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Optimization of the lighting system for a Hydraulically Integrated Serial Turbidostat Algal Reactor (HISTAR): Economic implications

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ABSTRACT

An estimated 28% of the production cost in HISTAR systems that are artificially illuminated is attributed to the lighting cost. This cost estimated is based on an operational configuration comprised of eight CFSTRs, a system dilution rate (D_s) of 0.640 d^{-1}, and 400 W metal halide lamps positioned at an elevation of 38.1 cm over the culture. Deterministic model simulations of the volumetric productivity (P_v), photosynthetic efficiency (E_o) and lighting cost (LC) under various management strategies, operational parameters and reactor design configurations were performed and compared to the simulation results obtained for the original configuration. The simulations showed that LC may be reduced by 35.5% by switching from a metal halide (MH) to high-pressure sodium (HPS) light source at an optimum system dilution rate $D_s = 0.641\ d^{-1}$. LC may be reduced by an additional 17.8% through decreasing the lamp elevation to 25.4 cm. Increasing the wattage of the light source from 400 to 1000 W in the last six reactors would reduce the LC by 13% from the original cost. Overall, using HPS lamps at 25.4 cm height, with six 1000 W and two 400 W lamps at a $D_s = 0.641\ d^{-1}$ will result in a 54% overall LC reduction compared to the original configuration of HISTAR. This represents a 13% reduction in the overall microalgal production cost for HISTAR.

1. Introduction

The focus on, and thus the economic importance of, microalgae will continue to grow as conventional uses and the development of new applications increase (e.g., Chisti, 2007; Mayfield and Franklin, 2005; Evens et al., 2000; Hu et al., 1998a). Conventional uses include applications in the aquacultural, agricultural, food production, cosmetic, pharmaceutical, and environmental industries (e.g., Del Campo et al., 2007; Daneshvar et al., 2007; Molina Grima et al., 2003; Pulz, 2001; Muller-Feuga, 2000; D'Souza and Loneragan, 1999; Duerr et al., 1998; Richmond et al., 1990). More recently developed applications include the photosynthetic conversion of CO_2 emissions to valuable biomass (Hu et al., 1998a; Watanabe and Hall, 1996), the treatment of carcinoma through extracts (Acien Fernandez et al., 2000; Carbonnelle et al., 1999), and the production of alternative energy sources including hydrogen and biodiesel (Huntley and Redalje, 2007; Miao and Wu, 2006; Xu et al., 2006; Greenbaum et al., 2001; Ghirardi et al., 2000; Woodward et al., 2000). Based on current and potential markets, microalgae have become a product valued at $1.25 billion $year^{-1}$ in the U.S. and around the world, not including processed products (Becker, 2007; Pulz and Gross, 2004).

Independent of application, the increased demand for microalgae requires a renewed effort in the design of highly efficient culture reactors capable of low-cost, continuous production while maintaining desired product quality (Duerr et al., 1998). Depending on culture system type and size, microalgal costs may range from \$20 (kg dry wt)$^{-1}$ up to \$1000 (kg dry wt)$^{-1}$. The higher end of the cost scale refers to indoor, batch production systems used in the aquaculture industry to provide feed to aquatic organisms (Muller-Feuga, 2000; Duerr et al., 1998). The lower cost refers to production of microalgae for uses other than aquaculture feed (Borowitzka et al., 1991; Donaldson, 1991; De Pauw and Persoone, 1988). Microalgal production costs for aquaculture feeds must be below the \$50–100 (kg dry wt)$^{-1}$ (Duerr et al., 1998). Production costs for other applications such as fuels should be even lower. It has been estimated that the production cost of microalgal biomass

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Nomenclature

μ_{max}	maximum specific growth rate (d^{-1})
μ_n	specific growth rate in $CFSTR_n$ (d^{-1})
τ_s	hydraulic retention time (d)
ν	light/dark cell cycling frequency
A_s	surface area of the CFSTR (m^2)
c	energy price (\$0.091 $(kW\,h)^{-1}$)
D_n	local dilution rate for $CFSTR_n$ (d^{-1})
D_s	system dilution rate (d^{-1})
d_n	culture depth for $CFSTR_n$ (m)
E_o	photosynthetic efficiency (%)
E_n	elevation of the lamp over $CFSTR_n$ (cm)
F_D	factor representing the effect of self-shading on growth rate
H	heat of combustion of microalgae (J (g dry wt)$^{-1}$)
h	time of lamp use (h)
I_{a_n} (PAR)	average scalar irradiance in $CFSTR_n$ (μmol s^{-1} m^{-2})
I_{opt}(PAR)	optimum scalar irradiance (μmol s^{-1} m^{-2})
I_{os_n} (PAR)	surface irradiance for $CFSTR_n$ (μmol s^{-1} m^{-2})
I_{z_n} (PAR)	scalar irradiance (μmol s^{-1} m^{-2}) at z_n depth in $CFSTR_n$
k_0(PAR)	overall scalar attenuation coefficient (m^{-1}) = $k_w + k_b X_n$
k_a	light diffusion coefficient through air (μmol s^{-1} m^{-2} cm^{-1})
k_b	biomass attenuation coefficient (m^2 (g dry wt)$^{-1}$)
k_{e_n}	decay rate in $CFSTR_n$ (d^{-1})
k_w	water attenuation coefficient (m^{-1})
LC	production lighting cost (\$ (kg dry wt)$^{-1}$)
n	numerical position of the specific CFSTR in the series
N	total number of CFSTRs in HISTAR
P_a	areal productivity ((g dry wt) m^{-2} d^{-1})
P_v	volumetric productivity ((g dry wt) m^{-3} d^{-1})
P	periodic function that describes biorhythms
P_{adj}	proportional influence of the biorhythms on microalgal growth
Q_f	culture media flow (m^3)
Q_T	total flow (m^3)
Q_{tb}	inoculum flow from turbidostats (m^3)
V_c	culture volume (m^3)
V_n	volume of $CFSTR_n$ (m^3)
W	lamp wattage (W)
X_8	biomass concentration in $CFSTR_8$ ((g dry wt) m^{-3})
X_n	concentration of biomass in $CFSTR_n$ ((g dry wt) m^{-3})
X_{tb}	concentration of biomass in the turbidostats ((g dry wt) m^{-3})
z_n	depth within $CFSTR_n$ (m)

cultured with currently available technology could be lowered to approximately \$2.95–3.80 (kg dry wt)$^{-1}$ if it is assumed that carbon dioxide is obtained at no cost from utilities, nutrients are obtained at no cost from wastewater discharges and the production facilities could be scaled to 10,000 tons year^{-1}(dry wt) using natural light. These conditions, however, have not been met in any of the existing facilities around the world (Chisti, 2007; Sánchez Mirón et al., 2003).

Due to the lower initial capital investment, microalgal culture in open ponds/raceways is very popular (e.g., Del Campo et al., 2007; Grobbelaar, 2007; Spolaore et al., 2006). In fact, a review by Carvalho et al. (2006) indicated that all of the commercial, phototrophic microalgal culture systems in the United States (and around the world) are extensive open ponds or raceways. The use of these systems for intensive, high yield cultures of specific monoculture microalgal species can be difficult, as the systems are vulnerable to contamination either by undesirable species that compete for resources with the cultured species or by predators that can reduce substantially the biomass yield and cause culture collapse. Also, manipulation of environmental conditions in open, extensive systems is difficult. Microalgal photobioreactors represent a culture alternative with a yield higher than extensive pond systems (Benson et al., 2007; Carvalho et al., 2006; Rusch and Christensen, 2003; Evens et al., 2000; Camacho Rubio et al., 1999; Garcia Camacho et al., 1999). While the initial capital investment will be greater, higher productivity (based on area and energy input), greater photosynthetic efficiency and a higher level of control of the biomass produced (Benson and Rusch, 2006; Rusch and Christensen, 2003; Scragg et al., 2002; Acien Fernandez et al., 2001; Lee, 2001; Theegala et al., 1999; Rusch and Malone, 1998) make photobioreactors a viable alternative for microalgal culture for certain applications. Large scale, industrial applications (i.e., biofuels) will require the integration of both intensive and extensive technologies to provide an environment advantageous to the cultured microalgal species.

