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ARTICLE

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Indirect regulation of temperature in raceway reactors by optimal management of culture depth

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Abstract

Temperature and irradiance are the two most relevant factors determining the performance of microalgae cultures in open raceway reactors. Moreover, inadequate temperature strongly reduces the biomass productivity in these systems even if enough sunlight is available. Controlling the temperature in large open raceway reactors is considered unaffordable because of the large amount of energy required. This study presents an indirect method for temperature regulation in microalgae raceway reactors by optimizing the culture depth. First, the effect of the culture depth on the raceway temperature is analyzed for different seasons of the year. Afterward, a simulation study is presented where the proposed control approach is compared to the normal operation mode with constant volume in the reactor. This study is also extended to industrial scale. Relevant improvements on the temperature factor and biomass production are presented. The developed knowledge allows the improvement of the performance in open raceway reactors up to 12% without involving additional energy and costs, being a suitable solution for large industrial reactors that until now have no options for controlling the temperature.

KEYWORDS
biotechnology, microalgae, raceway reactor, temperature control, temperature model

1 | INTRODUCTION

The production of microalgae biomass is very important due to the properties of these microorganisms and the derived products that can be obtained from biomass. From the treatment of biomass, food (Wolfgang, 2004), products for the chemical industry (Hempel et al., 2012) or biofuel (del Rio-Chanona et al., 2018; Moody et al., 2014; Rodolfi et al., 2009) can be obtained. In addition, thanks to the photosynthesis process carried out by microalgae, their cultivation contributes to the mitigation of CO_2, or even to the treatment of wastewater (Acién et al., 2016).

Microalgae biomass production is carried out in photobioreactors, mainly divided into two types. On the one hand, closed photobioreactors allow precise control of operating conditions and are focused on high-value microalgae that are susceptible to contamination. On the other hand, open reactors are characterized by higher biomass production volumes and are oriented to resistant microalgae strains, since it is not possible to control all the variables that affect the microalgae growth. This second type of reactor is the most common one on an industrial scale due to its operation simplicity and its low maintenance costs (Oswald & Golueke, 1960; Weissman & Goebel, 1987).

The influence of temperature in a microalgae-based process in open photobioreactors is a crucial aspect, not only in biomass production but also in the choice of production areas, since it can negatively affect the crop when temperature exceeds certain

limits (Ras et al., 2013). Therefore, multiple results and studies can be found about the effect of temperature on growth rate and biomass production for algae and cyanobacteria (Singh & Singh, 2015). In Nalley et al. (2018), a study of the effect of temperature, ranging from 9°C to 32°C on growth rate and biomass production in a composition of 26 algae species from five different functional groups is presented. On the other hand, the effect of temperature on the microalgae *Tetraselmis* sp. is analyzed in Darvehei et al. (2018), where the effect of light is considered independent of temperature. The effect of high temperatures has been shown to be more detrimental to biomass production, as described in Béchet et al. (2017), where the impact of high temperatures on algae activity and viability is modeled.

It is possible to find multiple examples of models in the literature, where both the incident light in the reactor and its temperature are taken into account. One of these cases can be found in Béchet et al. (2013), where a review of the state of the art in this topic is carried out, exposing which are the most promising or viable models. In Barceló-Villalobos et al. (2019), the variations in culture conditions in an open thin-layer were studied, both in terms of position inside the reactor and time of the daylight cycle. A comprehensive model developed for microalgae growth in outdoor ponds under fluctuating light intensity and temperature conditions is presented in Huesemann et al. (2016). In Bernard and Rémond (2012), a simple model for the influence of light and temperature on the growth of algae is developed, estimating their production outdoors, based on the growth model presented in Camacho-Rubio et al. (2003). These models have been widely used to develop new biomass growth models (Solimeno et al., 2015). All these different models can be used as design tools coupled with production models, which allow the estimation of the process behavior based on environmental conditions. Moreover, these models can be used to determine the suitability of a certain area for the production of microalgae biomass.

Despite the fact that the influence of temperature on the outdoor production of biomass is widely analyzed and studied in the literature, temperature control techniques are scarce (Guzmán et al., 2020). In Waller et al. (2012), a particular design of the reactor is proposed to minimize the diurnal and seasonal temperature fluctuations, but based on an unconventional design and adapted to a specific area of Arizona. On the other hand, recently, in Ryu et al. (2019), a heat exchanger based on wasted heat from flue gases is proposed to heat the reactor volume up for temperature regulation purposes. However, although this solution is available from a technical point of view, it requires a complex and expensive installation. Moreover, the proposed system does not allow cooling of the reactor, being a critical aspect for the cultivation of microalgae in warm areas. One of the most interesting techniques is presented in De-Luca et al. (2016), where an optimization strategy is used based on a microalgae productivity prediction model together with weather forecasts. In this study, the fresh medium injection and culture removal rates are controlled to maintain the biomass concentration and pond temperature at their optimal values at two locations in France. Later, this strategy was used in De-Luca et al. (2017) to analyze the improvement in productivity in the operation of the reactor.

It appears that there is a lack of solutions for the temperature regulation problem in raceway reactors, where the tradeoff between efficiency and profitability is managed. So, this study presents a simple method for temperature regulation by varying the volume in the reactor throughout the daytime period, in a similar way as the strategies presented in De-Luca et al. (2016, 2017). The core idea is based on the influence of the atmospheric conditions and the culture depth on the reactor temperature. A culture depth optimizer has been designed to determine the culture depth variation that minimizes the difference between the reactor temperature and the desired optimal value. The control of the culture depth in the reactor is carried out by means of the harvesting and dilution processes, being a method that does not require the use or installation of new devices for cooling or heating the reactor medium. However, differently from the strategy presented by De-Luca et al., where harvesting and dilution are done at the same time with their corresponding flows variable, in the approach presented in this paper these processes are not simultaneous, that is, if the dilution process is active, no harvest is performed, and vice versa. An appreciable difference between both approaches resides in the calculation of dilution rates, in this case being fixed and established based on operation experience and dependent on the season of the year. On the other hand, a different cost function is used, where in this approach the culture depth is selected as the decision variable instead of the flow rates. The optimization approach is carried out taking into account the values of the environmental conditions at each moment, without making use of weather forecast. In this way, and using a small optimization time, it is possible to improve the computational cost considerably, without affecting the performance to a great extent. By applying certain constraints in the optimizer, satisfactory results have been obtained in terms of modifying the reactor temperature aimed at increasing the biomass production. A simulation study has been performed for different seasons of the year to show the advantages of the proposed approach, in comparison with a normal operation with constant volume.

The article is organized as follows. Section 2 presents the reactor that was used to collect the real data and to validate the models. Moreover, the temperature model for raceway reactors and the microalgae growth model are briefly described. In Section 3, the description of the culture depth optimizer and the results obtained are presented, along with a comparison with the normal reactor operation by using constant volume along the day and a simulation of an industrial scale raceway reactor. Finally, Section 4 states the conclusions and future works.

2 | MATERIALS AND METHODS

This section collects detailed information about reactor dimensions, the raceway reactor temperature model and the microalgae specific growth rate model.

