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Research Article

Impact of light quality and quantity on growth rate kinetics of *Selenastrum capricornutum*

Microalgal biomass produced in indoor photobioreactors can be used as inoculum for large-scale outdoor cultures or directly for the production of high-value bioproducts due to the higher control of these cultures compared with outdoor systems. One of the main costs of indoor microalgal cultures is the illumination. This work can be used as a basis for the optimization of the light source for indoor microalgal biomass production, based on the light source type, irradiance, productivity, growth rate, attenuation coefficients, and contaminant growth on the reactor's side-walls. Four commercially available near 400-W artificial light sources for microalgal cultures (metal halide (MH), high-pressure sodium (HPS), Son Agro®, and fluorescent) were compared. The light elevation and the surface scalar irradiance were shown to have a linear relationship. The attenuation coefficient in air (k_a) was highest with Son Agro®. A linear partition of the attenuation coefficient between the water and biomass and an exponential relationship between average scalar irradiance and depth were found. An empirical overall scalar attenuation coefficient for each light source was obtained. The lowest maximum observed growth rate was obtained with fluorescent light ($0.98\,d^{-1}$) and the highest with Son Agro® ($2.39\,d^{-1}$). The highest growth on the reactor's wall was obtained with Son Agro®. Further studies resulted in a higher maximum specific growth rate and optimum irradiance for HPS ($2.37\,d^{-1}$ and $460\,\mu mol\,s^{-1}\,m^{-2}$) compared with those observed with MH ($1.73\,d^{-1}$ and $391\,\mu mol\,s^{-1}\,m^{-2}$).

Keywords: Attenuation coefficient / Light dynamics / Light source / Microalgal culture / Spectrum

Received: December 6, 2010; *revised:* April 10, 2011; *accepted:* May 2, 2011

DOI: 10.1002/elsc.201000217

1 Introduction

Industrial microalgal cultivation for bio-products, third-generation biofuel production and CO_2 sequestration has seen tremendous interest over the past several years [1–6]. These efforts have increased due to rise in oil prices [7–9], the efforts to reduce CO_2 emissions and the large acreage needed for bioethanol [3]. Microalgal-based biofuel is a renewable resource, has no net emissions of CO_2 or sulfur to the atmosphere and [10] and can be produced on land with low agricultural value and low-quality water. Other processes, such as distillation, fermentation, or catalytic conversion can be used to obtain fatty acids, glycerol, alcohols [10–13], and other high-value components (β-carotene, ω-3 fatty acids, bioplastics, etc) [4, 14–19]. While microalgal production costs are curently higher than terrestrial crops, their greater photosynthetic efficiency results in higher productivity [5, 20–22].

Several methods are being considered for the production of microalgae [2, 3, 23–25]. Open-ponds/raceways have been favored due to lower capital cost and operational simplicity [6, 15, 24, 26–28], but the use of these systems for intensive, high-yield cultures can be problematic. Open systems are vulnerable to environmental conditions and to contamination that can reduce productivity or even collapse a culture [2, 29]. Microalgal photobioreactors represent a higher yield alter-

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Abbreviations: **HPS**, high-pressure sodium; **HISTAR**, Hydraulically Integrated Serial Turbidostat Algal Reactor; **MH**, metal halide; **PAR**, photosynthetically available radiation; **TSS**, total suspended solids

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native to extensive systems [28, 31–33], but with a higher capital investment. A likely scenario for industrial scale production is the use of both enclosed photobioreactors and open ponds/raceways in a hybrid system. This strategy will take advantage of the higher densities and quality of the culture that can be obtained in closed systems [2, 6, 24, 25, 33, 34] to produce a high-quality inoculum and the lower cost of open ponds [15, 27, 35, 36] for biomass production.

Regardless of design, all phototrophic culture systems must consider the interrelationship of light energy with cell growth, culture density, and accumulation of the desired bioproduct [30, 37–42] such as lipids, proteins, bioactive compounds, biopolymers, and others. Light energy is the main limitation of microalgal growth [2, 26, 21, 43]. While each microalgal species will have specific light requirements, the photosynthetic efficiency can be optimized through culture depth, mixing, dilution rate, or hydraulic retention time and the spectral distribution of the natural or artificial light source [28, 44–47]. A general understanding of the relative impact of light quantity and quality on the microalgal culture for a specific reactor design can be gained by direct comparison of the growth kinetics under varying artificial light sources. Understanding the effect of quality and quantity of light on microalgal growth can provide valuable guidelines for the system design.

