

The parameters and the constant variables tested for the factorial design and the respective levels of variables tested are listed in Table 1. All the heat flux described in Eq. (1) is a function of different input parameters to be evaluated, their relationship is presented in Table 2.

A factorial design (Mead, 1990) with all 15 parameters presented in the mechanistic model was carried out. Each parameter ranges at two levels on this factorial design. As there are 15 parameters being investigated a full factorial DOE requires 2^{15} or 32,768 test conditions. Because of the high number of tests a fractional factorial design of 2^8 or 128 test conditions was used. Then, the

Table 1
Parameters and constant variables and their respective values for DOE approach.

Definition	Parameter	Unit	Values tested
Ground surface constants	Ground reflectivity	–	0.20[a] and 0.50[b]
	Ground emissivity	–	0.80[a] and 0.95[b]
	Ground heat capacity	J/kg K	750[b] and 2400[a]
	Ground density	kg/m^3	2.4×10^3[a] and 4.0×10^3[b]
	Ground thickness	m	0.02[b] and 0.10[a]
	Ground conductivity	W/m K	1.0[b] and 2.0[a]
Photobioreactor constants	Wall transmittance	–	0.2 and 0.9
	Reactor emissivity	–	0.80[c] and 0.95[d]
	Wall conductivity	W/m K	0.2[e] and 1.05[f]
	Wall thickness	m	3.0×10^{-3} and 6.0×10^{-3}
	Air volume fraction as bubbles	m^3/s	1.3×10^{-4} and 6.67×10^{-6}
	Reactor height	m	1.0 and 3.0
	Reactor width	m	0.5 and 2.0
	Reactor distance between plates	m	0.05 and 0.2
	Shading factor	–	1.0 and 0.3
Water constants	Water density	kg/m^3	998
	Water heat capacity	J/kg K	4.18×10^3
	Water latent heat	J/kg	2.45×10^6
Air constants	Air emissivity	–	1
	Air conductivity	W/m K	2.63×10^{-2}
	Air heat capacity	J/kg K	2.0×10^3
	Air density	kg/m^3	1.20
	Atmospheric diffusion coefficient	–	0.20

[a] Clay soil.
[b] Concrete.
[c] Turbid water.
[d] Clean water.
[e] Glass.
[f] Acrylic.

Table 2
Description of the heat fluxes and their respective main input parameter to be tested.

Input parameters	Heat fluxes										
	Q_A	Q_B	Q_C	Q_D	Q_E	Q_F	Q_G	Q_H	Q_J	Q_K	Q_L
Ground reflectivity				x		x					
Ground emissivity				x			x				
Ground heat capacity							x				
Ground density							x				
Ground thickness							x				
Ground conductivity							x				
Wall transmittance	x	x	x	x	x	x	x				
Reactor emissivity	x	x	x	x	x	x	x				
Wall conductivity											x
Wall thickness											x
Air in flow rate									x	x	
Reactor height	x	x	x	x	x	x	x	x			x
Reactor width	x	x	x	x	x	x	x	x			x
Reactor distance between plates	x	x	x	x	x	x	x	x			x
Shading factor		x		x							

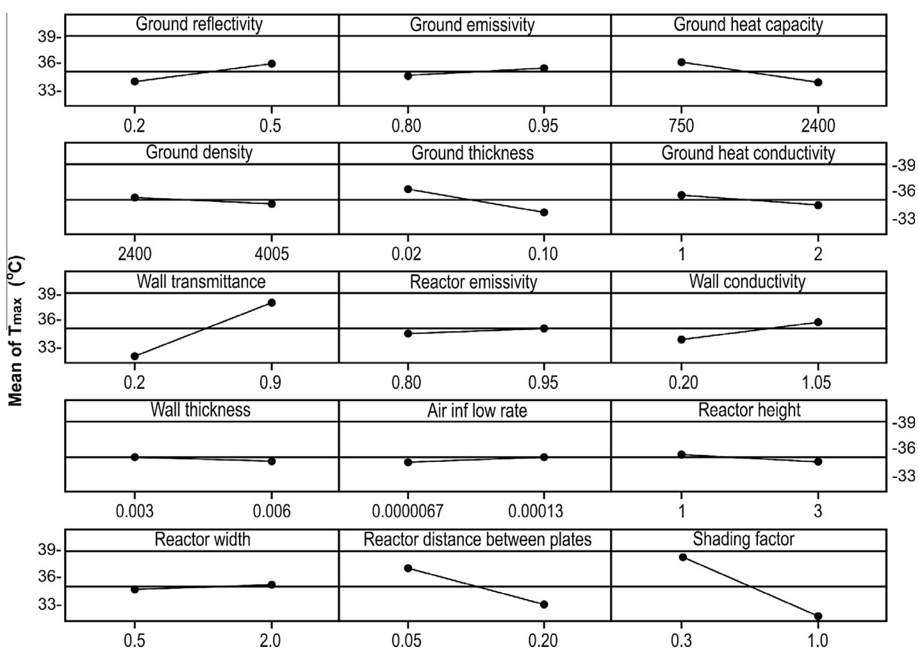

Fig. 1. Main effects on the broth temperature (T_{min} and T_{max}) from two-level factorial design.

