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Breathable waveguides for combined light and CO₂ delivery to microalgae

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ABSTRACT

Suboptimal light and chemical distribution (CO₂, O₂) in photobioreactors hinder phototrophic microalgal productivity and prevent economically scalable production of biofuels and bioproducts. Current strategies that improve illumination in reactors negatively impact chemical distribution, and vice versa. In this work, an integrated illumination and aeration approach is demonstrated using a gas-permeable planar waveguide that enables combined light and chemical distribution. An optically transparent cellulose acetate butyrate (CAB) slab is used to supply both light and CO₂ at various source concentrations to cyanobacteria. The breathable waveguide architecture is capable of cultivating microalgae with over double the growth as achieved with impermeable waveguides.

KEYWORDS

Microalgae
Cyanobacteria
Waveguide
Membrane contactor
Photobioreactor

ABBREVIATIONS: PBR, photobioreactor; OD_{750nm}, optical density at 750 nm; CAB, cellulose acetate butyrate; PET, polyethylene terephthalate.

1. INTRODUCTION

Microalgal-based photobioreactors (PBRs) are a promising technology for renewable biofuel and high-value bioproduct generation. (Angermayr et al., 2015; Kumar et al., 2011; Savakis and Hellingwerf, 2015). Given the strong dependence of microalgal photosynthesis on light intensity and chemical concentration (CO_2 , O_2), optimal production necessitates tight control of these conditions throughout (Carvalho et al., 2011; Kumar et al., 2011; Savakis and Hellingwerf, 2015). While open pond PBRs benefit from design simplicity (Medipally et al., 2015), they have not been cost-effective due to light and chemical supply limitations that cause gradients throughout the reactor that limit photosynthetic efficiency and culture density (Brennan and Owende, 2010; Norsker et al., 2011; Richardson et al., 2012). In contrast, closed PBRs allow greater photosynthetic productivities and densities (Brennan and Owende, 2010; Norsker et al., 2011; Olivieri et al., 2014; Posten, 2009), due to improved light distribution and CO_2 and O_2 transport (Posten, 2009). However, strategies that benefit light distribution often negatively impact chemical control, and vice versa (Norsker and Barbosa, 2012).

Delivering the optimal amount of light to cells is critical to reactor design (Graham et al., 2015). Illumination control in closed PBRs has traditionally been accomplished by turbulent perfusion (Norsker and Barbosa, 2012; Norsker et al., 2011). Turbulent mixing and bulk flow moves cells through a light gradient for time-averaged intensity exposure (Posten, 2009). While effective, this fluid circulation is energy-intensive, and is impractical at large scales (Nagarajan et al., 2013; Norsker and Barbosa, 2012). For example, in tube pilot plant reactors, liquid pumping requires 53 – 60% of operational power (Acien et al., 2012; Norsker and Barbosa, 2012). These approaches bring cells to light. An alternative

illumination strategy is to distribute light to cells via waveguides in reactors. Waveguiding distributes light through large volumes of culture, and shifts operational cost (pumping) to capital cost (material). Recently, reactors using planar waveguides have demonstrated improved light distribution, photosynthetic productivity, cell density, and modular scalability (Ahsan et al., 2015; Pierobon et al., 2014). However, waveguides developed to date occupy significant reactor volumes (5 – 33%), limiting volumetric productivity (Ahsan et al., 2015; Dye et al., 2011; Xue et al., 2013). Furthermore, all waveguide reactor strategies reported to-date are impermeable, choking cultures of vital CO₂.