Independent of design strategy, mass cultures of microalgae must be optimized to minimize costs. The light regime is a critical parameter impacting culture growth and composition, and thus, production cost (Meseck et al., 2005; Tzovenis et al., 2003; Geider and Platt, 1986). Designs must optimize the exposure of the algal cell to light (Ugwu et al., 2005; Barbosa et al., 2003; Acien Fernandez et al., 1998). This can be accomplished by controlling the depth or thickness of the culture (d_n), mixing rate (better represented as cell light/dark cycling frequency, ν), system dilution rate (D_s) for continuous systems, culture density (X_n), and distance of the lamp from the culture (E_n) for artificially illuminated systems (Molina et al., 2001; Zou and Richmond, 1999; Hu et al., 1998b; Molina Grima et al., 1994; Goldman, 1979). Consideration of the spectral output and irradiance (I) of the lamp to be used for a reactor is also important in the design of an artificial lighting system (Jeon et al., 2005) since it constitutes a significant portion of the production cost and, therefore, is a likely source of cost reduction (Berg-Nielsen, 2006; Pulz and Scheibenbogen, 1998; Kirk, 1994; Goldman, 1979).

The relationship between growth rate and irradiance for various species of microalgae peaks differently under varying spectrums of light depending on their ecological evolution and adaptation (e.g., Pascal et al., 1998; Iglesias-Prieto and Trench, 1997; Acien Fernandez et al., 1997). However, the complex relationships between all of these parameters and microalgal productivity can be modeled to gain a fundamental understanding of system design and operation and, subsequently, production economics (e.g., Evens et al., 2000; Acien Fernandez et al., 1998; Chapra, 1997; Kirk, 1994; Jorgensen, 1979; Steele, 1965; Ryther, 1959).

The effects of the light spectrum on light dynamics and microalgal quantum yield have been extensively documented (Chapra, 1997; Acien Fernandez et al., 1997; Kirk, 1994; Steele, 1965; Emerson and Lewis, 1943; Clarke, 1939), and various models of microalgal growth kinetics have been proposed. Several researchers have reported that an exponential model is the best fit for specific growth rate (μ_n) (Evens et al., 2000; Pulz and Scheibenbogen, 1998). However, in cultures where self-shading is high, the peak of the relationship between μ_n and the average scalar irradiance (I_{a_n} (PAR)) becomes so broad that a hyperbolic model provides a better fit (Acien Fernandez et al., 1997; Molina Grima et al., 1996). Steele's equation, an exponential peak-shaped function, adequately models photoinhibition in shallow or moderately dense cultures where self-shading is minimal. This self-shading effect on the relationship between I_{a_n} (PAR) and μ_n occurs because it allows maximal growth and photolimited growth deep in the reactor simultaneous to photoinhibited growth near the surface (Molina Grima et al., 1996).

Optimization of design and operational parameters for artificial lighting systems will result in maximizing photosynthetic efficiency (E_o) in the reactor and minimizing the production lighting cost (LC) under a specific lighting regime (Acien Fernandez et al., 1998; Watanabe and Hall, 1996). These two performance indicators are indirectly related. E_o is the ratio of biochemical energy produced to energy supplied in the form of photosynthetically active radiation (PAR) (Pulz and Scheibenbogen, 1998; Molina Grima et al., 1994; Goldman, 1979). The design and operational parameters manipulated to optimize the lighting system for microalgal reactors are those that have some influence on culture biomass density (X_n); average scalar irradiance in the reactor (I_{a_n} (PAR)); or the relationship between I_{a_n} (PAR) and specific growth rate (μ_n) (Rossignol et al., 2000; Molina Grima et al., 1999; Hu et al., 1998b; Acien Fernandez et al., 1998). The critical lighting system operational parameters include; the distance of the lamp source from the microalgal culture (E_n), the system dilution rate (D_s) and the mixing rate (light/dark cell cycling frequency, ν) (Acien Fernandez et al., 2001; Molina et al., 2001; Drapcho and Brune, 2000; Garcia Camacho et al., 1999; Rusch and Malone, 1998; Molina Grima et al., 1994). The critical lighting system design parameters include the culture depth (d_n) (Molina Grima et al., 2000; Zou and Richmond, 1999; Hu et al., 1998b); the light spectrum (determined by the type of lamp) and the lamp intensity (wattage; W) (Acien Fernandez et al., 2000; Pulz and Scheibenbogen, 1998; Goldman, 1979).

This paper presents the findings of several optimization and cost analysis studies performed on strategic scenarios for reducing the lighting cost of the Hydraulically Integrated Serial Turbidostat Algal Reactor (HISTAR) operated under artificial illumination (Benson et al., 2007; Benson and Rusch, 2006; Rusch and Christensen, 2003; Rusch and Malone, 1998). E_o and LC were estimated based on simulations generated by a deterministic model, described in detail in Benson et al. (2007). This productivity model was based on a series of mass balances within each CFSTR of HISTAR. Simulations were run to estimate the cost effectiveness of changing the lamp type, number of reactors, the lamp elevation, and increasing the wattage of the lamps. Biomass changes over time were simulated under the above scenarios and used to estimate productivity and therefore, E_o and LC as in other optimization papers (Acien Fernandez et al., 1998; Muller Feuga et al., 1998; Pulz and Scheibenbogen, 1998; Watanabe and Hall, 1996). Previous investigations identified MH and HPS as the best performing lamps (Benson, 2003). Productivity, E_o and LC were compared for metal halide (MH) and high-pressure sodium (HPS) lamps at four different system dilution rates, two to eight reactors and three lamp elevation regimes. The best combination of lamp type, dilution rate, lamp elevation and number of reactors was then used to simulate the effect of changing the lamp wattage in the reactors.

2. Methods and materials

2.1. HISTAR description and operation

HISTAR (Fig. 1) consists of two, sealed turbidostats hydraulically linked to a series of open, continuous-flow stirred-tank reactors (CFSTRs; Rusch and Christensen, 2003). The sealed turbidostats produce a dense microalgal inoculum that is injected (Q_{tb}) into the first CFSTR along with the culture media (Q_f), creating a hydraulic gradient across the CFSTRs. The series of CFSTRs serves as a biomass amplification unit. In theory, the hydraulic regime within the series of CFSTRs is maintained to assure the local dilution rate (D_n) within each reactor is always greater than specific growth rate of any potential suspended contaminant. As a result, inadvertent contaminants entering the CFSTRs are washed out before they have time to multiply and reach detrimentally high numbers. The appropriate environment for microalgal growth is provided by a low system dilution rate (D_s; determined by D_n and the number of CFSTRs (N)). D_s can be manipulated by changing the number of CFSTRs or by adjusting the total flow ($Q_T = Q_f + Q_{tb}$) within a specific range.

The experimental CFSTRs from which data were collected were vertical cylinders (0.91 m diameter), with a culture depth and system volume of approximately 0.64 m and 3.6 m^3, respectively. The sealed turbidostats produced a high quality, dense monoalgal inoculum that was injected into the first CFSTR at 10-min intervals and automatically controlled to vary in duration in response to the turbidostat biomass density (Rusch and Christensen, 2003; Rusch

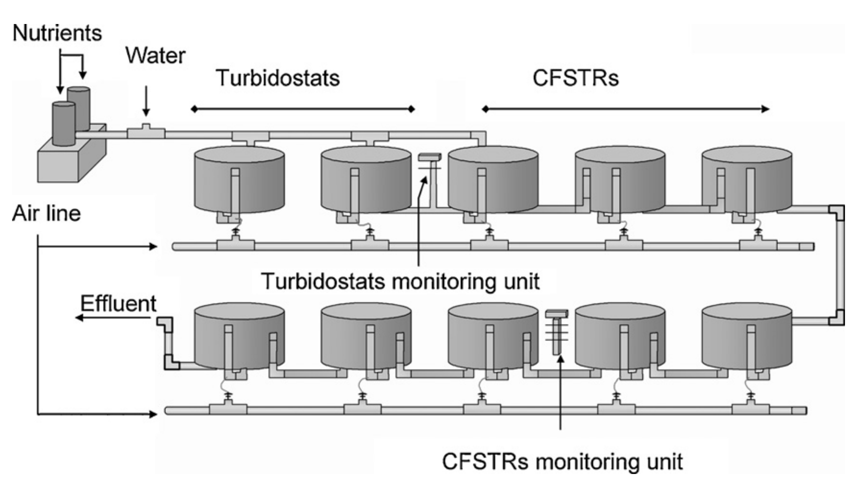

Fig. 1. The HISTAR system (3.6 m^3 culture volume) consists of two sealed turbidostats and eight open continuous-flow, stirred-tank reactors (CFSTRs).

and Malone, 1998; Theegala, 1997). Prior to these optimization studies, HISTAR was typically operated at a $D_s = 0.641\ d^{-1}$ and $E_n = 38.1$ cm, resulting in approximate mean P_v and P_a of 25.5 (g dry wt) $m^{-3}\ d^{-1}$ and 19.9 (g dry wt) $m^{-2}\ d^{-1}$, respectively and an estimated lighting cost of \$63 (kg dry wt)$^{-1}$. These estimates were for *Selenastrum capricornutum* and will vary depending on the microalgal species cultured and the operational conditions of the culture.