analysis of variance ANOVA was used to evaluate the results of the simulation *i.e.* the broth temperature from each of the 128 test conditions.

3. Results and discussion

The results from ANOVA shows seven significant input parameters for evaluation with a P_{value} under 0.05: ground reflectivity, ground heat capacity, ground thickness, wall transmittance, wall conductivity, reactor distance between plates, shading factor. However, the wall transmittance of the reactor ($F_{transmittance}$ = 144,821), the distance between plates ($F_{distance\_plates}$ = 62,913) and the shading factor ($F_{shading}$ = 174,739) are the parameters that most affect the model, their F value is higher than the $F_{calculated}$ value (31,247). There is a negative correlation between the shading factor (−0.549) and the reactor distance between plates (−0.329) and the broth temperature, and a positive correlation with the reactor wall transmittance (0.499). The magnitude of the main effects from the simulation results is observed in Fig. 1 where the minimum and the maximum broth temperature (T_{min} and T_{max}, respectively) for each parameter are compared with the average temperature. The shading factor means the percentage of the

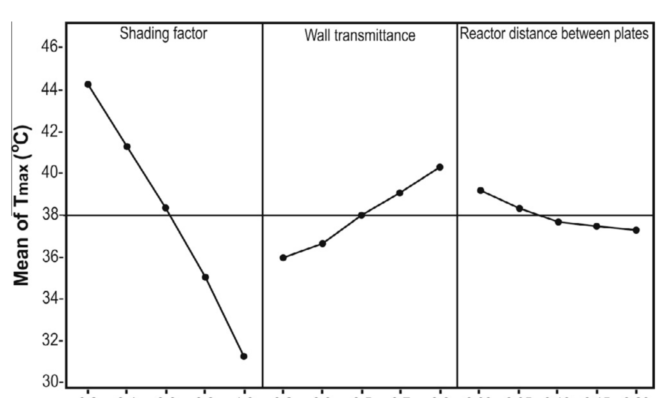

Fig. 2. Mean values for tested parameters and reactor maximum temperature.

photobioreactor protected from the irradiation where 0 means without shading and 1 means the reactor totally protected from the solar direct radiation. The wall transmittance has a similar effect, for low values of transmittance less irradiation reaches the photobioreactor.

An accurate analysis of the effect on the photobioreactor broth temperature of the parameters shading factor, reactor distance between plates and reactor wall transmittance was carried out by a five-level full factorial DOE. The ANOVA results for these selected parameters and their combination are significant, however, the shading factor seems to be the parameter which most affects the reactor broth temperature. The mean values for T_{max}, shading factor, reactor wall transmittance and distance between plates are presented in Fig. 2. The effect of shading in the model response can be clearly observed in the graph presented in Fig. 3a, where five different values for shading were tested and a mean value for reactor wall transmittance and distance between plates was set. The same analysis was made ranging reactor wall transmittance (Fig. 3b) and distance between plates (Fig. 3c) by fixing a mean value for the other two parameters.

The reactor temperature profile observed in Fig. 3a–c is similar. However, the amplitude for the shading curves is higher. Reducing the distance between the plates the broth temperature causes a variation in a shorter period of time during the day. A different result was described by Bechet et al., (2010) on the simulation of the column photobioreactor temperature profile, where the peak of predicted temperature decreases when reducing the reactor radius. This was explained by the increase in the forced convection in the column photobioreactor, however, it is not observed in a flat plate photobioreactor.

Another factor that should be taken into account is that the illuminated area for flat plate photobioreactors is higher when compared to tubular or column reactors. Also, there is a difference between the irradiation reaching the photobioreactor surface and the irradiation absorbed by the culture medium. The irradiation absorbed by the culture system depends of the biomass concentration, where more concentrated medium absorbed less radiation (Garcia-Malca et al., 2009; Feng et al., 2011). Generally, the specific growth rate (μ) increases with increasing irradiance, reaching a maximum value μ_{max} (Morita et al., 2001a,b). However, too much light may lead to photoinhibition resulting to lower specific growth rates (Feng et al., 2011; Satyanarayana et al., 2011).