Control of the chemical environment is also critical to photobioreactor operation. One traditional approach is to bubble CO₂ at a single node and circulate the culture through the reactor loop. This approach suffers from chemical hold-up in the reactor, that is, CO₂ depletion and O₂ accumulation. The alternative approach is to bubble CO₂ throughout reactor panels. Bubbling throughout the illuminated culture in flat panel reactors effectively removes chemical gradients and enables the greatest productivities, densities and photosynthetic efficiencies. However, bubbles on the top surface of the reactor panels scatter light strongly. Thus, improved chemical transport is achieved at the expense of light distribution and usage (Janssen et al., 2003). Bubbling is also expensive. In tube pilot plant reactors, active aeration and CO₂ costs are respectively 7 – 16% and 15 – 44% of nutrients-plus-utilities costs (Acién et al., 2012). Further, aeration and CO₂ costs are each 5 – 10% of capital-plus-operation costs (Nagarajan et al., 2013; Norsker et al., 2011). Alternative aeration architectures based on nanoporous membrane contactors achieve single-phase gas-to-liquid mass transfer, and cost-effective CO₂ delivery and utilization (Bilad et al., 2014; Gabelman and Hwang, 1999; Markov et al., 1995). Recently, hollow fiber membrane

contactors have demonstrated enhanced mass transfer of CO₂ to cells in photobioreactors (Ahsan et al., 2015; Kalontarov et al., 2014; Kim et al., 2011). With high density cultures, however, a high density of hollow fibers is required to avoid CO₂ limitations (Ahsan et al., 2015; Kalontarov et al., 2014). While membrane contactors clearly show promise for photobioreactors, and have been deployed at scale in waste water treatment (Bilad et al., 2014; Judd, 2011), all current efforts involved opaque membrane materials that block light.

In this work, an integrated illumination and aeration architecture is demonstrated, using a single transparent, hydrophobic, nanoporous material - a breathable waveguide - to simultaneously distribute light and CO₂ throughout a microalgal culture. Use of a single surface for combined delivery leverages the similar length scale of light and CO₂ dispersion (mm to cm) in high density cultures (Janssen et al., 2003; Ni and Pereira, 2000). The phototrophic biomass growth of batch cultures of *S. elongatus* were evaluated in carbon-limited and -replete conditions, using cellulose acetate butyrate first as a contactor for CO₂ permeation alone, and then as a breathable waveguide. Positive growth response to CO₂ permeation was observed and double the growth was achieved with waveguide illumination and breathability as compared to waveguide illumination alone.

2. MATERIALS AND METHODS

2.1 Microorganism and cultivation

The microalgae used for all experiments was a T2SE-null mutant of the freshwater cyanobacteria *Synechococcus elongatus* PCC 7942 with kanamycin resistance, donated by Professor Rakefet Schwarz (Bar-Ilan University, Israel). The mutation permits biofilm growth, but this capacity was not used. This species was selected for its high-affinity carbon uptake in CO₂-rare media, which enabled clear evaluation of CO₂-limited growth

(Price et al., 2004; Woodger et al., 2005). Additionally, *S. elongatus* is a model organism in photosynthetic studies, and is one of four microalgal species that have received great attention as direct producers of high-value biofuels and bioproducts, due to their amenability to genetic modification. Ethanol, isobutyraldehyde, and free fatty acid production in *S. elongatus* has been demonstrated (Atsumi et al., 2009; Ruffing and Jones, 2012; Savakis and Hellingwerf, 2015; Schwarz et al., 2011; Woods et al., 2004).

The culture was grown in modified BG-11 media (Sigma-Aldrich, C3061), supplemented with 50 µg/mL kanamycin and 80 mM HEPES buffer, pH-adjusted to 8.0 with NaOH and kept at a temperature of 27 ± 1 °C. The culture was maintained in a shaken incubator flask with ambient $0.05 \pm 0.01\%$ CO₂ headspace. Culture depth and 0.1 optical density at 750 nm (OD_{750nm}) were maintained by daily dilution with fresh media. The incubator and experiment reactors were illuminated with red light (632 – 638 nm), which enables strong growth response in lieu of the solar spectrum, and is standard practice when using monochromatic sources (Cuaresma et al., 2009; Graham et al., 2015; Jain et al., 2015). In the incubator, an array of 632 nm LEDs (OSRAM Opto Semiconductors) and light-diffusers provided uniform area illumination.

2.2 Breathable waveguide material

Cellulose acetate butyrate (CAB) was chosen as a breathable waveguide material for this study, due to its optical transparency, biocompatibility, relatively high gas permeability (32 and 6.2 Barrer to CO₂ and O₂, respectively), and relatively low cost and water

impermeability. A comparative table of permeabilities and costs of a selection of other candidate breathable waveguide materials is presented in Supplementary Material.