Irradiance in an aqueous medium can be quantified in terms of incident (downward) or scalar (all directions). Photosynthetically available radiation (PAR) represents the energy contained between the wavelengths of 400–700 nm. Scalar (PAR) is most representative of the light energy available to microalgal cultures [48]. In highly turbid waters, such as microalgal cultures, the ratio of scalar PAR/downward incident PAR can be as high as 2.5 [49]. The spectral distribution of a light source can affect the diffusion of photons in air [50] and their absorbance in the aqueous media [49, 51, 52] due to changes in photon energy at different wavelengths [53]. Therefore, the diffusion coefficient in air (k_a) and aqueous media (k_0(PAR)) [38] and the spectral distribution will vary for each light source and depth [54–56].

The changes in spectral distribution affect microalgal growth and composition [57–59]. Insufficient photon energy can hinder microalgal growth, but photoinhibition can occur at high scalar irradiance [60]. Self-shading depends on the culture depth, reactor configuration, dilution, and mixing rates. Self-shading reduces the scalar irradiance in the culture system [55, 56, 61, 62]. The optimal average scalar irradiance (I_{opt}) and maximum growth rate (μ_{max}) for a microalgal species will vary for each light source. The relationship between these two parameters and the spectral output of the light source is complex and perhaps qualitative in nature. While these relationships are highly empirical in nature, they tend to follow the Lambert–Beers law. Defining the attenuation coefficients in air and aqueous media, the μ_{max} and the optimum irradiance for specific light sources provides information for the optimization of the lighting system in an algal culture.

In this work, four commercially available light sources: metal halide (MH), high-pressure sodium (HPS), a blue light-enhanced HPS (Son Agro®), and cool white compact fluorescent lamps (fluorescent) were compared. The comparison was based on the k_a (air attenuation coefficient), k_w (water attenuation coefficient), and k_b (biomass attenuation coefficient) effects on culture growth and promotion of contaminant wall growth. This work provides a basis to understand the effects of the light source on microalgal productivity in culture systems similar to the one developed in our work group (Hydraulically Integrated Serial Turbidostat Algal Reactor) (HISTAR) and facilitates the optimization of the light utilization. The results with respect to microalgal growth and biofouling can be used as a reference for the election of light sources in other bioreactor designs.

2 Materials and methods

Four light sources, MH, HPS, Son Agro®, and fluorescent were compared to determine the best light source for a microalgal culture system. A suite of experiments with the four light sources was conducted to determine: (i) surface scalar irradiance (I_{os}(PAR) as a function of light elevation (E); (ii) scalar irradiance (I_z(PAR)) with respect to depth (z) and biomass (X); (iii) average scalar irradiance (I_a(PAR)) in reactor with respect to biomass concentration ; (iv) net specific growth rate (μ) with respect to I_a(PAR)); and (v) wall growth biomass after 28 days. The relationships among these parameters for the different light sources were estimated and compared. The two light sources with the best performance were further studied to obtain I_{opt}(PAR), and μ_{max}.

2.1 Experimental setup

To determine the effect of the light sources on the microalgal growth, an experimental unit based on the design of the HISTAR developed at LSU [31, 63] was used. The experimental unit is a completely mixed (by a 7.62 cm diameter airlift, with 40 LPM air flow) vertical open-top cylinder, (92.7 cm diameter) with a culture depth of approximately 65.7 cm (Fig. 1). The reactor received surface illumination. Irradiance was measured at the surface and at different depths of the culture. During the growth rate studies, the experimental unit was operated in a batch mode for better control of the experiments. The light studies were performed in the flow-through mode so the culture could be maintained at specific concentrations for the duration of each experiment.

Four light sources were selected based on the similarities between the spectral output and the wavelengths of highest quantum yield for green algae (Fig. 2; [68]). All experiments were executed using continuous lighting from 400 W MH, 400 W HPS, 430 W Son Agro®, and eight 42 W (total 336 w; the closest to 400 W available) compact fluorescent light sources.

Selenastrum capricornutum, a common model organism, was selected as the experimental species. The experiments were performed at $28 \pm 1^{\circ}C$. CO_2 was used to maintain the pH at 7 ± 0.4. F/2 media (Kent Marine) was continuously fed to maintain a target of 4 mg NO_3-N L^{-1} and less than 2.25 mg PO_4-P L^{-1}. Once the algal culture was established, biomass density was monitored through optical density (OD) according to Standard Methods 8111G.4c ([69]; UV spectrophotometer absorbance at 750 nm). A regression of total suspended solids (TSS) and OD was developed at the end of