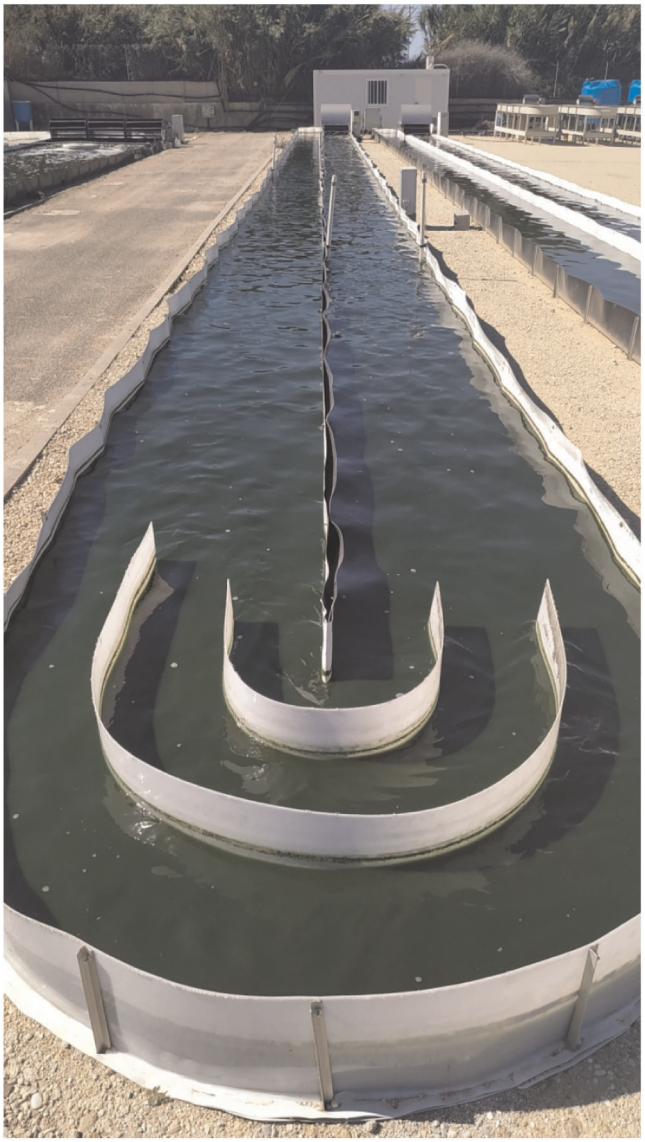

FIGURE 1 Raceway reactor [Color figure can be viewed at wileyonlinelibrary.com]

2.1 | Raceway reactor

As a base model, this study takes into account the dimensions of a raceway reactor (Figure 1) located at the "IFAPA" research center, next to the University of Almería (Almería, Spain). The reactor has a total surface of 80 m^2 and is composed of two 80 m long channels, connected by a 1 m wide U-shaped bends. The channel walls are made of low-density polyethylene of 3 mm thickness while the curves and sump walls are made of high-density polyethylene of 3 mm thickness. The mixing of the culture inside the reactor is made by a paddlewheel of aluminum blades with a diameter of 1.5 m, driven by an electric motor (W12 35 kW, 1500 rpm; Ebarba), with gear reduction (WEB Ibérica). The control of the paddlewheel is performed with a frequency inverter (CFW 08 WEB Ibérica) at a constant velocity of 0.2 m/s. Carbonation is performed inside a sump located 1.8 m downstream of the paddlewheel, which dimensions are 1.0 m depth, 0.65 m length and 1.0 m width. In this sump, CO_2 gas or air can be injected through three plate membrane diffusers at the bottom of the sump (AFD 270; EcoTec).

TABLE 1 Measuring sensors

Measure	Model
Wind speed	Anemometer Thies Clima 4.3400.30.000
Global solar irradiance	Pyranometer Kipp & Zonen CM 6B
Ambient temperature	Sensor Delta Ohm HD 9008TRR
Relative humidity	Sensor Delta Ohm HD 9008TRR

The measurements of the climatic conditions are obtained from a meteorological station, where Table 1 shows the model of the sensors for the measurable variables, which represent the inputs to the temperature model. The sampling period for the measurements is one second.

2.2 | Microalgae strain

The microalgae strain used in the reactor corresponds to *Scenedesmus almeriensis* (CCAP 276/24) species. A detailed study about its characteristic parameters and conditions related to pH, dissolved oxygen and temperature can be found in Barceló-Villalobos et al. (2019). The pH value ranges from 3 up to 10, but the net photosynthesis rate is close to the maximal value around 8. Regarding the temperature, the value ranges from 12 to 46 °C, but the optimum range is around 30°C. The culture medium used in the growth of the microalgae has been freshwater and Mann & Myers medium prepared using fertilizers ($0.14 g L^{-1} K(PO_4)_2$, $0.18 g L^{-1} Mg(SO_4)_2$, $0.9 g L^{-1} NaNO_3$, $0.02 ml L^{-1}$ Welgro, and $0.02 g L^{-1}$ kalentol) as in Fernández et al. (2012).

2.3 | Temperature estimation model

The temperature model used in this paper is based on the model described by Béchet et al. (2011), and applied to a raceway reactor in Rodríguez-Miranda et al. (2020), where the complete model is described and validated. The temperature is calculated from a thermal balance in the reactor, in such a way that the temperature of the medium can be estimated from a series of environmental input variables that are solar irradiance, ambient temperature, relative humidity and wind speed. Other input variables are culture depth and soil temperature, which can be easily estimated or approximated, instead of measured. Extensive data were used to validate the model in a wide range of temperature conditions.

As shown in Rodríguez-Miranda et al. (2020), the dynamic evolution of temperature is obtained from the reactor thermal balance in equilibrium, represented with the following equation:

$$\frac{dT_w}{dt} = \frac{\begin{array}{c} Q_{irradiance} + Q_{radiation} + Q_{evaporation} + Q_{convection} \\ + Q_{conduction} + Q_{inlet} - Q_{outlet} \end{array}}{h \cdot A \cdot C_p \cdot \rho}, \quad (1)$$

where T_w (°C) is the temperature of the culture in the reactor, h (m) represents the culture depth, A (m^2) is the surface of the reactor, C_p ($J\,kg^{-1}\,°C^{-1}$) is the specific heat capacity of the culture, ρ ($kg\,m^{-3}$) is the density of the culture, $Q_{irradiance}$ (W) represents the heat flow from sunlight, $Q_{radiation}$ (W) is the heat flow from long-wave radiation, $Q_{evaporation}$ (W) shows the heat flow produced by the evaporation process in the reactor, $Q_{convection}$ (W) is the heat flow caused by convection, $Q_{conduction}$ (W) represents the heat flow between the reactor and the layer under it through the conduction process, Q_{inlet} (W) is the heat that is added when new medium is supplied to the reactor, and Q_{outlet} (W) is the heat that is subtracted when medium is removed from the reactor during harvesting.

Through the model described and initial temperature conditions, it is possible to estimate the temperature in the raceway reactor over time. As can be seen in Equation (1), the temperature depends on culture depth. Thus, the culture depth can be modified to adjust the temperature in a range close to the optimum delimited by the microalgae strain such as will be shown in this paper.

For the calculation of the inlet medium heat flux in the reactor, the temperature model (1) has been used to estimate the temperature of a reservoir of 100 m^3. In this way, the temperature variation that the input medium may suffer throughout the day can be accurately estimated. Normally, this value is taken fixed, as in De-Luca et al. (2016, 2017), commonly as the average temperature of the day. However, this parameter is very important in the optimizer and greatly affects the reactor temperature when dilution occurs. Thanks to the estimation using the model, both the temperature of the culture and of the inlet medium can be taken into account.