2.2. Productivity model

A deterministic productivity model was developed and calibrated for simulating microalgal productivity in HISTAR under various lamps, operational conditions and CFSTR configurations. The details of the model are presented in Benson et al. (2007), subsequently, only a summary is provided here. The model is based on a series of mass balances around each of the eight CFSTRs:

$$\frac{\partial X_n}{\partial t} V_n = Q_T X_{n-1} - Q_T X_n + (\mu_n - k_{e_n}) X_n V_n \quad (1)$$

where

$$\mu_n = \mu_{\max}\left[[(1-P)P_{\mathrm{adj}}][F_D]\left[\frac{I_{a_n}(\mathrm{PAR})}{I_{\mathrm{opt}}(\mathrm{PAR})} e^{\left(\frac{-I_{a_n}(\mathrm{PAR})}{I_{\mathrm{opt}}(\mathrm{PAR})}+1\right)}\right]\right] \quad (2)$$

The series of mass balances are related by the first term on the right hand side of Eq. (1) as it defines the inflow from the previous CFSTR. For the first CFSTR, this term is replaced by inflows from the turbidostat ($Q_{tb} X_{tb}$) and culture media (Q_f). The specific growth rate (Eq. (2)) is a function of the maximum specific growth rate ($\mu_{\max}$), harmonics representing biorhythms $[(1-P)P_{\mathrm{adj}}]$ (Benson et al., 2008), effects of self-shading (F_D) and effects of the average scalar irradiance (I_{a_n} (PAR)). Previous studies by the authors have indicated that Steele's model best describes the effects of I_{a_n} (PAR) on μ_n within HISTAR (Benson et al., 2007; Benson and Rusch, 2006). I_{a_n} (PAR) can be estimated by integrating the Beer-Lambert Law over the depth of the culture (Acien Fernandez et al., 1998; Molina Grima et al., 1994):

$$I_{a_n}(\mathrm{PAR}) = \frac{1}{d_n}\int_0^{d_n} I_n(z_n)dz_n = \frac{I_{os_n}(\mathrm{PAR})(1-e^{-k_0(\mathrm{PAR})d_n})}{k_0(\mathrm{PAR})d_n} \quad (3)$$

A unique set of values for the parameters in the last term of Eq. (2) and (3) describe the light dynamics and growth kinetics for a given microalgal species under a specific lamp. The light dynamics and growth rate parameters estimated using MH (Benson and Rusch, 2006) and HPS (Fig. 2) lamps were used to calibrate the HISTAR productivity model (Table 1).

Volumetric system productivity (P_v) is a function of the biomass density in the last CFSTR and the system dilution rate (Rusch and Christensen, 2003; Rusch and Malone, 1998). Low D_s, or high hydraulic retention time (τ_s), provides the time required to increase density as the culture moves through the system and is harvested from the last reactor. Areal productivity (P_a) can be calculated by multiplying P_v by the culture depth (d_n) and is useful for comparing different types of reactors and production costs.

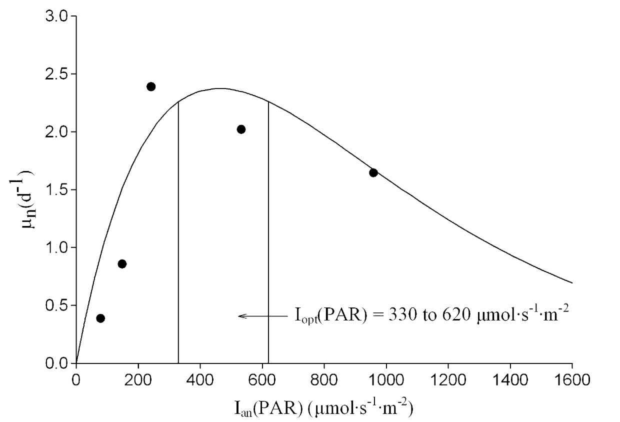

Fig. 2. A growth curve for *S. capricornutum* was developed following the Steele's model. The culture was done under HPS lamps at $D_s = 0.641\ d^{-1}$.

$$P_v = X_8 D_s \quad (4)$$

$$P_a = P_v d_n \quad (5)$$

The performance of microalgal cultures is often expressed as photosynthetic efficiency (E_o):

$$E_o = \left[\frac{P_v V_c H}{I_{os_n}(\mathrm{PAR})A_s}\right] \times 100 \quad (6)$$

Photosynthetic efficiencies can also be calculated for cultures using artificial light if the conversion of PAR (μmol $s^{-1}\ m^{-2}$) to J $d^{-1}\ m^{-2}$ takes into consideration the spectrum of light produced by the specific type of lamps. The conversion process is complex, and the spectral distribution curve of the radiant output of the lamp must be known in order to make the conversion. However, conversion factors of various commonly used lamps have been published to facilitate these processes (Gensier, 1984). For example, the conversion factors for converting W m^{-2} from MH and HPS lamps to μmol $s^{-1}\ m^{-2}$ are 4.6 and 5.0, respectively. This is equivalent to 5.32×10^{-5} (MH) and 5.78×10^{-5} (HPS) μmol $s^{-1}\ m^{-2}$ per J $d^{-1}\ m^{-2}$.

A more practical way of evaluating the performance of a lighting system for comparative purposes is to estimate the lighting cost normalized to production:

$$\mathrm{LC} = \frac{Whc}{1000 \times \mathrm{net}\, P_v V_c} \quad (7)$$

Where the net P_v equals the total P_v minus the input from the turbidostats. The HISTAR productivity model summarized in the previous section was modified to include the calculation of E_o and LC via the incorporation of Eqs. (6) and (7). The model was used for simulation of HISTAR performance under HPS and MH lamps.

2.3. Model simulations

The calibrated model was used to simulate the effects of lamp type, system dilution rate, number of CFSTRs, lamp elevation and

Table 1
The light dynamics and growth rate parameters utilized in the simulations were experimentally estimated.

Light source	Light elevation I_{Eo} (μmol $s^{-1}\ m^{-2}$), k_a (μmol $s^{-1}\ m^{-2}\ cm^{-1}$)	Light attenuation k_w (m^{-1}), k_b (m^2 (g dry wt)$^{-1}$)	Growth rate $\mu_{\max}$ (d^{-1}), I_{opt} (μmol $s^{-1}\ m^{-2}$)
Metal halide	$I_{Eo} = 597.7$[a], $k_a = -7.464$[a]	$k_w = 1.97$, $k_b = 0.0575$	$\mu_{\max} = 1.73$, $I_{opt} = 391$
High pressure-sodium	$I_{Eo} = 569.53$[a], $k_a = -5.32$[a]	$k_w = 1.91$, $k_b = 0.0659$	$\mu_{\max} = 2.37$, $I_{opt} = 460$

[a] For light elevation E_n = 25.4–45.7 cm.

wattage on P_v, E_o and LC. The simulations were 19 days in duration to correspond with the mean duration of the HISTAR data sets used for model calibration. Data for the first 2 days were not used in the calculations as the system was not as steady state. A simulation was performed to compare the model results with data collected from the experimental system, using real inoculum data. After the initial calibration runs using real data, several simulations were performed with fixed inoculums of 31 (g dry wt) d^{-1} to explore the effects of different parameters on the system performance. Eight scenarios were simulated to select the optimal combination of lamp type and system dilution rate (see Section 2.3.1). These eight scenarios were also used to investigate the consequences of decreasing the number of CFSTRs (see Section 2.3.2) and the effect of lamp elevation (Section 2.3.3). The best combination of lamp type, system dilution rate, number of CFSTRs and lamp elevation (determined by productivity) was then used as the operational condition for additional simulations to investigate the potential lighting efficiency and economic consequences of increasing the wattage of the lamp (see Section 2.3.4).