The wall transmittance of the photobioreactor changes according to the raw material used in the plates. For different types of plastics the transmittance ranges from 0.90 to 0.80 (Coltro and Borghetti, 2007) a similar value is used for glass. The wall transmittance can be used as a parameter to block infrared light or limit light irradiance within a spectrum optimal for microalgae cultivation (photosynthetic active radiation PAR 400 to 700 nm).

The distance between the plates of the reactor is the only parameter related to the reactor geometry that is strongly related to temperature. This distance is directly proportional to the volume of the reactor and a lower temperature variation is observed for higher volumes. For flat plate photobioreactors the preferred distance between the plates is 0.10 m (Grima et al., 1999; Zhang et al., 1999). A minimum distance is required for the light–dark cycle of the microalgae and to avoid photoinhibition (Morita et al., 2001a,b; Yun and Park, 2003). Both affect the specific growth rate and, consequently, the biomass concentration.

According to Bechet et al., (2010) five heat fluxes are dominant in the heat mechanistic model: radiation from the reactor (Q_A), solar radiation (including direct (Q_B), diffuse (Q_C) and reflected radiations (Q_F)), radiation from the air (Q_D), radiation from the ground (Q_E), and convection (Q_H). However, in this study the solar

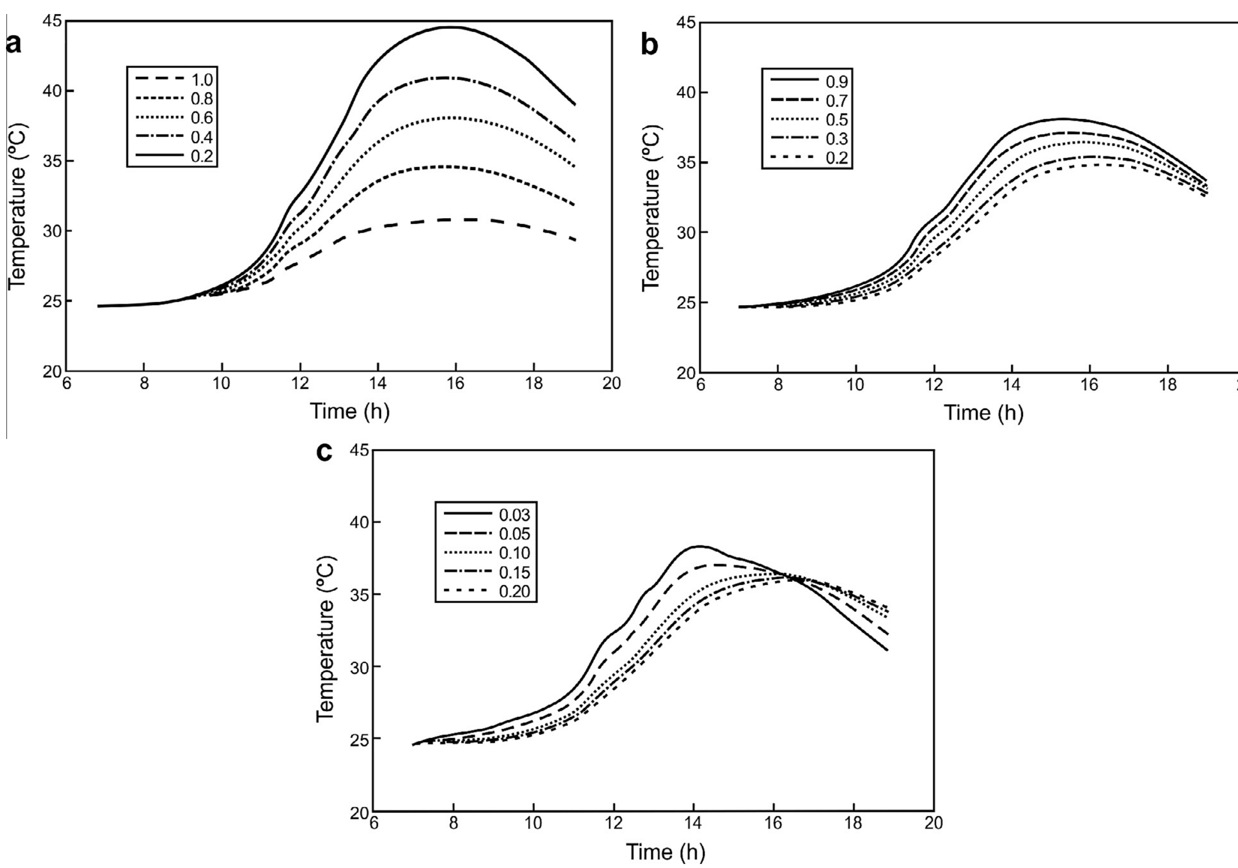

Fig. 3. Variation in the culture medium temperature for (a) shading factor range 0.2–1.0, (b) reactor wall transmittance range 0.2–0.9 and (c) reactor distance between plates ranges 0.03–0.2 m.