2.4 | Microalgae growth rate model

The microalgae growth rate model has been used extensively in literature (Barceló-Villalobos et al., 2019; Bernard & Rémond, 2012; Camacho-Rubio et al., 2003) and was formulated in Solimeno et al. (2015). This model states that the microalgae growth rate, μ, is made up of four factors that depend on solar radiation (I_{av}), culture temperature (T_w), the pH, and the dissolved oxygen (DO) in the reactor. The growth rate model is described by the following equation:

$$\mu = \mu(I_{av}) \cdot \bar{\mu}(T_w) \cdot \bar{\mu}(\mathrm{pH}) \cdot \bar{\mu}(\mathrm{DO}). \quad (2)$$

The factors of temperature, pH and dissolved oxygen are dimensionless and the overline indicates that are normalized and vary between 0 and 1. Therefore, the maximum productivity is determined by the solar radiation factor, when the rest of the factors have a unit value. The biomass growth rate depending on solar irradiance (Molina-Grima et al., 1994) is calculated as follows:

$$\mu(I_{av}) = \mu_{max} \cdot \left(\frac{{I_{av}}^n}{I_k^n + {I_{av}}^n} \right), \quad (3)$$

where μ_{max} (day^{-1}) is the maximum microalgae growth rate, I_k ($\mu E\,m^{-2}\,s^{-1}$) is the irradiance requested to achieve half of the maximal growth rate or photosynthesis rate, n (−) is a form parameter and I_{av} ($\mu E\,m^{-2}\,s^{-1}$) is the average irradiance (Molina-Grima et al., 1994) that can be calculated at each time instant according to the following equation:

$$I_{av} = \frac{I_0}{K_a \cdot C_b \cdot h}(1 - e^{-K_a \cdot C_b \cdot h}), \quad (4)$$

where I_0 ($\mu E\,m^{-2}\,s^{-1}$) is the solar irradiance on an horizontal surface, K_a ($m^2\,g^{-1}$) is the microalgae extinction coefficient, C_b ($g\,m^{-3}$) is the microalgae biomass concentration and h (m) is the culture depth in the reactor.

Table 2 contains the values of the characteristic parameters for the microalgae strain *Scenedesmus almeriensis* used in this study. These parameters have been obtained based on normal operation of the reactor with a fixed culture depth of 15 cm.

As commented above, the rest of the factors in Equation (2) are normalized factors that affect $\mu(I_{av})$. The temperature factor $\bar{\mu}(T_w)$, developed by Bernard and Rémond (2012) and validated with extensive data, shows a cardinal model that represents the influence of the culture temperature on the microalgae growth rate. The temperature factor can be obtained from the following equation:

$$\bar{\mu}(T) = \frac{(T - T_{max}) \cdot (T - T_{min})^2}{\begin{array}{l} (T_{opt} - T_{min}) \cdot ((T_{opt} - T_{min}) \cdot (T - T_{opt}) - (T_{opt} - T_{max}) \\ \cdot (T_{opt} + T_{min} - 2 \cdot T)) \end{array}}. \quad (5)$$

Similarly, the pH factor $\bar{\mu}(\mathrm{pH})$ represents the influence of the pH in the culture on the growth rate and can be calculated as follows:

$$\bar{\mu}(\mathrm{pH}) = \frac{(\mathrm{pH} - \mathrm{pH}_{max}) \cdot (\mathrm{pH} - \mathrm{pH}_{min})^2}{\begin{array}{l} (\mathrm{pH}_{opt} - \mathrm{pH}_{min}) \cdot ((\mathrm{pH}_{opt} - \mathrm{pH}_{min}) \cdot (\mathrm{pH} - \mathrm{pH}_{opt}) \\ - (\mathrm{pH}_{opt} - \mathrm{pH}_{max}) \cdot (\mathrm{pH}_{opt} + \mathrm{pH}_{min} - 2 \cdot \mathrm{pH})) \end{array}}. \quad (6)$$

The dissolved oxygen factor $\bar{\mu}(\mathrm{DO})$ represents the influence of dissolved oxygen on the culture and depends only on a maximum value, which is detrimental to growth if exceeded. It can be expressed as follows:

TABLE 2 Characteristic parameters of the microalgae strain *Scenedesmus almeriensis*

Parameter	Value	Unit
μ_{max}	0.9	day^{-1}
I_k	120	$\mu E m^{-2} s^{-1}$
n	2	–
K_a	0.08	$m^2 g^{-1}$

TABLE 3 Minimum, maximum, and optimum values for the main variables

Variables	Minimum	Optimum	Maximum	Unit
Temperature (T_{min}, T_{opt}, T_{max})	12	30	46	℃
pH (pH_{min}, pH_{opt}, pH_{max})	3	8	10	–
Dissolved oxygen (DO_{2max})	–	–	300	%

$$\bar{\mu}(\mathrm{DO}) = 1 - \left(\frac{\mathrm{DO}_2}{\mathrm{DO}_{2\mathrm{max}}}\right)^m, \tag{7}$$

The maximum, minimum, and optimum values depend on microalgae strain analysis and are shown in Table 3 (Barceló-Villalobos et al., 2019).

To show better the temperature effect on the process productivity, it is assumed that the pH and the dissolved oxygen variables are perfectly controlled (Pawlowski et al., 2015) and thus the corresponding factors described by (6) and (7) are considered equal to one. In this way, the oxygen productivity model only depends on solar radiation and temperature.

The objective of this study is to improve the biomass productivity (P_b), which represents the amount of biomass that can be obtained per unit of surface per day. This value will be taken as a reference when evaluating the results and its calculation is expressed by the following formula:

$$P_b = C_b \cdot h \cdot \mu, \tag{8}$$

where P_b (g m^{-2} day^{-1}) is the microalgae biomass productivity.

3 | RESULTS AND DISCUSSION

This section presents the temperature regulation approach based on changes on the liquid volume in the reactor, and its comparison with a fixed culture depth solution. First, the effect of the culture depth on the biomass productivity is analyzed by using the model presented in the previous section. Afterward, the proposed control approach to regulate the temperature is proposed and a detailed simulation study is presented using real environmental data gathered at the reactor location. It is important to mention that changes in water depth also modifies the light availability inside the reactor, being this effect also taken into account during the analysis.

3.1 | Culture depth effect on the medium temperature

As commented above, pH and dissolved oxygen are assumed to be at the optimal values all the time. This is possible if adequate design and operation of the reactor is performed (Barceló-Villalobos et al., 2018; de Godos et al., 2014; Mendoza et al., 2013, 2013). Therefore, in this study, the growth rate only depends on the solar radiation, which cannot be controlled, and on the reactor temperature, which can be modified in different ways such as discussed in Section 1. In this study, temperature will be changed by varying the volume of the medium in the reactor.