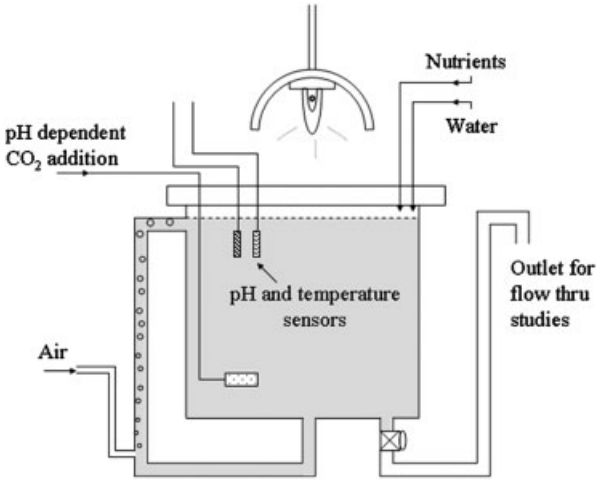

Figure 1. A schematic diagram of the experimental unit that was designed to replicate an individual CFSTR in the HISTAR.

each study and used to calculate biomass concentration (TSS, g dry wtm^{-3}) based on OD. Scalar irradiance was measured using a bulb quantum sensor (Li-Cor model LI-1935A).

2.2 Light elevation study

The relationship between light elevation (E) and I_{os}(PAR) was investigated to optimize E. The inverse relationship of light intensity and distance of the source [50, 70] can be modified by reflectors and other characteristics of light sources and will affect the attenuation coefficient of the irradiance before it reaches the water surface. The parameters I_{Eo} and k_a were estimated following a linear relationship (Eq. 1) [38].

$$I_{os}(\text{PAR}) = I_{E0} - \text{k}_a E \tag{1}$$

I_{os}(PAR) was measured with each light source at nine elevations (E), between 25.4 and 45.7 cm above the culture surface. It was expected that above 46 cm the light source would become ineffective and below 25.4 cm it would be logistically impractical due to splashing from the culture. For the measurements, the light was centered over the reactor insure symmetrical surface light distribution. The culture surface area was divided into four concentric rings. Light readings were taken centrally within one of the four rings. The readings were taken at the center and at 12.7, 25.4, and 38.1 cm out from the center. An area-weighted average of the surface light was calculated.

2.3 Light attenuation studies

Triplicate studies were conducted at three different biomass concentrations for each light source to determine the relationship between z, I_a(PAR), and X and to estimate the k_0(PAR). Although the Beer–Lamberts law assumptions that include low biomass density, monochromatic light and unidirectional light path [54, 71–74] do not necessarily hold true for photobioreactors, the Beer–Lamberts law (Eq. 2)

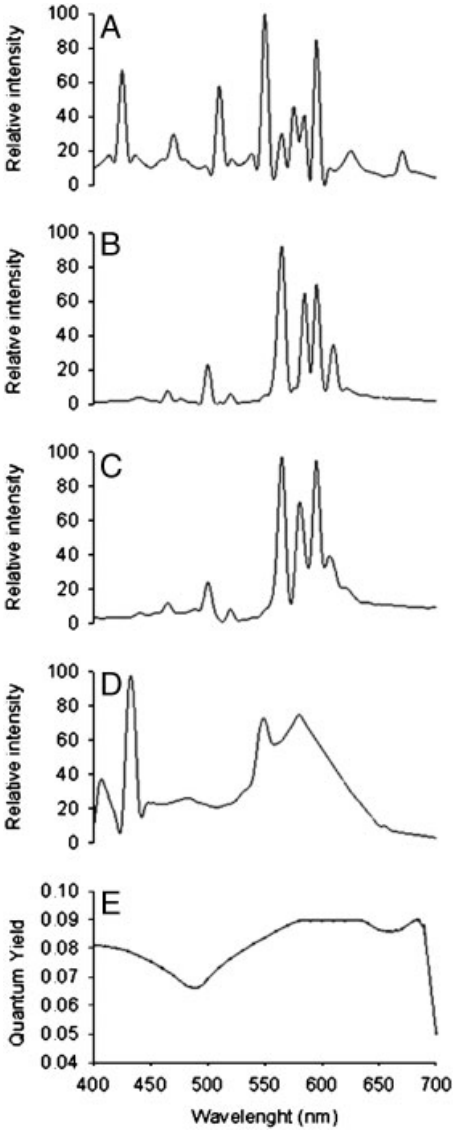

Figure 2. The light spectrums of four light sources; (A) metal halide (after [64]); (B) HPS (after [65]); (C) Son Agro® (after [66]); (D) Fluorescent light (after [67]); and (E) Quantum yield of *Chlorella* cells (after [68]).