2.3 Breathable reactor design and operation

Five breathable reactors were fabricated, as shown in Fig. 1(a). For each reactor, constant output from a 634 ± 14 nm LED (Avago Technologies) and collimator lens (Thorlabs) provided uniform-area intensity top-down through 13 mL of culture in a black-anodized 25 mm ID aluminum cylinder. A glass window above the culture sealed 3 mL of initially ambient atmosphere (0.05% CO_2), such that 0.7 ± 0.1 mM of total inorganic carbon (herein C_i - the sum of $\text{CO}_{2(\text{aq})}$, H_2CO_3 , HCO_3^- and CO_3^{2-} species) was initially available to cells. The bottom of the culture contacted a highly gas-permeable, white, hydrophobic membrane (Pall, Versapor 200 R), which reflected diffuse light into the culture. A test material could be fastened directly below. The Versapor membrane served to maintain identical illumination conditions, independent of membrane test material. Both membranes sealed the culture against a polyethylene terephthalate (PET) sheet, with a CO_2 permeability of 0.27 Barrer (Goodfellow, ES303020). Flowing CO_2 diffused into the culture from below. Ambient pressure, air-balanced CO_2 mixtures were flowed at 1.4 L/min with $75 \pm 2\%$ relative humidity. Water vapor added to the gas stream mitigated water loss due to permeation ($< 5\%$).

Five cases were tested in triplicate: (i) CAB contactor with $0.05 \pm 0.01\%$ CO_2 , (ii) CAB contactor with $0.50 \pm 0.06\%$ CO_2 , (iii) CAB contactor with $5.00 \pm 0.02\%$ CO_2 , (iv) impermeable glass disk (negative control) and (v) no additional material with $5.00 \pm 0.02\%$ CO_2 (positive control). All cultures were initially at 0.10 ± 0.02 $\text{OD}_{750\text{nm}}$. After 65 hours of growth, individual culture densities were measured with 0.001 $\text{OD}_{750\text{nm}}$ uncertainty (custom

software written in Ocean Optics OceanView). To mitigate the impact of transitory growth rates on steady-state growth, cultures were not exposed to a change in photon flux when experiments were initiated, as discussed in Supplementary Material. To avoid the possibility of micronutrient-limited growth, experiments were halted after 65 hours so that densities did not exceed $\sim 0.7 \text{ OD}_{750\text{nm}}$.

2.4 Breathable waveguide reactor design and operation

The breathable waveguide reactor is schematically illustrated in Fig. 1(b). A 638 nm laser diode was focused by a plano-concave/-convex lens pair (Thorlabs) into a $0.3 \text{ mm} \times 24 \text{ mm}$ line beam profile. The beam was coupled at 0° angle into a 1 mm-thick CAB sheet, which emitted surface intensities spanning $20 - 40 \mu\text{mol m}^{-2} \text{ s}^{-1}$. Waveguide losses were quantified, as discussed in Supplementary Material. The CAB sheet supported 20 mL of media (no headspace) and a $24 \text{ mm} \times 93 \text{ mm} \times 2 \text{ mm}$ slab of *S. elongatus* hydrogel culture. A PMMA block gently pressed the hydrogel against the waveguide. The hydrogel was prepared by mixing 10 mL each of $0.2 \text{ OD}_{750\text{nm}}$ culture and 4% wt/vol alginic acid sodium salt (Sigma-Aldrich) in modified BG-11 media. The alginate was crosslinked by setting the mixture on top of a gel containing 4% wt/vol agarose (Sigma-Aldrich) and 100 mM of CaCl_2 in deionized water. Use of a hydrogel culture ensured an initially uniform distribution of cells at $0.1 \text{ OD}_{750\text{nm}}$ in the reactor. Hydrogels are commonly used to immobilize cells for biomedical applications (Hoffman, 2001). CO_2 was flowed below the reactor at the same conditions as for breathable reactors, in addition to 0% CO_2 flow (99.998% N_2). Duplicate cultures were grown at 0.05 and 0.5% CO_2 source concentrations, and single cultures were grown at 0 and 5% CO_2 source concentrations. After 65 hours, the

hydrogel was removed and a center region of uniform density was cut out and de-gelled by addition of 10% wt/vol sodium citrate in order to evaluate optical density due to waveguide CO₂ permeation.