As a first stage, the effect of the culture depth variation on the reactor temperature is analyzed. Figures 2 and 3 show the variations of the reactor temperature as a result of Equation (1), the normalized

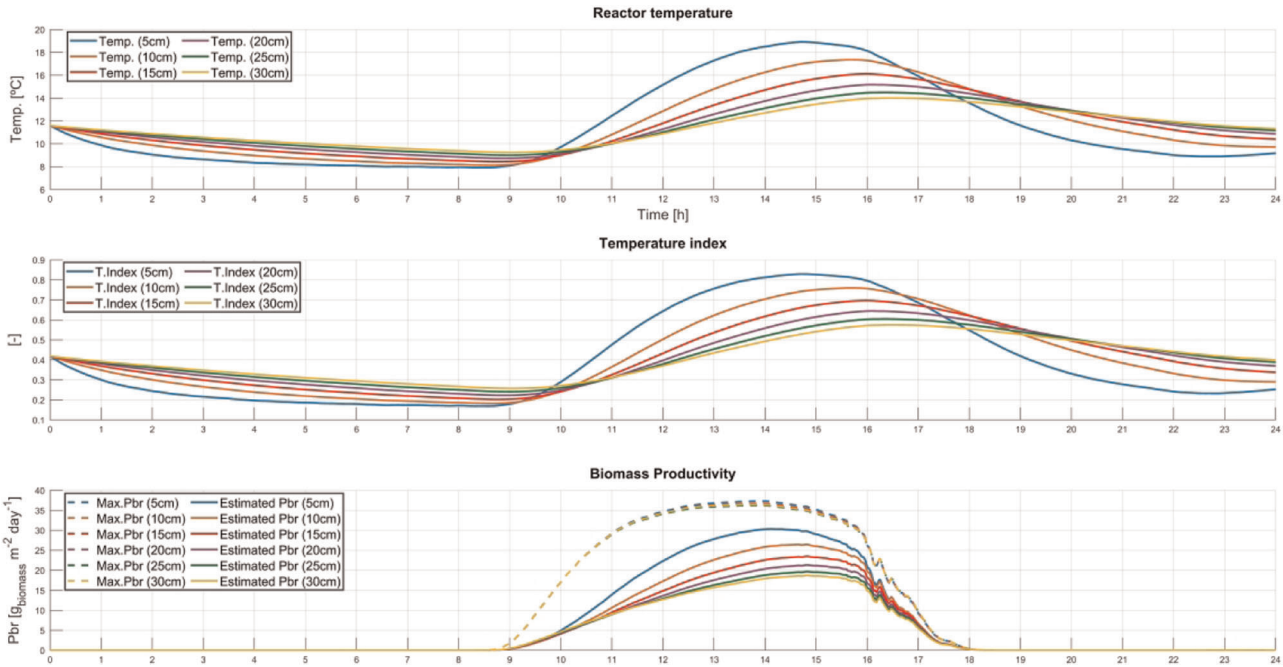

FIGURE 2 Temperature and biomass productivity differences by liquid depth on January. *Pbr*. referes to the biomass productivity, *T. index* to the temperature factor represented by Equation (5) and *Temp*. to the reactor temperature by Equation (1) [Color figure can be viewed at wileyonlinelibrary.com]

temperature factor from Equation (5), and the biomass productivity from Equation (2) for different culture depths and for winter and summer seasons, respectively. The culture depth was varied from 5 to 30 cm. As observed, the microalgae growth is highly affected based on the culture depth modifications. In the figures, the maximum biomass productivity when all cardinal factors for pH, dissolved oxygen and temperature are equal to one in Equation (2) is represented by the dashed line. On the other hand, the estimated productivity by modifying the temperature factor according to the culture depth variations and keeping the pH and dissolved oxygen factors equal to one is represented by solid lines. Table 4 shows the initial biomass concentration used for each case, where these values represent the optimal biomass concentration to operate a microalgae raceway reactor in continuous mode. The biomass concentration represents the grams of biomass for each liter of medium in the reactor.

Figure 2 represents one day of January, as representative of the winter season. The maximum temperature profile is reached with a culture depth of 5 cm, being the closest to the optimum temperature (30 ℃ such as described in Table 3). In this way, with this culture depth, the maximum value is reached during the daytime period for the temperature model index and, therefore, the highest value of growth rate. On the contrary, a culture depth of 30 cm maintains a temperature profile with less amplitude, reaching the lowest temperature value during the daytime period, decreasing the temperature index and, therefore, the growth rate.

Figure 3 represents one day of August, as representative of the summer season. Unlike Figure 2, in this case, the maximum temperature profile, which occurs also with a culture depth of 5 cm, has a temperature value above the optimal growth value. For this reason, the temperature index in this case is the lowest one, causing a decrease in the growth rate. On the other hand, a culture depth of 30 cm keeps a lower temperature profile, with values closer to the optimal value, increasing so the temperature index and the growth rate.

These figures demonstrate how the culture depth affects the reactor temperature and, consequently, the growth rate. The maximum and minimum values depend on the season, but they can be modified in a range by changing the culture depth in the reactor. Thus, the objective of this study is to modify the volume of the medium in the reactor during the daytime period to regulate its temperature and maximize the temperature index in the growth rate model.

TABLE 4 Initial biomass concentration for each culture depth

	Biomass concentration (g L^{-1})	
Level (cm)	January	August
5	0.97	2.25
10	0.48	1.12
15	0.32	0.75
20	0.24	0.56
25	0.19	0.45
30	0.16	0.37

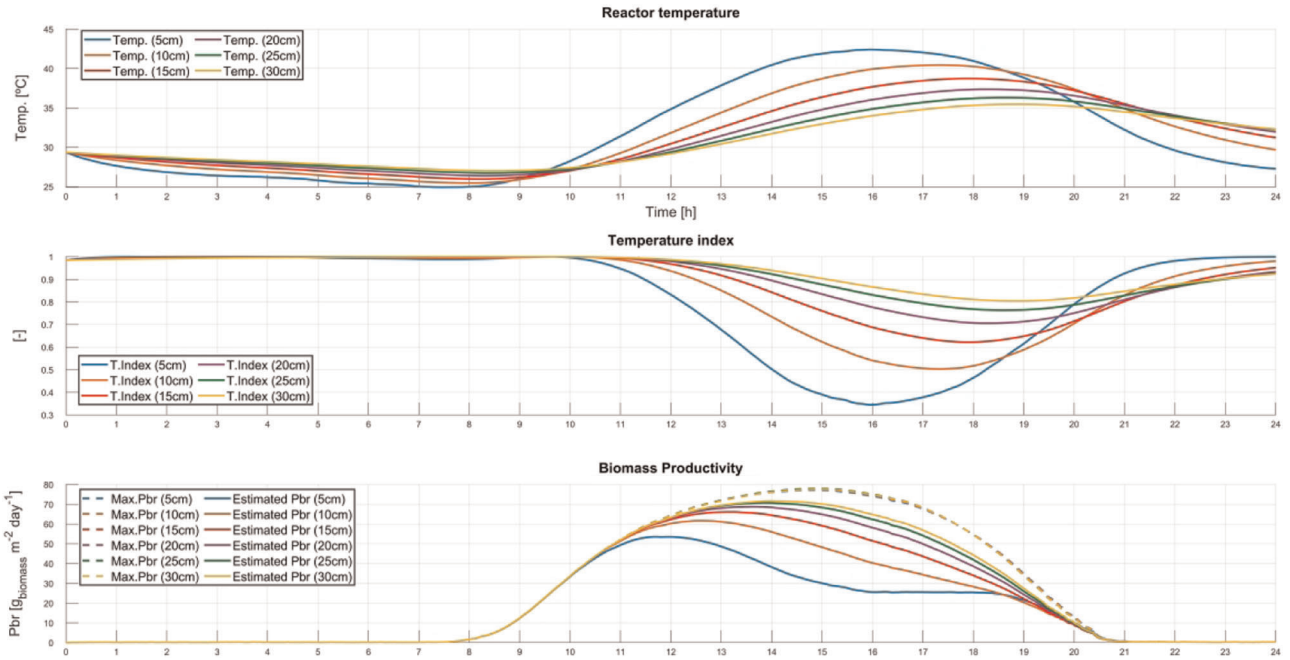

FIGURE 3 Temperature and biomass productivity differences by liquid depth on August. *Pbr*. referes to the biomass productivity, *T. index* to the temperature factor represented by Equation (5) and *Temp.* to the reactor temperature by Equation (1) [Color figure can be viewed at wileyonlinelibrary.com]