represents a reasonable and widely used approach for investigation of light attenuation. Algal species vary in pigment composition and therefore have different active absorption spectral profiles. Therefore, an approach where the overall scalar attenuation coefficient (Eq. 3; [38]) is a function of separate water and biomass attenuations is more adequate in high-density and deeper cultures.

$$I_z(\text{PAR}) = I_{os}(\text{PAR})\text{e}^{-k_0(\text{PAR})z} \tag{2}$$

$$k_0(\text{PAR}) = k_w(\text{PAR}) + k_b(\text{PAR})X \tag{3}$$

I_z(PAR) was measured at 3.81 cm depth increments with an LI-COR 1000 with an underwater spherical quantum sensor. Horizontal readings were taken at 0, 12.7, 25.4, and 38.1 cm

from the center of the reactor. The volume of the reactor was thus sliced into 12 horizontal discs and each disc divided into four concentric rings as in the surface light studies. The light reading locations were central to the volume of each ring. An area-weighted average for each disc was calculated.

Beer–Lamberts law (Eq. 2) was used to describe light penetration in the microalgal culture. X was factored into k_0 (Eq. 3) in the exponential equation. The k_0(PAR) for each light source was estimated through a nonlinear regression of I_z versus depth for the nine light attenuation studies with each light source. A linear regression of the nine k_0(PAR) for each light source was used to estimate k_w and k_b. The regressions were calculated using the SigmaPlot® Windows ver. 11 (Systat Software, 2008).

The I_a(PAR) within the reactor was determined using Eq. (4). This analysis was repeated for various biomass concentrations to determine the relationship between X and I_a(PAR).

$$I_a(\mathrm{PAR}) = \frac{1}{d}\int_0^d I(z)\mathrm{d}z = \frac{I_{os}(\mathrm{PAR})(1 - e^{-k_0(\mathrm{PAR})\cdot d})}{(k_0(\mathrm{PAR})\cdot d)} \quad (4)$$

2.4 Growth kinetics

A series of growth kinetic studies was conducted to determine the relationship between μ and I_a(PAR) and estimate growth-kinetic parameters (i.e. I_{opt} and μ_{max}) of the Steele's model for the two most promising light sources. Several models of microalgal growth kinetics have been proposed attempting to address photoinhibition. Steele's model (Eq. 5; [75]) is one of the simplest that includes photoinhibition at high light levels and is adequate for modeling growth in shallow batch reactors [40, 55, 61, 76, 77].

$$\mu = \mu_{max}\frac{I_a(\mathrm{PAR})}{I_{opt}(PAR)}e^{1-\frac{I_a(\mathrm{PAR})}{I_{opt}(\mathrm{PAR})}} \quad (5)$$

Preliminary investigations in the experimental unit estimated the maximum observed growth (μ_{mxob}) for comparison of all four light sources. The relationship between I_a(PAR) and X (Eqs. 2–4) was used to determine the average scalar irradiance at 4-h intervals during the development of biomass–growth curves for each light source. OD of the microalgal culture in the experimental unit was recorded in triplicate at 4-h intervals from three sample locations within the reactor. A regression of TSS versus OD at 750 nm was developed to allow determination of the biomass concentration as TSS (g dry wtm^{-3}) based on OD readings. The experiments were continued until the stationary growth phase was reached. The μ_{mxob} was estimated, for each of the four light sources, by the maximum slope of the plot of the natural log of TSS over time.

Growth rate studies were conducted at higher light intensities, where photoinhibition may occur to estimate the parameters and best model of the relationship between I_a(PAR) and μ (Eq. 5), using μ_{maxobs} as an estimate of μ_{max}. A 2-L reactor was constructed and a bulb quantum sensor centrally positioned in the bottom. Ten different growth studies similar to those conducted in the experimental unit, five for MH and five under HPS light were completed in this smaller reactor. The other two light sources were not used due to undesirable performance in the preliminary growth studies (poor growth or high side-wall growth).

2.5 Side-wall growth studies

The side-wall growth promoted by the four light sources was estimated through the biomass coverage of the walls of the experimental unit. Wall scrapings (area = 6.452 cm^2) were collected in three vertical transects at 5.08 cm increments after 28 days of culture growth. The mean dried weight (mg dry wtcm^{-2}) was determined for all the sample sites along the transects.

2.6 Statistical analysis

Definition of the relationships and parameter estimation was achieved by regression analysis using the SigmaPlot® 11.0 (Systat Software, 2008). The correlation coefficient for the k_a of the light sources was calculated and t-tests [78] were performed to determine differences. The k_0(PAR) was calculated by a non-linear regression (exponential) of I_z(PAR) versus z. A linear regression of k_0(PAR) versus X was used to determine k_w and k_b.