3. RESULTS AND DISCUSSION

3.1 Breathable reactors with bulk LED illumination

Permeation experiments were conducted to assess the growth of *S. elongatus* due to CO₂ permeation through 0.25 mm thick transparent CAB contactors. After 65 hours of incubation, various levels of CO₂ permeation affected final culture density, as shown in Fig. 2(a). The growth results are plotted with negative and positive control reactors which used glass or no material in place of CAB, respectively. Growth increased with increasing CO₂ concentration applied below the permeable membranes. The high density achieved in the 5% CO₂-permeated CAB reactors matched that of the positive control case (5% CO₂ with no CAB contactor), indicating that the presence of the CAB contactor did not detectably reduce cell growth. The small densities achieved in the ambient (0.05%) CO₂-exposed CAB reactors did not detectably outperform the negative control reactors (0% CO₂ permeated). The more moderate (0.5%) CO₂ concentration led to strong, carbon-efficient growth, at 76% of the final density of the 5% CO₂ cases, with only a tenth of the CO₂ supplied. Measurements of pH taken before and after experiments confirm similar relative abundance of HCO₃⁻ in all breathable reactors, as discussed in the Supplementary Material. Further, the presence of strong pigment absorption peaks in all final culture spectra confirm the health of cultures (as shown in Fig. S1 in Supplementary Material). These results demonstrate that CAB contactors can effectively deliver useful concentrations of CO₂ to

cultures with moderately elevated CO₂ levels supplied, while occupying minimal reactor volume.

While membrane contactors provided CO₂ for culture growth (Fig. 2(a)), the cultures nonetheless suffered from self-limiting shading, particularly at higher densities. The light distribution within each of these cultures at the end of the experiment are shown in Fig. 2(b), in comparison to the starting distribution. Initially all cultures had over 100 $\mu\text{mol m}^{-2} \text{s}^{-1}$ of light, an intensity associated with light-replete, steady-state growth rates (Graham et al., 2015; Mackenzie et al., 2004). However, as cultures grew and density increased, growth in all reactors became light-limited. While continuous culture circulation during cultivation mitigated the effect of light gradients, fluid flow merely reduces the impact of top-down illumination gradients without solving the problem. The light mapping in Fig. 2(b) illustrates the coupled nature of light and CO₂ delivery, and makes the case for distributing both light and CO₂ more effectively within cultures using breathable waveguides.

3.2 Breathable waveguide reactors with waveguide illumination

To test the effectiveness of the breathable waveguide architecture, experiments were performed where light was supplied from the surface of a CAB waveguide. Hydrogels containing microalgal culture were positioned directly above the waveguide, and surrounded by a PMMA housing. Since this housing did not fully block atmospheric gas permeation, only the central regions of hydrogel cultures were collected and analyzed, in which growth is primarily caused by CO₂ permeation through the waveguide below. In order to fully accommodate laser light input into the edge of the waveguide, the CAB slab used was four times thicker (1 mm) than those in section 3.1, with four times less CO₂

transmissibility. The relative growth trends obtained with this setup can inform the feasibility of combined waveguide permeation and illumination.

The final optical densities of hydrogel cultures incubated over 65 hours (Fig. 3) used various CO₂ source concentrations with the breathable waveguide architecture: simultaneous waveguide illumination and CO₂ permeation. The overall positive trend of increasing growth with increasing source concentration is consistent with results from breathable reactor experiments (Fig. 2(a)), albeit within a different reactor configuration. More than double the final density achieved with 5% CO₂ source concentration, as compared to negative controls (0% CO₂), indicates carbon-replete hydrogel cultures. Weaker growth at reduced CO₂ source concentrations indicates relative carbon-limitation, where 0.05% and 0.5% CO₂-premerated cultures marginally outperformed controls. In the analyzed region of all hydrogel cultures, the presence of strong pigment absorption peaks indicated viable culture health, similar to that observed of final cultures in breathable reactor experiments (Fig. S1 in Supplementary Material). Overall, the positive growth results from breathable waveguide and permeation experiments together demonstrate the utility of a breathable waveguide architecture to distribute both light and CO₂ to microalgae.