3.2 | Culture depth optimization

In the temperature regulation problem for microalgae production, the objective is to keep the medium temperature T_w as close as possible to the optimum strain temperature $T_{optimum}$. In this way, the normalized temperature factor given by Equation (5) will be increased and thus the biomass productivity will be maximized. Therefore, the optimization problem proposed in this study is given by the following equation:

(9)

subject to:

$$\frac{dT_w(t)}{dt} = \frac{Q_{total}(t)}{h(t)\cdot A\cdot C_p\cdot \rho}, \tag{10}$$

$$h_{min} \le h(t) \le h_{max}, \tag{11}$$

$$-\Delta h_{max} \le \Delta h(t) \le \Delta h_{max}, \tag{12}$$

$$T_{min} \le T_w(t) \le T_{max}, \tag{13}$$

where Q_{total} is the sum of all heat terms in the right part of Equation (1). On the other hand, the culture depth should be limited to avoid overestimated harvesting or dilutions. Therefore, minimum (h_{min}) and maximum (h_{max}) culture depth values are included in the optimizer based on the dilution parameter (the % of volume that can be added or removed from the reactor so that the biomass concentration is the same as at the beginning of the day) and on the variation in reactor volume. Likewise, to avoid sudden changes in the culture depth, a maximum increment (Δh_{max}) of 0.5 cm on the depth has been established for each iteration of the optimizer, performed with a period of half an hour. Finally, the reactor temperature is limited between T_{min} and T_{max} values that are determined by the characteristics of the microalgae strain (see Table 3) to avoid a detrimental effect on the microalgae growth.

The culture depth adjustment in the reactor is carried out from the removal of volume by means of a harvesting pump or the injection of water from a reservoir (with a temperature lower than the reactor one) from a dilution pump. Harvesting and dilution processes are typically employed in the daily raceway operation. The harvesting consists in the extraction of liquid from the reactor and its storage in a tank, for the subsequent treatment of the microalgae biomass. On the other hand, the dilution process consists in replenishing the harvested liquid by injecting fresh medium with nutrients into the reactor, coming from a reservoir. Commonly, these processes are carried out in the morning, one after the other, but by means of the optimizer it is possible to choose the optimal time to carry them out to vary the temperature in the reactor, and thus improving the biomass productivity.

The proposed control architecture consists of two layers. An upper layer, with a sampling period of 30 min, where the optimizer presented by Equation (9) calculates the optimal culture depth set-point according to the proposed cost function. In the lower layer, a culture depth control is carried out by means of the harvesting and dilution pumps, with a sampling period of 1 s. These sampling periods have been chosen in the simulation study to represent the behavior of a physical pump and to avoid instantaneous changes in the volume of the reactor. However, it is possible to modify the sampling period to represent different scenarios, such as changes in the set-point less than half-hour or greater.

3.3 | Simulation study

For the study, the models described in Sections 2.3 and 2.4 were used as simulators, in addition to real environmental data. Such as described above, with the proposed culture depth optimizer, it is possible to determine a set-point for the culture depth in the reactor to modify the temperature value and maximize the growth rate of the microalgae. Thus, in this study, the aim is to compare the temperature and the growth of the microalgae using the culture depth optimizer contrasted with the normal operation of a reactor with a fixed culture depth of 15 cm. The simulation tests represent a day in January (winter) and a day in August (summer), to establish the differences between two seasons where the temperature reaches its maximum and minimum values.

For the different seasons, initial biomass concentration of 0.32 ($g\,L^{-1}$) during winter and 0.75 for summer have been used. In addition, a dilution of 8% has been set for the winter period and 23% for the summer period. In winter, due to the low temperature and low growth rate of the microalgae, the biomass concentration is lower, as well as its dilution. On the other hand, summer is the period of greatest growth of the microalgae, with a higher concentration of biomass and the maximum annual dilution value.

Two initial tests were carried out in which no dilution or harvest restrictions were taken into account in the reactor. For these tests, culture depth regulation limits have been established between 5 and 30 cm. Figures 4 and 5 show the results of the tests without restrictions.

The normal operation of the reactor (represented in red) is carried out in continuous mode, harvesting microalgae every day, but keeping the volume at a constant value. When harvesting occurs (at the same time every morning), culture is removed from the reactor while fresh medium is added at the same time, so that the volume of the reactor is kept constant.

Figure 4 represents the results obtained without restrictions for a day in January. The red and dashed curves represent the normal operation of a reactor with a fixed culture depth of 15 cm. On the other hand, the blue curves represent the results obtained by regulating the culture depth of the reactor by using the proposed approach. Figure 4f represents biomass productivity, being 56% lower with culture depth regulation compared to normal operation due to low culture depth during the daytime period. In contrast, Figure 4a shows the temperature in the reactor for both cases, being higher in the case of the regulated culture depth. As a result of the culture depth regulation, the temperature in the reactor is higher than in normal operation, getting closer to the optimum value. As the temperature is at a maximum value closer to the optimum,

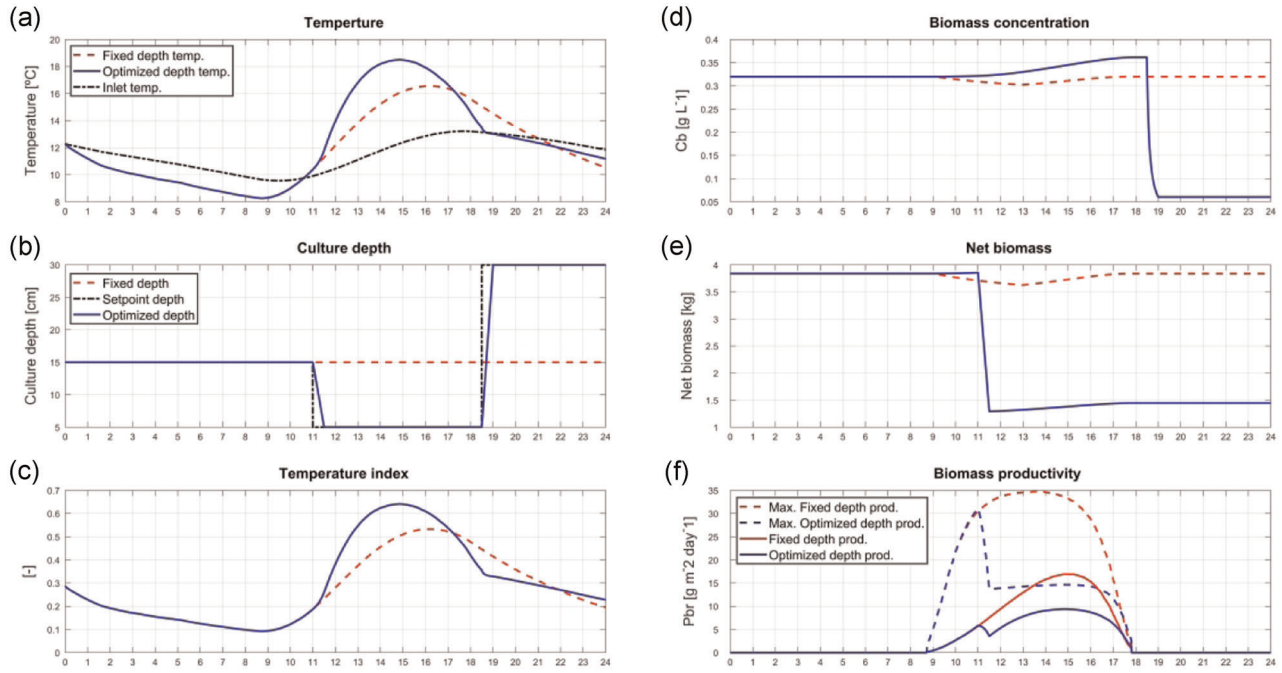

FIGURE 4 Biomass productivity comparison without constraints in one day of January. Red dashed lines represent the results for normal reactor operation (fixed depth), while the solid blue lines represent the results applying the culture depth optimizer [Color figure can be viewed at wileyonlinelibrary.com]

the temperature factor represented in Figure 4c increases during the daytime period by 21% more than the temperature factor with fixed culture depth. Figure 4b shows the culture depth in the reactor throughout the day. A lower culture depth allows an increase in the temperature of the reactor. Therefore, during the daytime period, the culture depth in the reactor is at the minimum possible culture depth value (5 cm), allowing an increase in temperature with respect to the fixed culture depth operation. The culture depth optimizer