3 Results and discussion

3.1 Light elevation studies

The relationship between I_{os}(PAR) and E was determined and k_a was estimated for each of the four light sources (Fig. 3, Table 1). The k_a values provided an estimation of the attenuation of the irradiance between the light source and the culture surface. The k_a for Son Agro® and MH lights showed no significant difference ($p = 0.326$), and were higher than the other light sources (7.78 and 7.46 μmol s^{-1} m^{-2} cm^{-1}). The HPS and fluorescent lights had k_a of 5.32 and 0.69 μmol s^{-1} m^{-2} cm^{-1}, respectively. The low k_a for the fluorescent light indicates that a large part of the irradiance reaches the culture surface.

The optimization of E minimizes photolimitation due to low I_a(PAR) while avoiding photoinhibition at the surface due to high I_{os}(PAR). Some reactors are designed to minimize the distance between the light source and the microalgal culture [79], but the coexistence of photolimitation and photoinhibition [55, 61, 62] requires optimization and not just minimization of E. The mean surface scalar irradiance (I_{os}(PAR)) values for MH, HPS, Son Agro®, and fluorescent light at $E = 35.6$ cm (the mid-range of the elevations investigated) were 330, 378, 467, and 74 μmol s^{-1} m^{-2}, respectively. Photoinhibition is negligible at this elevation for all light sources. The light reaching the surface of the culture (I_{Eo}) per unit of electric power was 1.73, 1.43, 1.50, and 0.30 μmol s^{-1} m^{-2} W^{-1}) for the Son Agro®, HPS, MH, and fluorescent light respectively. Mean I_{os}(PAR) under Son Agro® lamps at 25.4 cm elevation was 551 μmol s^{-1} m^{-2} thus photoinhibition needs to be considered under Son Agro® light at 25.4 elevation or less.

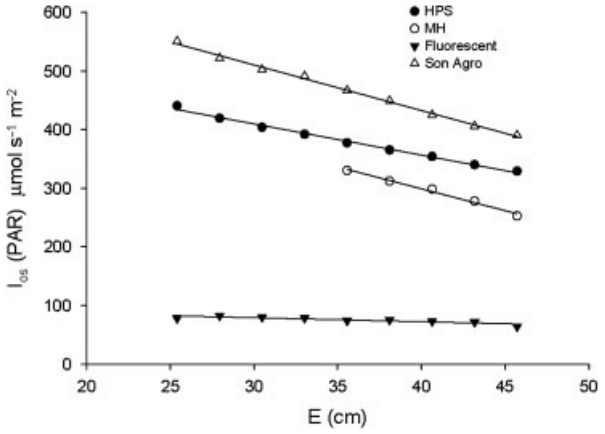

Figure 3. Relationship of surface scalar irradiance (I_{os}(PAR)) and elevation of the light source (E; cm) in the experimental unit under MH, HPS, Son Agro®, and fluorescent light (valid for $E_n = 25.4$ cm to 45.7).

Table 1. The estimated parameters associated with the various studies on the light and growth rate dynamics in an microalgal reactor under MH, HPS, Son Agro®, and compact white fluorescent light

Light source	Light elevation	Light attenuation	Growth rate
	I_{Eo} (µmol s^{-1} m^{-2}) k_a (µmol s^{-1} m^{-2} cm^{-1})	$k_0 = k_w + k_b X$ (m^{-1})	μ_{max} (d^{-1}) I_{opt} (µmol s^{-1} m^{-2})
Metal halide	$I_{Eo} = 598$ $k_a = 7.46$	$1.97 + 0.0575X$	$\mu_{max} = 1.73$ $I_{opt} = 391$
High pressure sodium	$I_{Eo} = 570$ $k_a = 5.32$	$1.91 + 0.0659X$	$\mu_{max} = 2.37$ $I_{opt} = 460$
Son Agro®	$I_{Eo} = 744$ $k_a = 7.78$	$1.65 + 0.0630X$	Not estimated
Fluorescent	$I_{Eo} = 100$ $k_a = 0.69$	$1.74 + 0.0813X$	Not estimated

3.2 Light attenuation studies

The relationship between z, I_a(PAR), and X and the k_0(PAR) for each of the light sources was investigated. The graphs obtained with the fluorescent and Son Agro® light sources are presented for illustration purposes (Fig. 4). Four representative examples of the decay constant calculation for each light source are plotted in Fig. 5. A linear regression of the decay constant (k_0(PAR) = $k_w + k_b X$) versus X was used to obtain the water (k_w) and biomass (k_b) components of k_0.