2.3.1. Impact of lamp type and system dilution rate

Daily P_v, E_o and LC were estimated for simulated HISTAR operation at four D_s levels (0.265, 0.385, 0.641, and 1.127 d^{-1}) and two lamp types (400 W MH and 400 W HPS) centered 38.1 cm above each CFSTR.

2.3.2. Impact of number of CFSTRs

P_v and LC were estimated for simulated HISTAR operation utilizing N = 2–8 CFSTRs to investigate the number of reactors that would render the HISTAR design most cost effective from a lighting perspective. As CFSTRs were added to the design, another lamp was needed, and it was important to determine if system productivity increased enough to compensate for the energy cost of an additional lamp. The simulations were run with the same lamp types and D_s levels described in Section 2.3.1. The D_s levels and the daily inoculum mass were adjusted to correspond to the number of CFSTRs being modeled, maintaining a volumetric proportion. Since D_n is fixed to ensure the flushing of inadvertent contaminants from individual reactors, a reduction in N correspondingly reduces D_s ($D_s = D_n N$).

2.3.3. Impact of lamp elevation

The effect of lamp elevation (E_n) on LC, P_v and E_o was investigated by performing simulations at three E_n levels: 38.1, 25.4 cm and linear decreasing lamp height between these two values for all the CFSTRs. The simulations were performed at the same D_s and lamp types as described in Section 2.3.1. The optimization process for lamp elevation over the culture reactor considered both the practical and physiological aspects of the system. Practical considerations included cost and system management. Placement of the lamp at or near the culture surface would eliminate wastage of light energy outside the reactor, but would create problems with tank management including restricted access and splashing on the bulb. Placement at a height that results in the zone of influence falling outside the reactor would result in wasted light energy and increased costs. From a physiological perspective, placement of the lamp should result in an optimal culture I_{a_n} (PAR) and should minimize photoinhibition/photo-oxidation at the surface and light limitation at the bottom of the culture (Molina Grima et al., 2000; Acien Fernandez et al., 1998).

2.3.4. Impact of lamp wattage

The impact of increasing lamp wattage on P_v, E_o and LC was simulated by substituting the 400 W HPS lamps with lamps having wattages of 600 and 1000. To simulate an increase in wattage, I_{os_n} (PAR) was multiplied by the proportional increase in irradiance (μmol s^{-1} m^{-2}) generated by the original lamp to the irradiance generated by the desired lamp, beginning with $CFSTR_8$.

3. Results and discussion

The mode of HISTAR operation used as a baseline for comparison to the simulation results was D_s = 0.641 d^{-1} and illumination from 400 W metal halide lamps centered at E_n = 38.1 cm. The P_v under these conditions averaged 23.9 (g dry wt) m^{-3} d^{-1}, which compared extremely well with the simulated average (23.8 (g dry wt) m^{-3} d^{-1}; Fig. 3). The average P_a observed in the system was 16.6 (g dry wt) m^{-2} d^{-1}, while the simulation provided an estimate of 16.5 (g dry wt) m^{-2} d^{-1} with peaks up to 32 (g dry wt) m^{-2} d^{-1} (Fig. 3). These MH and HPS comparison simulations used actual experimental data. The rest of the simulations discussed were performed with fixed inoculums of 31 (g dry wt) d^{-1}.

3.1. Impact of lamp type and system dilution rate

The best D_s and lamp combination from those investigated was determined from a comparison of the P_v, LC and E_o data obtained from the eight simulations. Fig. 4 illustrates the correlation between LC and E_o for MH and HPS data simulated at D_s = 0.375 and 1.127 d^{-1}. As would be expected, LC is inversely related to E_o. During the transition phase, E_o is low, and the microalgal production cost for lighting is very high. By day 2 (this transition data were not considered in the calculations for mean LC and E_o), LC approaches the mean daily LC. Notice that the LC and E_o data indicate that HPS is a more effective lamp for HISTAR. E_o is an important performance indicator for a microalgal reactor, however, it does not tell the whole story for a series of CFSTRs. For example, E_o can increase with the use of additional lamps, but the added expense of energy for the additional lamp could cause the LC to increase instead of decrease.

HPS lamps produce a very high conversion of electrical power to visible light (>25%), and other researchers have also achieved good results with these lamps (Markager and Vincent, 2001; Pulz and Scheibenbogen, 1998). The best P_v, LC and E_o were obtained at a D_s = 0.641 d^{-1} when compared to the other three D_s levels investigated. This concurs with the predictions made in previous modeling studies of HISTAR (Rusch and Malone, 1998). In that

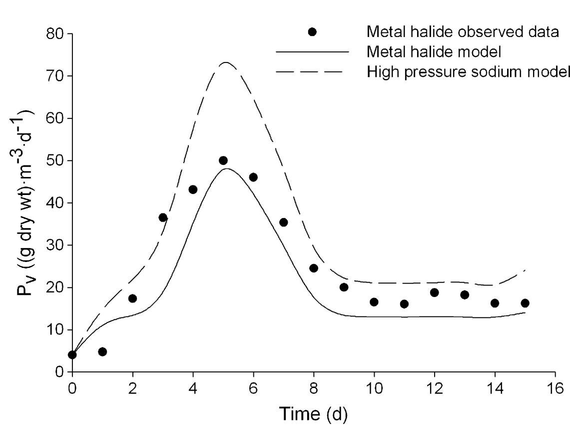

Fig. 3. The simulated volumetric productivity (P_v) of HISTAR using MH and HPS lamps at D_s = 0.641 d^{-1} was compared with actual MH production data.

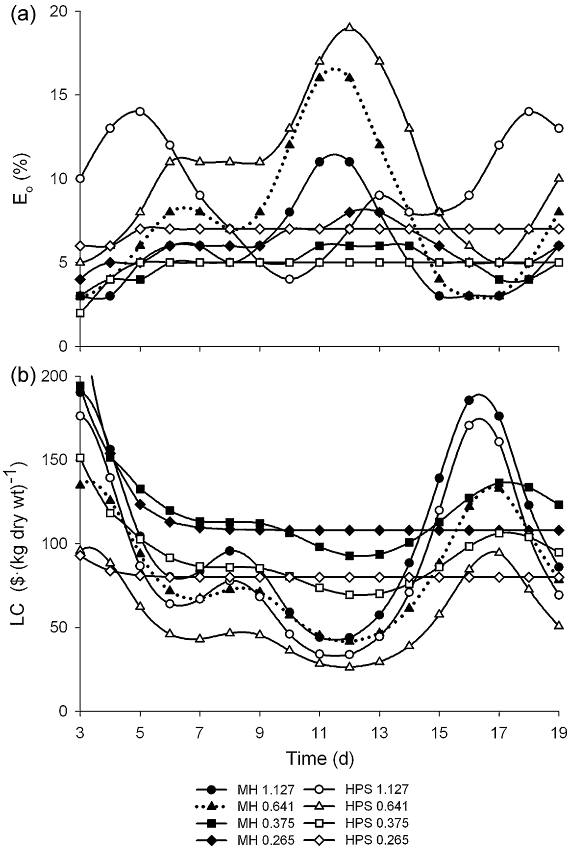

Fig. 4. (a) E_o and (b) LC were simulated for MH and HPS lamps at four different D_s levels (0.265 d^{-1}, 0.375 d^{-1}, 0.641 d^{-1} and 1.127 d^{-1}). The dotted line represents the simulation results of for the original configuration (D_s = 0.641 d^{-1}, MH lamp).