3.3 Future prospects

The combined delivery of light and CO₂ to microalgae from the single breathable waveguide studied in this work is a significant step towards high-density production in stacked reactors (Erickson et al., 2011). The performance of stacked slab waveguide architectures reported to-date have been limited by poor CO₂ dispersion, due to impermeable waveguides or low-permeability sources that occupy additional culture

volume (Ahsan et al., 2015; Kalontarov et al., 2014). In contrast, use of breathable waveguides stands to significantly improve chemical distribution within stacked reactors without additional density limitations. Results from this work suggest that elevated CO₂ source concentrations are necessary to ensure adequate permeation through CAB waveguides. However, future designs could rely on thinner materials for improved CO₂ transmissibility, or alternative materials for improved permeability, such as those presented in Table S1 in Supplementary Material. Together, these design improvements have the potential to sustain cultures with light and passive transport of ambient CO₂. Such an ideal breathable waveguide reactor would avoid the operational costs of culture circulation, active aeration, and elevated CO₂ that currently limit the economic scalability of biofuel and bioproduct production in traditional photobioreactors (Nagarajan et al., 2013; Norsker and Barbosa, 2012).

4. CONCLUSIONS

In summary, the present work demonstrates use of a breathable waveguide to simultaneously supply light and CO₂ to microalgae. Microalgal growth response to CO₂ permeation in CAB reactors was positive, with higher growth occurring at higher CO₂ concentrations. Use of CAB required elevated CO₂ concentration (5%) to enable carbon-replete growth. Simultaneous breathable waveguide illumination and CO₂ permeation in reactors enabled double the growth as achieved with waveguide illumination alone. In contrast to other, separate, often conflicting, light and chemical control strategies, the breathable waveguide architecture enables optimal use of culture area for combined delivery of light and CO₂.

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APPENDIX A. Supplementary material

Supplementary materials associated with this article can be found online, at ____.

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Fig. 1: Photobioreactor schematics. (a) Breathable reactor, with photograph shown at right. A shaker table was used to prevent cells from settling. (b) Breathable waveguide reactor, with photograph at right showing surface emission from 1 mm × 10 cm × 10 cm CAB waveguide in air (optical input is 70 ± 5 mW). All reactors were maintained at a temperature of 27 ± 1 °C; ambient relative humidity and ambient CO₂ concentration were $75 \pm 2\%$ and $0.05 \pm 0.01\%$, respectively. Optical characterization of both reactors is presented in Supplementary Material.

Fig. 2: Effect of CO₂ concentration on microalgal growth using breathable reactors. (a) Culture density growth over 65 hours with CAB contactor, and control membranes of high (+) and zero (-) gas permeability, exposed to CO_{2(g)} concentrations as indicated. Inset schematic of reactor illumination and CO₂ supplied from membranes. Optical densities and error bars represent the mean and the standard deviation of triplicate reactor experiments. (b) Calculated depth-wise light intensity distribution in reactors based on measurements. Shaded regions represent the maximum range of measurement uncertainties. The dashed line indicates the light intensity threshold below which the growth rate of *S. elongatus* is non-ideal.

Fig. 3: Effect of CO₂ concentration on microalgal growth using breathable waveguide reactors with simultaneous illumination and CO₂ permeation. Optical densities measured after 65 hours. Inset schematic of breathable waveguide with light and CO₂ supply. Error bars of 0 and 5% CO₂ single hydrogel cultures represent the range of repeated optical density measurements; error bars of 0.05 and 0.5% CO₂ cases represent the optical density difference between duplicate trials.

FIGURES

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