The k_w was higher for MH, followed by HPS, fluorescent, and Son Agro® light sources (Table 1). The attenuation due to biomass (k_b) was higher for the fluorescent light, followed by HPS, Son Agro®, and MH. The k_0(PAR) values estimated in the studies are similar to those reported by Desmit et al. (2005) for estuaries under natural solar irradiance. The attenuation due to the biomass ($k_b = 0.0575$–0.0813 m^2 g^{-1}) is comparable

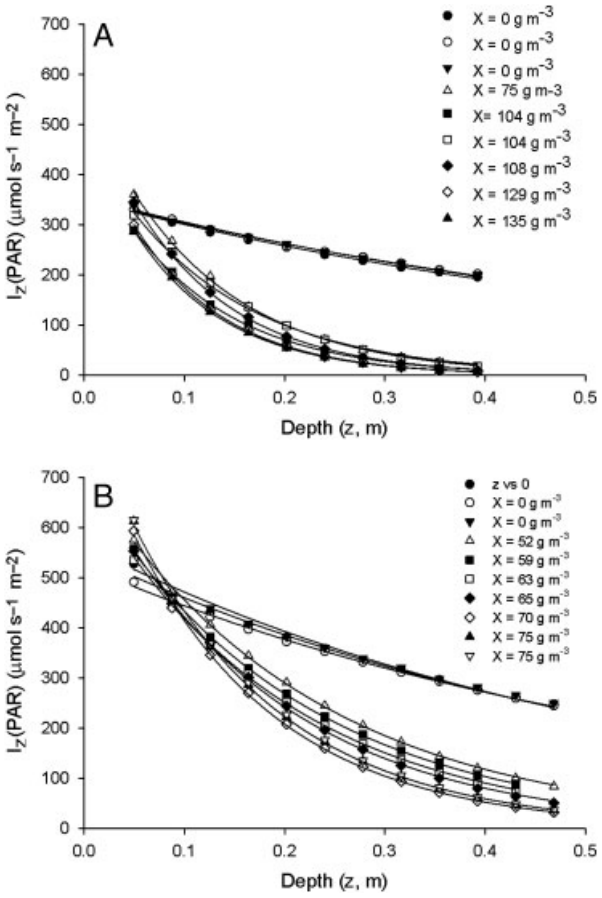

Figure 4. Examples of the light attenuation studies performed. (A) Fluorescent; (B) SonAgro® light sources.

to the results obtained by other authors [32, 61, 80] that estimated biomass absorption coefficients in the range of 0.0369–0.1035 m^2 g^{-1} for three microalgal species cultured under outdoor conditions. The comparison of these results, although obtained with a different calculation method, indicates that the patterns of attenuation of artificial illumination are similar to those of the natural light. The higher k_b and lower I_{E0} per watt of the fluorescent light indicate that this lamp is less efficient than the other three.

3.3 Growth kinetics and side-wall growth

The growth kinetics under light intensities and dynamics typical of HISTAR was investigated. Biomass concentration increased much faster under the MH, HPS, and Son Agro® compared with the fluorescent light (Fig. 6). The culture under the fluorescent light experienced a longer lag time of 130 h, compared with less than a 16-h with the other light sources. The longer lag and slower growth observed was probably due to the higher attenuation of the fluorescent light, making this light source less desirable for HISTAR. The growth rate under MH and HPS and Son Agro® lights was similar, but Son Agro® achieved a higher biomass concentration. This may

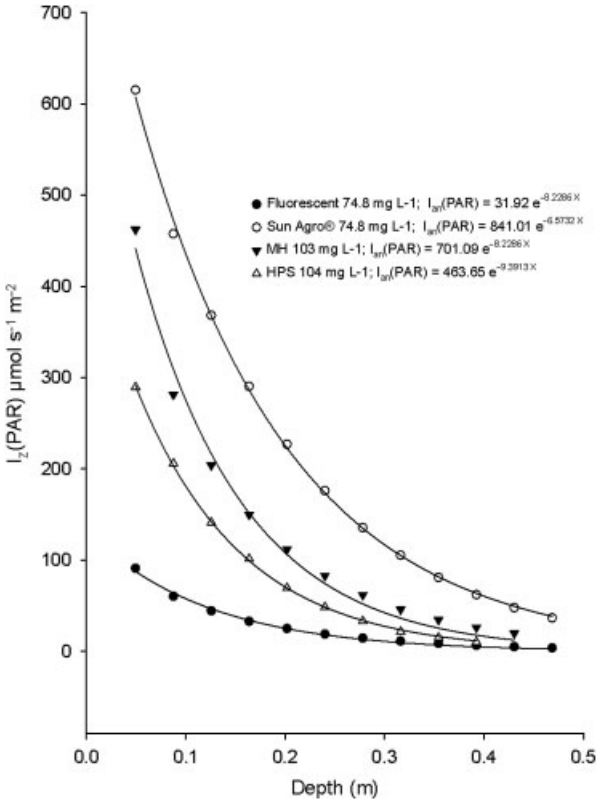

Figure 5. Examples for each of the four light sources (metal halide, HPS, Son Agro®, and fluorescent light) of the curves developed during the light attenuation study: four plots of average light scalar irradiance at a given depth. Each example light attenuation regression was taken at different but similar biomass concentrations as indicated in the figure.