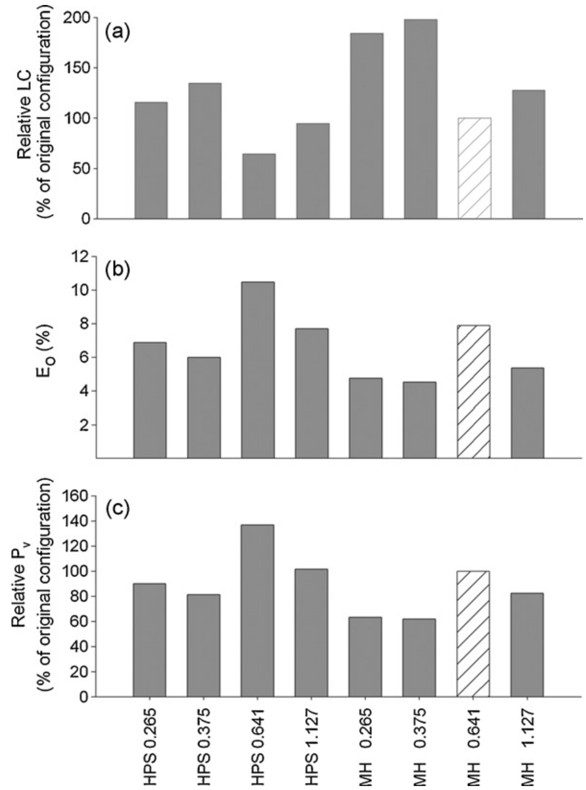

Fig. 5. Average daily (a) relative LC, (b)E_o and (c) relative P_v were simulated for MH and HPS lamps at four D_s levels (0.265 d^{-1}, 0.375 d^{-1}, 0.641 d^{-1} and 1.127 d^{-1}). The striped bar represents the original configuration (D_s = 0.641 d^{-1}, MH lamp). Relative LC and P_v values are represented as percentage of the original configuration.

study, the optimum D_s for HISTAR when growing a microalgal species with μ of 1.5 d^{-1} and inoculum of 25 (g dry wt) m^{-3} was predicted to be approximately 0.6 d^{-1}. Previous HISTAR experimental results for *S. capricornutum* showed an optimum D_s = 0.92 d^{-1} (unpublished data not included in the modeling exercise), which compares quite favorably with other published data (0.96 d^{-1}—Molina et al., 2001; 1.2 d^{-1}—Acien Fernandez et al., 1998) for tubular photobioreactors growing *Phaeodactylum tricornutum*.

Based on the simulation results, LC for D_s = 0.641 d^{-1} decreased by a mean of 35.5% (Fig. 5a), and E_o increased by 32.8% (to 10.47%; Fig. 5b) for HPS lamps compared to MH. These results are based on net biomass production. The average simulated daily E_o for the baseline HISTAR system operational set-up with fixed inoculum is 9.35%, which is comparable to the values reported in literature for other microalgal reactors. Torzillo et al. (1993) reported an E_o = 6.6% for an outdoor two-plane tubular photobioreactor, while Molina Grima et al. (1994) reported an E_o = 0.66–1.61% for an outdoor turbidostat. A cone-shaped, indoor helical tubular photobioreactor has achieved 6.8% (Watanabe and Hall, 1996).

The simulation results also indicated that the use of HPS lamps increased P_v by 36.7% to 42.6 (g dry wt) m^{-3} d^{-1} (P_a = 27.2 (g dry wt) m^{-2} d^{-1}) of total production (50.1% considering only net production; Fig. 5c). While *Spirulina* productivity has been reported to be as high as 66 (g dry wt) m^{-2} d^{-1} (Torzillo et al., 1986), most microalgal photobioreactors have P_a values <42 (g dry wt) m^{-2} d^{-1} (Molina et al., 2001; Acien Fernandez et al., 2001; Muller Feuga et al., 1998; Goldman, 1979). Ryther (1959) predicted that due to photoinhibition, the maximum sustainable P_a in a photobioreactor is 40 (g dry wt) m^{-2} d^{-1}. Tubular photobioreactors can surpass this threshold if P_a is determined by cross-sectional area (71 (g dry wt) m^{-2} d^{-1}), but if P_a is determined based on surface area of the solar receiver P_a drops to 16.8 (g dry wt) m^{-2} d^{-1} (Acien Fernandez et al., 1998), which is in the range of the data collected from HISTAR.

3.2. Impact of number of CFSTRs

The number of CFSTRs impacted the productivity of the system, and subsequently, the LC for artificially illuminated HISTAR systems. To compare the efficiency of increasing or decreasing the number of CFSTRs in the system, relative costs were calculated using the scenario with the lowest cost as the base. The relative cost and productivity for the different HISTAR configurations (lamp and D_s) are presented in Fig. 6a and b, respectively. As CFSTRs were added to the series (up to eight), two operational changes occurred. First, the steady state P_v in the added CFSTR was higher than that of the previous CFSTR in the series. However, the increase diminishes with each reactor added. Second, the HISTAR system was supplied with an additional lamp and an increase in LC was incurred for operation at D_s = 0.265 d^{-1} with four or more reactors. From an E_o perspective, the compensation point of the number of CFSTRs is achieved when the benefit of increased productivity via the use of additional CFSTR(s) is equal to or greater than the cost of the additional CFSTRs. The cost efficiency is maximized when the production cost is minimized. At D_s = 0.265 d^{-1}, the minimum cost is achieved with four CFSTRs for both lamp types. At D_s = 0.385 d^{-1}, the cost exhibited a slight increase with the number of CFSTRs. At D_s = 1.127 d^{-1}, the compensation point was not reached and, therefore, maximum light utilization did not occur. At 0.641 d^{-1}, a

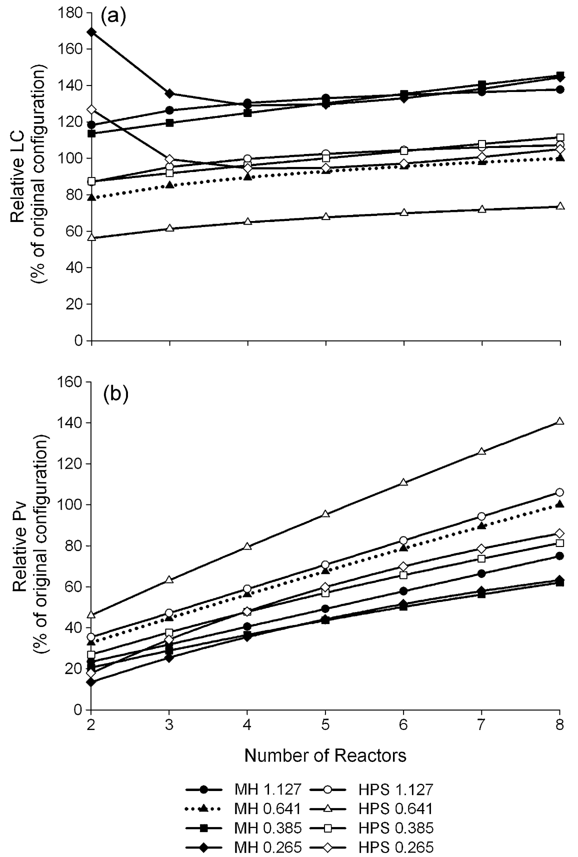

Fig. 6. The relative (a) LC and (b) P_v were simulated for MH and HPS lamps at four D_s levels (0.265 d^{-1}, 0.375 d^{-1}, 0.641 d^{-1} and 1.127 d^{-1}) and varying reactor number (N). Relative values are represented as percentage of the original configuration (dotted line; D_s = 0.641 d^{-1}, MH lamp and eight reactors).

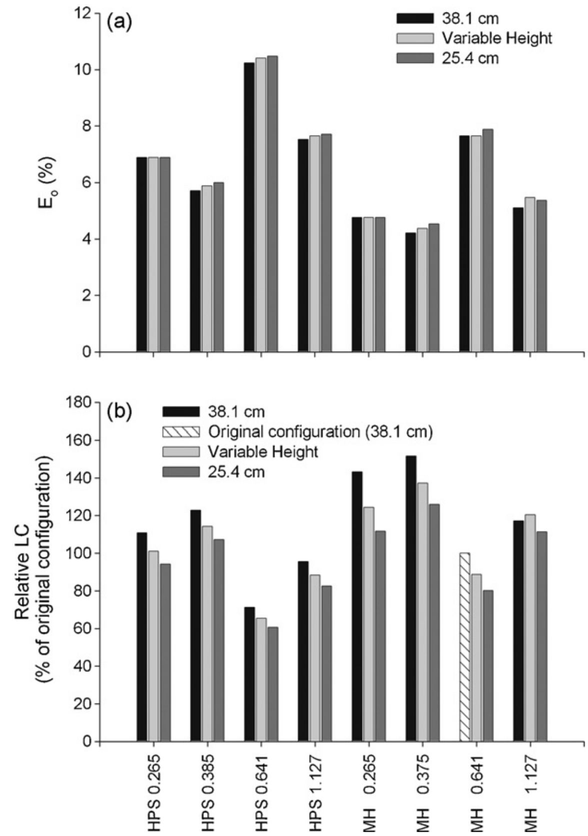

Fig. 7. (a) E_o and (b) relative LC were simulated for MH and HPS lamps at four D_s levels (0.265 d^{-1}, 0.375 d^{-1}, 0.641 d^{-1} and 1.127 d^{-1}) and three lamp elevations. Relative values are represented as a percentage of the original configuration (striped bar; D_s = 0.641 d^{-1}, MH lamp at an elevation of 38.1 cm and eight reactors).

slight increase in cost was observed with increasing number of reactors, but the productivity slope started to diminish between CFSTRs seven and eight, indicating a possible plateau after these reactors. Of the scenarios simulated, the maximum productivity (P_v = 42.6 (g dry wt) m^{-3} d^{-1}; P_a = 27.2 (g dry wt) m^{-2} d^{-1}) was achieved with eight CFSTRs, a D_s = 0.641 d^{-1} and HPS lamps. At this dilution rate, the difference in cost from 7 to 8 CFSTRs was minimal, indicating that the compensation point was near or at eight CFSTRs.