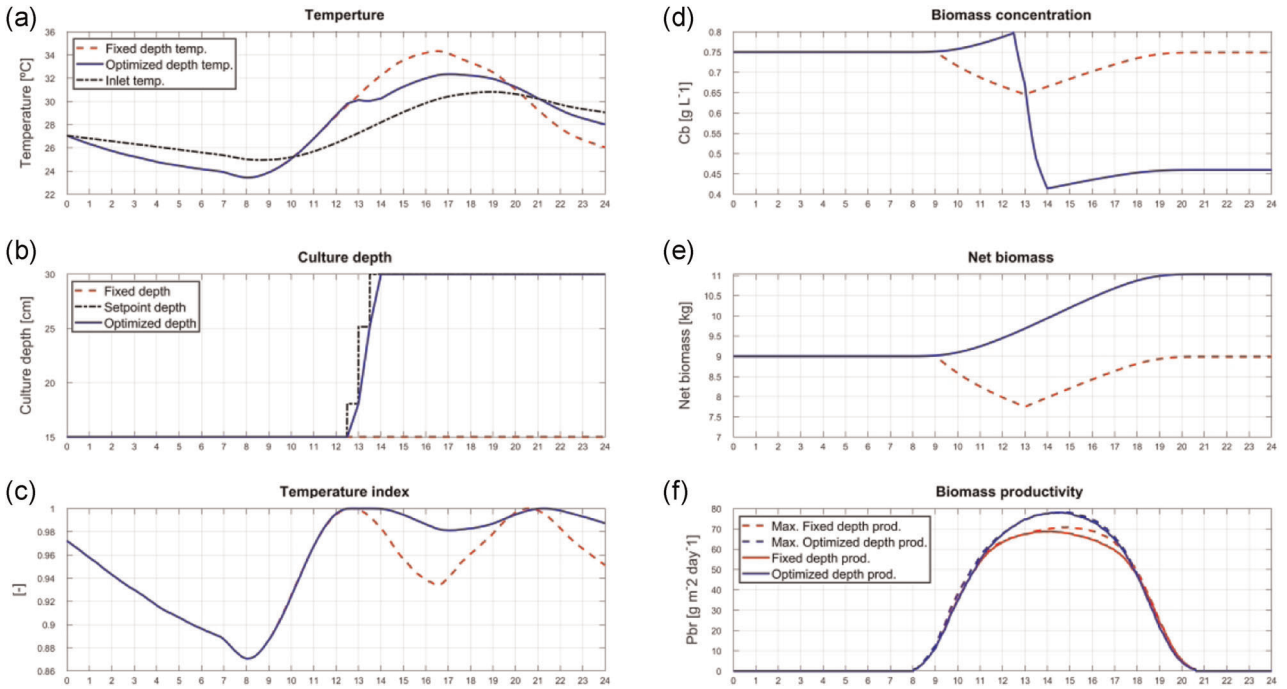

FIGURE 5 Biomass productivity comparison without constraints in one day of August. Red dashed lines represent the results for normal reactor operation (fixed depth), while the solid blue lines represent the results applying the culture depth optimizer [Color figure can be viewed at wileyonlinelibrary.com]

takes into account the temperature of the medium that is added to the reactor, so in this case, since the temperature of the medium is less than the temperature of the reactor, no medium (increase in culture depth) is added to maintain the reactor temperature closest to the optimum value. Figure 4e represents the net biomass, while Figure 4d shows the biomass concentration in the reactor. Since there are no restrictions on the dilution and harvesting of the reactor, the biomass values in the reactor decrease drastically, thus decreasing biomass productivity (Figure 4f). Therefore, the use of the unrestricted culture depth optimizer would be unfeasible.

Figure 5 shows the same test performed without constraints but for one day in August. In this case, temperatures are higher, as well as productivity. By regulating the culture depth, Figure 5f shows an increase of 13.6% in the biomass productivity with respect to the normal operation with fixed culture depth. The maximum temperature in the reactor (Figure 5a) decreases by 2°C with respect to the estimated with the fixed culture depth, improving the temperature index (Figure 5c) by 5%, since the regulated temperature is closer to the optimum temperature value. Unlike the month of January, the set-point of culture depth (Figure 5b) during the day increases until the maximum culture depth limit (30 cm), which allows the entry of fresh medium and increases the volume, decreasing the temperature of the reactor. On the other hand, Figures 5d and 5e show the biomass concentration and the net biomass in the reactor, respectively. These graphs show considerable variations due to the behavior of the optimizer, which acts without constraints, causing dilution and harvesting processes above their ideal values.

Due to the results related to the concentration of biomass and net biomass obtained by applying an optimizer without constraints (Figures 4 and 5), it is evident that the physical application is not feasible. Therefore, some constraints have been defined to represent a more realistic behavior and simulate a practical application of the optimizer in the reactor described in Section 2. Figures 6 and 7 represent the results obtained for a day in January and one day in August, using the culture depth optimizer with constraints. The main constraint applied is the dilution of the medium in the reactor, which allows the biomass to remain at a constant value at the beginning and the end of the day. The dilution constraint is achieved by regulating the minimum and maximum limits of culture depth provided by the optimizer. Note that this is a significant difference when compared to previous approaches found in the literature.

During the winter period, when temperature reaches its minimum values, the results obtained using the culture depth optimizer have been very similar to those obtained with a fixed culture depth such as observed in Figure 6. Due to the low temperature and radiation of this season, the maximum dilution is 8% of the total reactor volume, to ensure biomass production. Therefore, the culture depth limit is very close to its initial value, as can be seen in Figure 6b. This small variation in the culture depth does not have a great impact on the temperature of the reactor (Figure 6a), so the temperature factor of the growth model (Figure 6c) is practically the same for the two scenarios. As a consequence, the biomass productivity represented in Figure 6f are the same in both cases, without an appreciable improvement, with only an increase of 3%. However, observing the net biomass (Figure 6e) it can be seen that