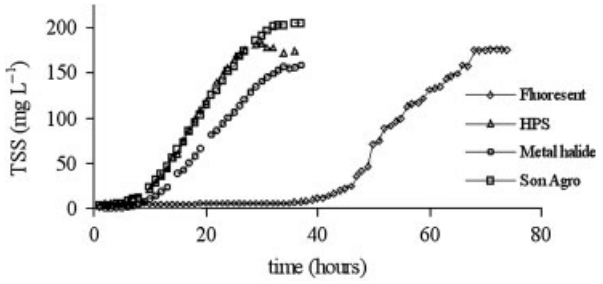

Figure 6. The change in biomass concentration in the experimental unit over time during growth rate studies under metal halide, HPS, Son Agro®, and fluorescent light.

indicate that in a series of CFSTRs, where the last CFSTR has higher biomass concentrations, Son Agro® may help to maintain a dense culture. The higher irradiance obtained with the Son Agro® may have promoted the higher biomass concentration with this source, compared with the other light sources, but the difference with HPS was not significant.

Cultures under fluorescent light had a much lower μ_{mxob} ($0.051\,h^{-1}$ or $1.224\,d^{-1}$) than with the other sources. The other three light sources had similar μ_{maxob} values ($1.81\,d^{-1}$ under MH light, $2.29\,d^{-1}$ for Son Agro® and 2.16 for HPS). The microalgal culture under Son Agro® grew well but crashed prior to 28 days due to wall-growth contamination. The higher irradiance obtained with the Son Agro® may have allowed more light to reach the wall of the reactor, promoting the growth of sessile algae. Wall-growth is composed of algae different than the target species and can maintain a population of predators. The predators can consume the microalgae in the culture, while the algae growing in the walls can compete for nutrients with the desired species and in some cases produce compounds harmful for the culture health [42].

Since μ_{max} varies with by microalgal species and light source, a culture can benefit from a light source that promotes desirable species and selects against undesirable ones [59]. Although HISTAR minimizes suspended growth contaminants by flushing them out, it does not address attached wall growth [63, 81]. Wall growth has been mentioned as one of the disadvantages of closed photobioreactors [42, 82]. The wall-growth cover under Son Agro® light after 28 days ($9.5\,mg\,cm^{-2}$) was 19 times that of the other three light sources, rendering it undesirable for microalgal cultures. The wall growth was $0.5\,mg\,cm^{-2}$ under MH light and $0.2\,mg/cm^{-2}$ under fluorescent light. No noticeable wall growth occurred under the HPS light source.

Studies at higher light intensities were done in a 2-L reactor under the most promising light sources (MH and HPS). Regression analyses of I_a(PAR) versus μ_{maxob} based on the Monod, Molina Grima, and Steele models were performed. Steele's equation was the best fit to the data since they were an exponential peak function. Acien Fernandez [55] found that Steele's equation adequately models photoinhibition in shallow or moderate density cultures but as density and self-shading increases the hyperbolic function becomes more appropriate. This self-shading effect on the relationship between I_a(PAR) and μ occurs due to maximal growth and photo-limited growth deep in the reactor simultaneous to photoinhibited growth near the surface [61]. Though Steeles equation represents well the data of the studies in 2 L reactors, hyperbolic function may be more appropriate for deeper and/or more concentrated cultures.

The nonlinear regression resulted in an estimated μ_{max} under MH light of $1.73\,d^{-1}$ ($p<0.0001$) at an I_{opt}(PAR) of $391\,\mu mol\,s^{-1}\,m^{-2}$. The μ_{max} under HPS light was estimated to be $2.37\,d^{-1}$ ($p<0.0001$) at an I_{opt}(PAR) of $460\,\mu mol\,s^{-1}\,m^{-2}$. The ranges of irradiance to obtain a $\mu>95\%$ of μ_{max} were $260–540\,\mu mol\,s^{-1}\,m^{-2}$ and $330–620\,\mu mol\,s^{-1}\,m^{-2}$ for MH and HPS respectively The values of μ_{max} calculated are comparable with those obtained by other authors [83–85] that reported a μ_{max} range of $1.59\,d^{-1}$ to $2.0\,d^{-1}$. Average scalar irradiances in the experimental unit never reached the estimated I_{opt}(PAR) under MH or HPS. Photo inhibiting I_a(PAR) values were seldom observed throughout the studies in the experimental unit and only at the surface of the culture. Therefore, photoinhibition was not a significant problem during this study but may be observed if higher electric power (wattage) is considered. Photoinhibition has been reported in literature in parts of the reactors closer to the light sources [86].