3.3. Impact of lamp elevation

The distance of the lamp (E_n) from the microalgal culture is recognized as an important design parameter (Muller Feuga et al., 1998; Molina Grima et al., 1994). Model simulations of E_o, P_v, P_a and LC performed under three E_n schemes indicated that the lamp elevation could be reduced to 25.4 cm (Fig. 7). With a lower lamp elevation the irradiance was excessive for the CFSTRs with lower biomass concentration, reducing the efficiency. This reduction was compensated by the increased E_o in the CFSTRs with higher biomass concentration. Consequently the E_o did not change dramatically by reducing the lamp height. The LC was decreased by reducing the lamp elevation from 5 to 22% depending on the D_s. The highest productivity was obtained with a D_s = 0.641 d^{-1}. For this D_s, the LC reduction was 17.8% considering net production. The estimated E_o for the HISTAR under a HPS lamp elevation of 38.1 cm was 10.23% for D_s = 0.641 d^{-1} and 10.4% for variable elevations. The highest net mean P_a (26.3 (g dry wt) m^{-2} d^{-1}) and P_v (41.2 (g dry wt) m^{-3} d^{-1}) were observed at D_s = 0.641 d^{-1} with HPS lamps at E_n = 25.4 cm. These values represent an increase of 83% compared with the net production with MH lamps at 38.1 cm under the same conditions. Though surplus irradiance with lamp elevation of 25.4 cm in the first reactor resulted in slightly lower E_o values, the I_{a_n} (PAR) is not high enough (over 460 μmol s^{-1} m^{-2}) for photoinhibition to occur. Therefore, the elevation of the lamps could all be decreased to 25.4 cm to increase the productivity of the system.

3.4. Impact of lamp wattage

Based on E_o, LC and mean scalar irradiance in each CFSTR, HPS lamps were found to be more efficient than MH (see Section 3.1). A Steele's model curve developed for *S. capricornutum* cultured under HPS lamps (Fig. 2) showed that a μ_{max} = 2.4 d^{-1} occurred around a mean I_{a_n} (PAR) = 460 mmol s^{-1} m^{-2}. Approximately 95% or greater of μ_{max} can be obtained within an optimum I_{a_n} (PAR) range of 330–620 μmol s^{-1} m^{-2} for the HPS lamps. Irradiance levels too far removed from I_{opt}(PAR) can impact growth due to insufficient light if the irradiance level is too low or photoinhibition if the level is too high. Both conditions (insufficient light and photoinhibition) would reduce productivity (Acien Fernandez et al., 1998; Molina Grima et al., 1999).

I_{os_n} (PAR) and I_{a_n} (PAR) could be enhanced via the application of higher power HPS lamps. The HISTAR system currently uses 400 W lamps, resulting in a LC = \$63 (kg dry wt)$^{-1}$. The use of 600 or 1000 W lamps (available commercially) would eliminate the light limitation as biomass increases in successive CFSTRs. The increasing productivity would compensate for the increased cost

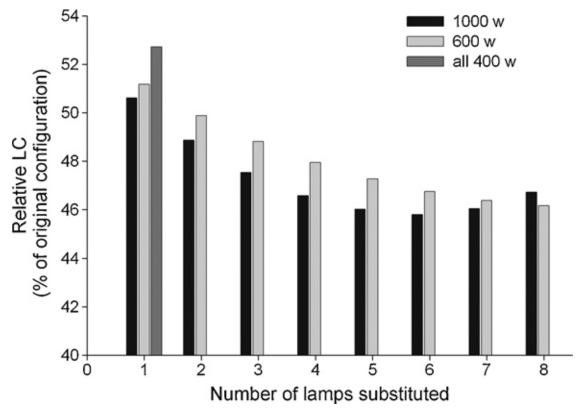

Fig. 8. The LC was simulated for scenarios involving the replacement of 1–8 of the 400 W HPS lamps with 600 and 1000 HPS watt lamps. The other operating conditions included $D_s = 0.641\ d^{-1}$ and $E_n = 25.4$ cm. The results are presented relative to the original configuration (MH lamps at 38.1 cm and $D_s = 0.641\ d^{-1}$).

of running higher wattage lamps in place of 400 W lamps. By substituting the I_{os_n} (PAR) values anticipated under 600 and 1000 W lamps into the HISTAR productivity model, new lighting costs could be estimated. In these simulations, one to eight of the 400 W lamps over the CFSTRs were substituted with 600 or 1000 W lamps starting with $CFSTR_8$. The simulations for the 600 W bulbs indicated that LC increased or was maintained at the same level with each substituted lamp. The lowest cost was obtained by substituting seven 600 W HPS lamps at a $D_s = 0.641\ d^{-1}$. This resulted in a 54% decrease in LC compared to the original HISTAR configuration. However, the difference in LC with five to eight 600 W lamps was <1% (Fig. 8). For the 1000 W simulations, the maximum P_a (81.89 (g dry wt) $m^{-2}\ d^{-1}$) and P_v (112 (g dry wt) $m^{-3}\ d^{-1}$) were obtained when all of the 400 W lamps were substituted with 1000 W lamps at a $D_s = 0.641\ d^{-1}$, indicating an increase of 151% over the productivity obtained with 400 W lamps. The best LC for this bulb was obtained substituting six 1000 W lamps, with a decrease of 54% from the original configuration. However, the difference in LC with six to eight 1000 W lamps was 1%, while the P_v was increased 7% with each additional lamp substituted.

4. Conclusions

A HISTAR productivity model was used to simulate P_v, E_o and LC for a variety of operational and design parameters deemed important for the optimization of the lighting regime and cost within the system. The mean simulated net productivity for the current operating conditions (metal halide lamps at 38.1 cm height and $D_s = 0.641\ d^{-1}$) was 22.5 (g dry wt) $m^{-3}\ d^{-1}$. The simulation results indicated that net P_v could be increased to 112 (g dry wt) $m^{-3}\ d^{-1}$ by using six 1000 and two 400 W HPS lamps at $E_n = 25.4$ cm and $D_s = 0.641\ d^{-1}$. The potential LC cost savings between the two operational schemes could be approximately 54% considering only net production. Changing the type of lamps used to HPS reduces the LC by 35.5%. The LC can be reduced by 17.8% via decreasing the elevation of the lamps to 25.4 cm. Using a combination of six 1000 W lamps with two 400 W lamps or seven 600 W lamps with one400 W lamp will further reduce LC by 13% to \$36.5 (kg dry wt)$^{-1}$ under the simulated conditions or to a cost of \$28.35 considering the actual lighting costs of HISTAR The total cost with this scenario is 46% from the original configuration. From a lighting perspective HISTAR should have at least eight CFSTRs. Since the LC is estimated to be 28% of the existing microalgal production cost in HISTAR the reduction of lighting costs by a 54% would result in a 13% reduction in the overall microalgal production cost for HISTAR.

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References

Acien Fernandez, F.G., Garcia Camacho, F., Sanchez Perez, J.A., Fernandez Sevilla, J.M., Molina Grima, E., 1997. A model for light distribution and average solar irradiance inside outdoor tubular photobioreactors for the microalgal mass culture. Biotechnol. Bioeng. 55, 701–714.