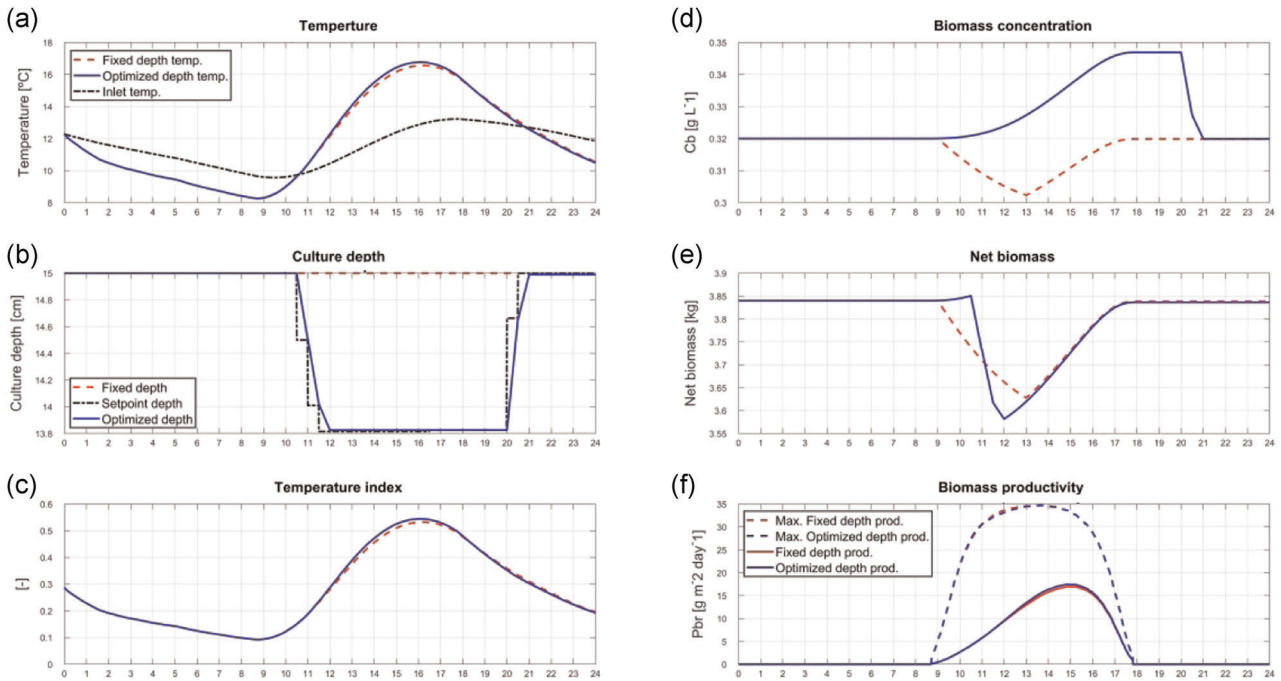

FIGURE 6 Biomass productivity comparison with constraints in January. Red dashed lines represent the results for normal reactor operation (fixed depth), while the solid blue lines represent the results applying the culture depth optimizer [Color figure can be viewed at wileyonlinelibrary.com]

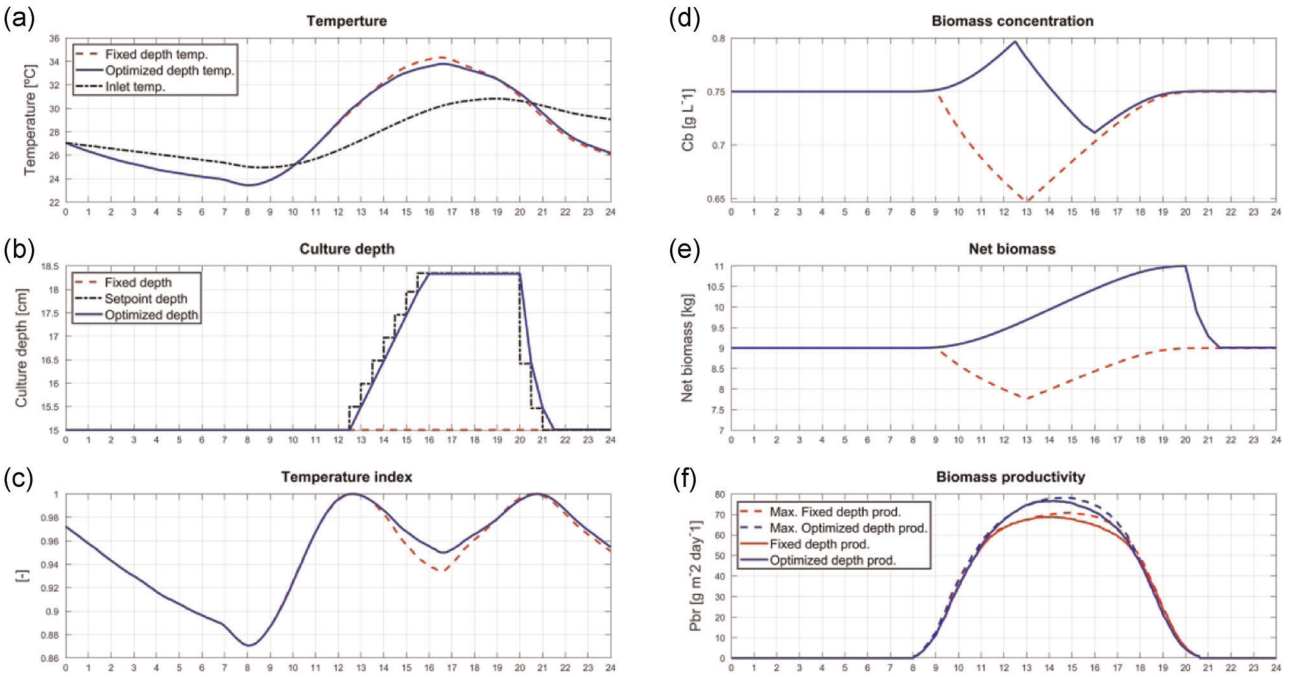

FIGURE 7 Biomass productivity comparison with constraints in August. Red dashed lines represent the results for normal reactor operation (fixed depth), while the solid blue lines represent the results applying the culture depth optimizer [Color figure can be viewed at wileyonlinelibrary.com]

the harvest occurs at the beginning of the day with a fixed biomass concentration value (Figure 6d), equal to the initial concentration for that period (Table 4), with a subsequent dilution at the end of the day. In this way, biomass is obtained without dilution, at a constant concentration, unlike harvesting with fixed culture depth, represented by the dashed line. Notice that the simulation and optimization of the full day only took 1.8 min.

Figure 7 represents the test with constraints for one day in August. During the summer period, biomass productivity increases due to higher temperatures and solar radiation, but with the drawback that an excessive temperature in the reactor can cause disastrous consequences for the microalgae. That is why this period is perfect to carry out a test applying the optimizer with constraints to check the differences with respect to the operation with fixed culture depth. In this scenario, the reactor temperature is above its optimum value, so the regulated culture depth (Figure 7b) is increased to its maximum value to allow the fresh medium to enter (at a lower temperature than the culture in the reactor) and increase the volume. In this way, the maximum temperature of the reactor decreases 1 ℃ with respect to the temperature with fixed culture depth (Figure 7a), improving the temperature factor (Figure 7c) by 2%. Due to the improvement in the temperature factor, there is an increase in biomass productivity of 11.5% with respect to the fixed culture depth (Figure 7f). Figure 7e shows the net biomass in the reactor, which grows during the day and is harvested when there is no solar radiation, when the biomass concentration value, shown in Figure 7d, is the highest. Unlike the regulated culture depth scenario, during fixed culture depth harvesting, the biomass concentration decreases over time. In this case the simulation and optimization also took 1.8 min of computational time.

So, the use of the culture depth optimizer in the raceway reactor has been shown to improve biomass productivity due to the temperature regulation performed. The results obtained in Figures 4 and 5 demonstrate the improvement on the temperature factor, although its application without constraints is not feasible in the real cultivation of microalgae. On the other hand, the results obtained by using the optimizer with constraints (Figures 6 and 7) achieve an increase in biomass productivity of 11.5% with respect to the operation of the reactor with fixed culture depth, for the month of August, where the productivity of biomass is higher.