I_a(PAR) with the HPS light source (191 μmol s^{-1} m^{-2}) during the growth studies was much lower than I_{opt}(PAR), An increased wattage in HPS light sources should be considered for HISTAR. Studies with higher wattage light sources should be done in the CFSTRs with lower biomass concentration when photoinhibition is more likely to occur.

3.4 Implications for the HISTAR system

The results of these studies indicate that MH and HPS light source would be the most appropriate for the HISTAR lighting system. Fluorescent light performed poorly in the growth rate studies and Son Agro® encouraged contaminant wall growth. Son Agro® promoted the highest microalgal growth and might be good for use in the last CFSTR of the HISTAR in which X determines the system productivity. Son Agro® light enhances μ of the suspended culture and can maintain denser X. Since the last CFSTR has a shorter remaining system residence time than the other CFSTRs contaminant wall growth species is likely to be washed from the system prior to establishment.

The suboptimal I_a(PAR) values observed in all the experimental unit studies indicate that the elevation of the light sources should be reduced to the minimal practical distance (25.4 cm). All the cultures grown in the experimental unit were initially light limited or became light limited once they reached X = 25 mg dry wt L^{-1} (under Son Agro®). Furthermore, irradiance values above the estimated I_{opt} were rarely observed and are not a significant issue under the light sources investigated. An alternative strategy for reducing light limitation in the CFSTRs would be to decrease culture depth.

4 Concluding remarks

The light dynamics and growth kinetics of microalgal cultures under near 400-watt MH, HPS, Son Agro® and fluorescent light sources where compared. The cool white compact fluorescent light promoted lower growth rates, compared with other light sources due to low average light intensity (high attenuation). The Son Agro® provided the greatest photo energy of the needed spectrum to the microalgae but unfortunately, it encouraged contaminating wall growth resulting in a crashed suspended culture. This light source may be successful in the last CFSTRs in systems like HISTAR where the suspended biomass concentration is high and the remaining system residence time is low. Although MH was an adequate light source, culture under HPS light had the best performance. The μ_{max} value of 2.37 d^{-1} for cultures under these light sources is higher than previously reported. Furthermore, wall growth appeared to be inhibited by this light source. The I_{opt} estimated for this light source was 460 μmol s^{-1} m^{-2}. The light intensity range for optimal growth (330 and 620 μmol s^{-1} m^{-2}) was not observed in the culture in the experimental unit. Therefore, wattage higher than 400-W should be considered if cost allows it. The optimal culture depth should also be considered as a strategy for addressing light limitation in HISTAR and similar systems.

Nomenclature

μ_{max}	[d^{-1}]	maximum specific growth rate
μ_{maxob}	[d^{-1}]	maximum observed specific growth rate
μ	[d^{-1}]	specific growth rate
d	[m]	depth of culture in CFSTR
E	[cm]	elevation of the light source over a CFSTR
I_a(PAR)	[μmol s^{-1} m^{-2}]	average scalar irradiance in CFSTR
I_{Eo}	[μmol s^{-1} m^{-2}]	surface irradiance when $E = 0$
I_{opt}(PAR)	[μmol s^{-1} m^{-2}]	optimum scalar irradiance
I_{os}(PAR)	[μmol s^{-1} m^{-2}]	surface irradiance
I_z(PAR)	[μmol s^{-1} m^{-2}]	scalar irradiance at z depth
k_0(PAR)	[m^{-1}]	overall scalar attenuation coefficient $= k_w + k_b X$
k_a	[μmol s^{-1} m^{-2} cm^{-1}]	light diffusion coefficient in air
k_b	[m^2 g^{-1}]	biomass attenuation coefficient
k_w	[m^{-1}]	water attenuation coefficient
U	[d^{-1}]	net specific growth rate in CFSTR
X	[g dry wt m^{-3}]	concentration of biomass in CFSTR
z	[m]	sample depth

This research was supported by the Louisiana Sea Grant Collage Program. The authors thank Marisa Sylvester, Nia Harris, Craig Plaisance and Finlay Moriasi for their assistance in the collection of the data.

The authors have declared no conflict of interest.

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