Acien Fernandez, F.G., Garcia Camacho, F., Sanchez Perez, J.A., Fernandez Sevilla, J.M., Molina Grima, E., 1998. Modeling of biomass productivity in tubular photobioreactors for microalgal cultures: effects of dilution rate, tube diameter and solar irradiance. Biotechnol. Bioeng. 58, 605–616.

Acien Fernandez, F.G., Sanchez Perez, J.A., Fernandez Sevilla, J.M., Garcia Camacho, F., Molina Grima, E., 2000. Modeling of eicosapentaenoic acid (EPA) production from *Phaeodactylum tricornutum* cultures in tubular photobioreactors. Effects of dilution rate, tube diameter, and solar irradiance. Biotechnol. Bioeng. 68 (2), 173–183.

Acien Fernandez, F.G., Fernandez Sevilla, J.M., Sanchez Perez, J.A., Molina Grima, E., Christi, Y., 2001. Airlift-driven external-loop tubular photobioreactors for outdoor production of microalgae: assessment of design and performance. Chem. Eng. Sci. 56, 2721–2732.

Barbosa, M.J., Janssen, M., Ham, N., Tramper, J., Wijffels, R.H., 2003. Microalgae cultivation in air-lift reactors: modeling biomass yield and growth rate as a function of mixing frequency. Biotechnol. Bioeng. 82 (2), 170–179.

Becker, E.W., 2007. Micro-algae as a source of protein. Research review paper. Biotechnol. Adv. 25, 207–210.

Benson, B.C. 2003. Optimization of the light dynamics in the Hydraulically Integrated Serial Turbidostat Algal Reactor (HISTAR). Ph.D. Dissertation. Louisiana State University, Baton Rouge, LA. 378 pp.

Benson, B.C., Rusch, K.A., 2006. Investigation of the light dynamics and their impact on microalgal growth rate in a Hydraulically Integrated Serial Turbidostat Algal Reactor (HISTAR). J. Aquac. Eng. 35 (2), 122–134.

Benson, B., Gutierrez-Wing, M.T., Rusch, K.A., 2007. The development of a deterministic model to investigate the impacts of the light dynamics on algal productivity in a hydraulically integrated serial. J. Aquac. Eng. 36, 198–211.

Benson, B., Gutierrez-Wing, M.T., Rusch, K.A., 2008. Application of the Fourier method to differentiate biological rhythms from stochastic processes in the growth of *Selenastrum capricornutum* Printz: implications for model development. J. Appl. Phycol. 20 (20), 103–111.

Berg-Nielsen, J. 2006. Production of Micro Algae-based Products. Algetech Produkter AS. Nordic Innovation Centre. Oslo, Norway. 28 pp. http://www.nordicinnovation.net/_img/production_of_micro_algea-based_products_final_report.pdf.

Borowitzka, M.A., Huisman, J.M., Osborn, A., 1991. Culture of the astaxanthin-producing green algae *Haematococcus pluvialis* 1. Effects of nutrients on growth and cell type. J. Appl. Phycol. 3, 295–304.

Camacho Rubio, F., Acien Fernandez, F.G., Sanchez Perez, J.A., Garcia Camacho, F., Molina Grima, E., 1999. Prediction of dissolved oxygen and carbon dioxide concentration profiles in tubular photobioreactors for microalgal culture. Biotechnol. Bioeng. 62 (1), 71–86.

Carbonnelle, D., Pondaven, P., Roussakis, C., 1999. Antitumor and anti proliferative effects from the marine diatom *Haslea ostrearia* against solid tumors: lung carcinoma (NSCLC-N6), kidney carcinoma (E39) and melanoma (M96) lines. Anticancer Res. 19 (1A), 621–632.

Carvalho, A.P., Meireles, L.A., Malcata, F.X., 2006. Microalgal reactors: a review of enclosed system designs and performances. Biotechnol. Prog. 22, 1490–1506.

Chapra, S.C., 1997. Surface Water-quality Modeling. The McGraw-Hill Co., Inc., NewYork.

Chisti, Y., 2007. Biodiesel from microalgae. Biotechnol. Adv. 25, 297–306.

Clarke, G.L., 1939. The utilization of solar energy by aquatic organisms. In: Poulton, F.R. (Ed.), Problems of Lake Biology. American Association for the Advancement of Science, pp. 27–38.

Daneshvar, N., Ayazloo, M., Khataee, A.R., Pourhassan, M., 2007. Biological decolorization of dye solution containing malachite green by microalgae *Cosmarium* sp. Bioresour. Technol. 98, 1176–1182.

Del Campo, J.A., Garcia-Gonzalez, M., Guerrero, M.G., 2007. Outdoor cultivation of microalgae for carotenoid production: current state and perspectives. Appl. Microbiol. Biotechnol. 74, 1163–1174.

De Pauw, N., Persoone, G., 1988. Micro-algae for aquaculture. In: Borowitzka, M.A., Borowitzka, L.J. (Eds.), Micro-algal Biotechnology. Cambridge University Press, Cambridge, UK, pp. 197–221.

Donaldson, J., 1991. Commercial production of microalgae at Coast Oyster Company. In: Fulks, W., Main, K.L. (Eds.), Rotifer and microalgae culture systems,