Another important factor in the comparison of both scenarios is the harvested biomass. In the optimized culture depth scenario, the addition or removal of liquid in the reactor is determined by a constraint on the maximum and minimum set-point for the culture depth that can be reached, determined by the dilution. When the culture removal occurs, the biomass is harvested with a determined biomass concentration. In Figures 6 and 7 (graphs d and e), it can be seen that harvesting occurs with a constant biomass concentration, decreasing the net biomass in the reactor. In this way, volume of medium with a higher biomass concentration can be obtained than during constant volume reactor harvesting (the normal operation). On the other hand, in the case of harvesting with fixed culture depth, by keeping the reactor volume constant, the concentration of biomass in the harvest decreases over time, due to the dilution of the reactor. Therefore, the yield in the harvest decreases, since the volume that is removed contains less biomass concentration over the harvesting. The increase in the biomass

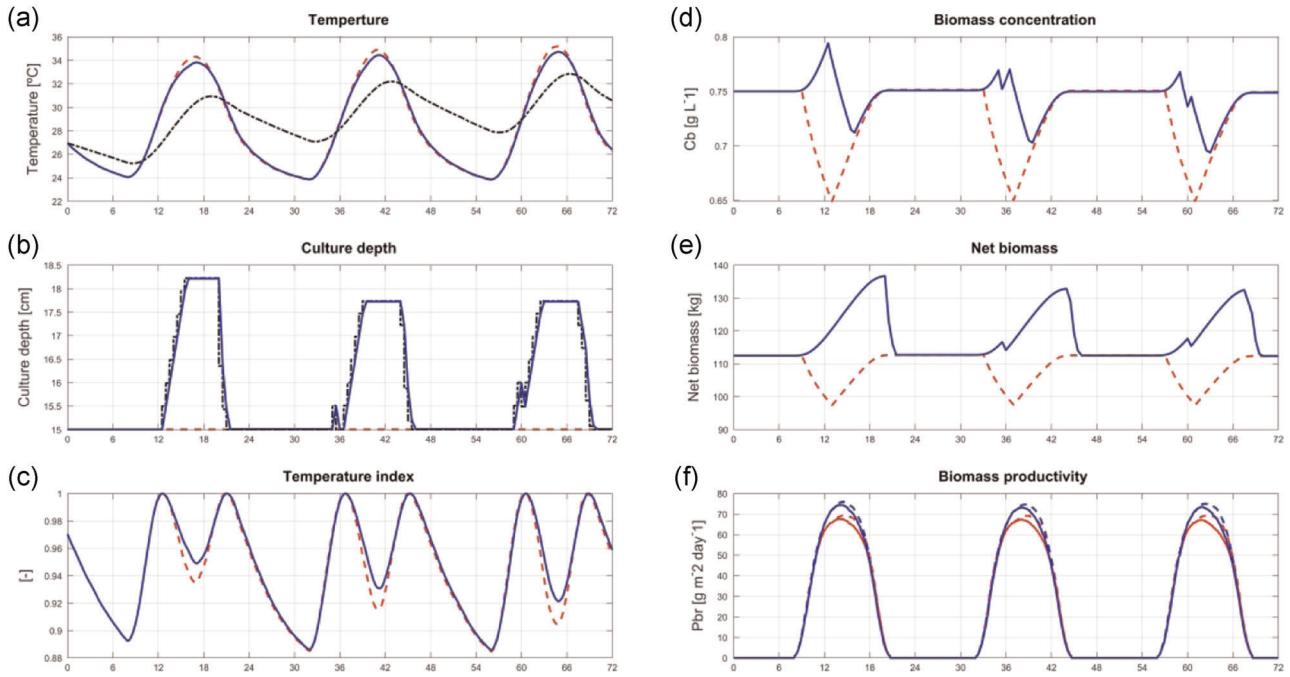

FIGURE 8 Biomass productivity comparison with constraints during thre consecutive days in August for an industrial-scale raceway reactor. Red dashed lines represent the results for normal reactor operation (fixed depth), while the solid blue lines represent the results applying the culture depth optimizer [Color figure can be viewed at wileyonlinelibrary.com]

concentration of the harvested medium using the optimizer has resulted in an increase in the amount of biomass harvested. During the month of January (Figure 6), the biomass productivity is very similar to the operation with fixed culture depth, without any appreciable improvement. That is why there is only an increase of 3% in the harvested biomass. On the other hand, during the month of August, where the biomass productivity is maximum, an additional 7.26% of biomass is obtained with respect to the operation with the fixed culture depth, which supposes a great increase and improvement in the production with respect to the normal operation of the reactor.

3.4 | Simulation results for an industrial raceway reactor

After verifying the effect of the optimizer and the improvement in biomass productivity during the month of August, a simulation of a 1000 m^2 industrial-scale raceway reactor was carried out (Grobbelaar, 2012). This simulation aims to highlight the benefits in the use of the optimizer applied to a large system, close to what would be an industrial-scale operation. Figure 8 represents the results of applying the optimizer to a large reactor during three consecutive days of August, compared to normal operation at constant volume. The behavior of the reactor in this simulation is very similar to the results obtained for the reactor described in Section 2 and represented in Figure 7. The temperature difference between normal operation and the use of the depth optimizer has been 1°C, with a dilution rate of 21%. Regarding the temperature index, represented in Figure 8c, an improvement of 2% is observed with respect to the normal operation of the reactor during each day. In this way, biomass productivity increases by 10.2% (Figure 8f), obtaining 5% more biomass during harvesting each day.

It is worth highlighting the simulation time (computational cost) of the results, being 1.8 min for 1 day and 5 min for 3 days. The tests have been carried out simulating the reactor operated at fixed volume and the reactor by applying the optimizer. Therefore, the simulation and optimization time applying only the optimizer is less than 1 min. Thanks to this low simulation time, it is possible to carry out simulation studies of several days in a row or apply the optimizer to the physical reactor in real time.

4 | CONCLUSIONS

This study presents a temperature regulation method by varying the volume in a microalgae raceway reactor from a culture depth optimizer. The results obtained with the application of the optimizer with constraints have been satisfactory, with an increase in biomass productivity of 11.5% during summer with respect to the operation of the reactor with fixed culture depth, due to the improvement in the temperature factor of the microalgae growth rate model. In addition, the results show that in the winter period, for this strain of microalgae, the biomass productivity is similar to the operation with fixed culture depth. Therefore, during this period, the use of the optimizer would not be profitable. On the other hand, the results for the month of August have shown not only an increase in the biomass

productivity but also an increase of 5% of the biomass in the harvesting process at an industrial scale.

The culture depth optimizer opens the door to new ways of controlling temperature and improving biomass productivity. Due to its characteristics and restrictions, the regulation is carried out by means of the dilution and harvesting processes in the reactor, so it does not require any expensive devices with respect to the normal operation of the reactor, such as heat exchangers for cooling and heating.

Furthermore, culture depth control in the reactor by applying the optimizer can be combined with weather forecasts to regulate the temperature in the reactor based on future scenarios, as done by De-Luca et al. (2017). Moreover, the dilution rate is a fixed parameter but it could be a variable parameter that depends on the microalgae and environmental conditions, in such a way that it can be combined with the culture depth optimizer to also control the biomass concentration. Therefore, the culture depth optimizer application serves as a design tool for temperature control architectures without the need for additional equipment.

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CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

AUTHOR CONTRIBUTIONS

Rodríguez-Miranda E. was responsible for the work, the design of the regulation approach and the writing of the manuscript. Guzmán J. L. is responsible for the optimization approach development. Acién F. G. contributed to project management and data analysis. Berenguel M. was responsible for the discussion section and revision of the manuscript. Visioli A. contributed to the revision of the manuscript and to the supervision of the work.

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