Table 3
Estimated values for the specific growth rate affected by the shading factor.

Microalgae species	Culture medium temp. (°C)	Maximum specific growth rate (1/d)	Shading factor	Irradiance reaching the reactor surface (W/m^2)	Estimated specific growth rate (1/d)	Reduction on the growth rate (%)
Chlorella sp.	40	5.76[a]	1.0	53	2.56	28
			0.8	106	4.20	17
			0.6	158	5.16	8
			0.4	211	5.63	2
			0.2	264	5.76	0

[a] Ho et al. (2011).

direct (Q_B) and reflected (Q_F) radiations have the major contribution on the broth temperature.

The shading factor is related to the total direct solar flux and the solar radiation reflected from the ground. This factor is used to describe when a physical element protects the reactor from the direct light irradiation. However, the shading factor not only has an effect on the reactor, but it also interacts with other parameters which describe the heat flux from the ground. This also has a secondary contribution to the broth temperature.

An analysis of the reduction in the specific growth rate by varying the percentage of irradiation reaching the reactor is presented in Table 3. The experimental specific growth rate observed for the microalgae *Chlorella* sp. at 40 °C is used to estimate the reduction in the growth rate for different shading values. In this calculation, the model for specific growth rate is described in Eq. (2):

$$\mu = exp(1 - 1/I_{max})x\mu_{max}xI/I_{max} \quad (2)$$

where μ is the specific growth rate (1/d); μ_{max} is the maximum value for growth rate (1/d); I is the average irradiance absorbed by the culture medium (W/m^2); and, I_{max} the maximum radiance reaching the reactor surface (W/m^2).

It is assumed that the average irradiance is totally absorbed by all the microalgae cells and the culture medium is distributed homogeneously and the value for μ_{max} without shading is equal to the experimental data. For I and I_{max} the data from the mechanistic model of Bechet et al., (2010) were used in all cases. Photoinhibition is disregarded in this model.

Comparing the expected values for specific growth rate and the experimental data obtained for μ_{max}, the highest reduction in this rate is observed when the photobioreactor is totally protected from the direct solar radiation, thus in this condition the microalgae growth is due only the reflected radiation. However, a lower specific growth rate may not results a decrease in productivity. Other factors must be taken into account such as temperature, biomass concentration, availability of nutrients, reactor fluid dynamics and geometry.

Other studies have evaluated the effect of temperature on the specific growth rate and the results show a reduction in biomass concentration when the temperature is above or below the range for optimal conditions (Goldman and Carpente, 1974; Zhang et al., 1999; Gutierrez et al., 2008; Feng et al., 2011; Bernard and Rémond, 2012). In the simple model developed by Bernard and Rémond (2012) to evaluate the effect of temperature and irradiance on microalgae growth it is observed that a small variation of temperature lead a significant decrease in the growth rate.

Most of commercial microalgae species have the optimal growth temperature below 35 °C, however, new thermo-tolerant species more adapted to extremes conditions such as the thermophilic specie *Desmodesmus* sp. has been studied. Huang et al., (2012) showed the viability to cultivate *Desmodesmus* sp. in tropical outdoor conditions with temperatures upto 46 °C and strong light irradiance up to 2600 μmol/m^2 s (Huang et al., 2012).

Temperature is a problem to be solved for any microalgae specie cultivated in large-scale outdoors conditions. To maintain high microalgal productivity on a large-scale production is necessary temperature control strategies that may represent higher costs and a considerable impact on the life cycle assessment of microalgal bioproducts. A detailed evaluation on the existing temperature models for microalgal production may lead to new strategies to optimized growth.

4. Conclusions

Limiting the irradiance reaching the reactor seems to be the best option to maintain the temperature range suitable for microalgae cultivation. However, it is necessary to understand and quantify the light and temperature dependence of microalgae growth and accumulation of valuable compounds such as lipids to design an efficient photobioreactor, predicting process productivity, optimizing operating systems and temperature control strategies for large-scale outdoor conditions.

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