Proceedings of the US–Asia Workshop, Honolulu, Hawaii, January 28–31. The Oceanic Institute, Hawaii, USA, pp. 229–236.
Drapcho, C.M., Brune, D.E., 2000. The partitioned aquaculture system: impact of design and environmental parameter on algal productivity and photosynthetic oxygen production. J. Aquac. Eng. 21, 151–168.
D'Souza, F.M.L., Loneragan, N.R., 1999. Effects of monospecific and mixed-algae diets on survival, development and fatty acid composition of penaeid prawn (*Penaeus* spp.) larvae. Mar. Biol. 133, 621–633.
Duerr, E.O., Molnar, A., Sato, V., 1998. Cultured microalgae as aquaculture feeds. J. Mar. Biotechnol. 7, 65–70.
Emerson, R., Lewis, C.M., 1943. The dependence of the quantum yield of *Chlorella* photosynthesis on the wave length of light. Am. J. Bot. 30 (3), 165–178.
Evens, T.J., Chapman, D.J., Robbins, R.A., D'Asaro, E.A., 2000. An analytical flat-plate photobioreactor with a spectrally attenuated light source for the incubation of phytoplankton under dynamic light régimes. Hydrobiologia. 434, 55–62.
Garcia Camacho, F., Contreras Gomez, A., Acien Fernandez, F.G., Fernandez Sevilla, J.M., Sanchez Perez, J.A., Molina Grima, E., 1999. Use of concentric-tube airlift photobioreactors for microalgal outdoor mass cultures. Enzyme Microb. Technol. 24, 164–172.
Geider, R.J., Platt, T., 1986. A mechanistic model of photoadaptation in microalgae. Mar. Ecol. Prog. Ser. 30, 85–92.
Gensier, W.G., 1984. Advanced agricultural instrumentation. In: Proceedings of the NATO Advanced Study Institute. Martinas Nijhoff Publishers, Dordrect, The Netherlands.
Ghirardi, M.L., Zhang, L., Lee, J.W., Flynn, T., Seibert, M., Greenbaum, E., Melis, A., 2000. Microalgae: a green source of renewable H_2. Trends Biotechnol. 18 (ER12), 506–511.
Goldman, J.C., 1979. Outdoor algal mass cultures II. Photosynthetic yield limitations. Water Res. 13, 119–136.
Greenbaum, E., Blankinship, S.L., Lee, J.W., Ford, R.M., 2001. Solar photobiochemistry: simultaneous photoproduction of hydrogen a oxygen in a confined bioreactor. J. Phys. Chem. B 105 (17), 3605–3609.
Grobbelaar, J.U., 2007. Photosynthetic characteristics of *Spirulina platensis* grown in commercial-scale open outdoor raceway ponds: what do the organisms tell us? J. Appl. Phycol. 19, 591–598.
Hu, Q., Kurano, N., Kawachi, M., Iwasaki, I., Miyachi, S., 1998a. Ultrahigh-cell-density culture of a marine green algae *Chlorococcum littorale* in a flat-plate photobioreactor. Appl. Microbiol. Biotechnol. 49, 655–662.
Hu, G., Faiman, D., Richmond, A., 1998b. Optimal tilt angles of enclosed reactors for growing photoautotrophic microorganisms outdoors. J. Ferment Bioeng. 85 (2), 230–236.
Huntley, M., Redalje, D.G., 2007. CO_2 mitigation and renewable oil from photosynthetic microbes: a new appraisal. Mitigation and Adaptation Strategies for Global Change. 12 (4), 573–608.
Iglesias-Prieto, R., Trench, R.K., 1997. Acclimation and adaptation to irradiance in symbiotic dinoflagellates. II. Response of chlorophyll–protein complexes to different photon-flux densities. Mar. Biol. 130 (1), 23–33.
Jeon, J.C., Cho, C.W., Yun, Y.S., 2005. Measurement of microalgal photosynthetic activity depending on light intensity and quality. Biochem. Eng. J. 27, 127–131.
Jorgensen, S.E., 1979. Handbook of Environmental Data and Ecological Parameters. Pergamon Press, New York.
Kirk, J.T.O., 1994. Light and Photosynthesis in Aquatic Ecosystems. Cambridge Univ. Press, Great Britain.
Lee, Y.K., 2001. Microalgal mass culture systems and methods: their limitation and potential. J. Appl. Phycol. 13, 307–315.
Markager, S., Vincent, W.S., 2001. Light absorption by phytoplankton: development of a matching parameter for algal photosynthesis under different spectral regimes. J. Plankton Res. 23 (12), 1373–1384.
Mayfield, S.P., Franklin, S.P., 2005. Expression of human antibodies in eukaryotic micro-algae. Vaccine 23, 1828–1832.
Meseck, S.L., Alix, J.H., Wikfors, G.H., 2005. Photoperiod and light intensity effects on growth and utilization of nutrients by the aquaculture feed microalgae, *Tetraselmis chui* (PLY429). Aquaculture 246, 393–404.
Miao, X., Wu, Q., 2006. Biodiesel production from heterotrophic microalgal oil. Bioresour. Technol. 97, 841–846.
Molina Grima, E.M., Garcia Camacho, F., Sanchez Perez, J.A., Contreras Gomez, A., Valdez Sanz, F., 1994. Outdoor turbidostat culture of the marine microalga *Tetraselmis* sp. Aqua. Fish. Manage. 25, 547–555.
Molina Grima, E., Fernandez Sevilla, J.M., Sanchez Perez, J.A., Garcia Camacho, F., 1996. A study on simultaneous photolimitation and photoinhibition in dense microalgal cultures taking into account incident and averaged irradiance. J. Biotechnol. 45, 59–69.
Molina Grima, E., Acien Fernandez, F.G., Garcia Camacho, F., Christi, Y., 1999. Photobioreactors: light regime, mass transfer, and scale-up. J. Biotechnol. 70, 231–248.
Molina Grima, E., Acien Fernandez, F.G., Garcia Camacho, F., Camacho Rubio, F., Christi, Y., 2000. Scale-up of tubular photobioreactors. J. Appl. Phycol. 12, 355–368.
Molina, E., Fernandez, J., Acien, F.G., Chisti, Y., 2001. Tubular photobioreactors design for algal cultures. J. Biotechnol. 92, 113–131.
Molina Grima, E., Belarbi, E.H., Acien Fernandez, F.G., Robles Medina, A., Christi, Y., 2003. Recovery of microalgal biomass and metabolites: process options and economics. J. Biotechnol. 20, 491–515.
Muller Feuga, A., Guedes, R.L., Herve, A., Durand, P., 1998. Comparison of artificial light photobioreactors and other production systems using *Potphyridium cruentum*. J. Appl. Phycol. 10, 83–90.
Muller-Feuga, A., 2000. The role of algae in aquaculture: situation and trends. J. Appl. Phycol. 35 (12), 527–534.
Pascal, A.A., Caron, L., Rousseau, B., Lapouge, K., Duval, J.C., Robert, B., 1998. Resonance Raman spectroscopy of a light-harvesting protein from the brown algae *Laminaria saccharina*. Biochemistry 37, 2450–2457.
Pulz, O., Scheibenbogen, K., 1998. Photobioreactors: Design and performance with respect to light energy input. Adv. Biochem. Eng. 59, 123–152.
Pulz, O., 2001. Photobioreactors: production systems for phototrophic microorganisms. Appl. Microbiol. Biotechnol. 5, 287–293.
Pulz, O., Gross, W., 2004. Valuable products from biotechnology of microalgae. Appl. Microbiol. Biotechnol. 65 (6), 635–648.
Richmond, A., Boussiba, S., Vonshak, A., Kopel, R., 1990. A new tubular reactor for mass production of microalgae outdoors. J. Appl. Phycol. 5, 327–332.
Rossignol, N., Lebeau, T., Jaouen, P., Robert, J.M., 2000. Comparison of two membrane-photobioreactors, with free of immobile cells, for the production of pigments by a marine diatom. Bioprocess Eng. 23 (5), 495–502.
Rusch, K.A., Malone, R.F., 1998. Microalgal production using a hydraulically integrated serial turbidostat algal reactor (HISTAR): a conceptual model. J. Aquac. Eng. 18 (4), 251–264.
Rusch, K.A., Christensen, J.M., 2003. The Hydraulically Integrated Serial Turbidostat Algal Reactor (HISTAR) for microalgal production. J. Aquac. Eng. 27 (4), 249–264.
Ryther, J.H., 1959. Potential productivity of the sea. Science 130, 602–608.
Sánchez Mirón, A., Ceron Garcia, M.C., Contreras Gómez, A., Garcia Camacho, F., Molina Grima, E., Chisti, Y., 2003. Shear stress tolerance and biochemical characterization of *Phaeodactylum tricornutum* in quasi steady-state continuous culture in outdoor photobioreactors. Biochem. Eng. J. 16, 287–297.
Scragg, A.H., Illman, A.M., Carden, A., Shales, S.W., 2002. Growth of microalgae with increased calorific values in a tubular bioreactor. Biomass Bioenergy 23, 67–73.
Spolaore, P., Joannis-Cassan, C., Joannis-Cassan, E., Isambert, A., 2006. Commercial applications of microalgae. Rev J. Biosci. Bioeng. 101 (2), 87–96.
Steele, J.H., 1965. Notes on some theoretical problem in production ecology. In: Goldman, C.R. (Ed.), Primary Production in Aquatic Environments. University of California Press, Berkeley, pp. 213–235.
Theegala, C.S. 1997. A computer automated hydraulically integrated serial turbidostat algal reactor (HISTAR): mathematical modeling and experimental analysis. Ph.D. Dissertation. Louisiana State University, Baton Rouge, LA.
Theegala, C.S., Malone, R.F., Rusch, K.A., 1999. Contaminant washout in a hydraulically integrated serial turbidostat algal reactor (HISTAR). J. Aquac. Eng. 19 (4), 223–241.
Torzillo, G., Pushparaj, B., Bocci, F., Balloni, W., Materassi, R., Florenzano, G., 1986. Production of *Spirulina* biomass in closed photobioreactors. Biomass 11, 61–74.
Torzillo, G., Carlozzi, P., Pushparaj, B., Montaini, E., Materassi, R., 1993. A two-plane tubular photobioreactor for outdoor culture of *Spirulina*. Biotechnol. Bioeng. 42, 891–898.
Tzovenis, I., De Pauw, N., Sorgeloos, P., 2003. Optimisation of T-ISO biomass production rich in essential fatty acids. I. Effect of different light regimes on growth and biomass production. Aquaculture 216, 203–222.
Ugwu, C.U., Ogbonna, J.C., Tanaka, H., 2005. Characterization of light utilization and biomass yields of Chlorella sorokiniana in inclined outdoor tubular photobioreactors equipped with static mixers. Process Biochem. 40, 3406–3411.
Watanabe, Y., Hall, D.O., 1996. Photosynthetic production of the filamentous cyanobacterium *Spirulina platensis* in a cone-shaped helical tubular photobioreactor. Appl. Microbiol. Biotechnol. 44, 693–698.
Woodward, J., Orr, M., Greenbaum, E., 2000. Biotechnology: Enzymatic production of biohydrogen. Nature 405 (6790), 1014.
Xu, H., Miao, X., Wu, Q., 2006. High quality biodiesel production from a microalga Chlorella protothecoides by heterotrphic growth in fermenters. J. Biotechnol. 126, 499–507.
Zou, N., Richmond, A., 1999. Effect of light-path length in outdoor flat plate reactors on output rate of cell mass and of EPA in *Nannochloropsis* sp. J. Biotechnol. 70 (13), 351–356.