

Photosynthetic CO₂ Mitigation using a Novel Membrane-based Photobioreactor

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ABSTRACT

Biological carbon control, or photosynthesis, offers many advantages. Biomass developed from photosynthesis has numerous beneficial uses, including a potentially renewable source of biodiesel and other biofuels. It also offers potentially very low operating costs compared to other CO₂ separation processes for coal-fired power plants. The work presented here, partially funded by the Department of Energy, describes the design and development of an engineered photobioreactor for CO₂ recycling. The objectives of this study were: (1) to build a pilot-scale prototype of the membrane-based photobioreactor; (2) to demonstrate its operation and performance the thermophilic *Chlorogleopsis*; and (3) to characterize the growth and CO₂ assimilation of *Chlorogleopsis* at different light levels. Results of testing using a strain of *Chlorogleopsis* isolated by Dr. Keith Cooksey of Montana State University have indicated that thermophilic cyanobacteria can grow in a sustainable, continuous fashion via photosynthesis using only solar power in saturated flue gas. The results also indicate that suspension of viable thermophilic organisms on vertically-suspended growth surfaces drastically reduces overall system footprint compared to the equivalent purely aquatic system. Further, coupling a full-spectrum, solar-tracking photon collection and delivery system via fiber optics allows the bioreactor to optimize growth and further reduce system footprint. Finally, coupling the delivery of water (during normal growth phase) and harvesting systems into the same fluid delivery mechanism has facilitated improved growth rates, while reducing system costs.

INTRODUCTION

It is generally believed that a portfolio of options will be needed to address the complexities of greenhouse gas emission control. Engineered photosynthetic systems offer advantages as a viable near-to-intermediate term solution for reduced carbon emissions in the industrial and energy sectors. Such systems could minimize capital and operating costs, complexity, and the energy required to transport CO₂, which are factors that pose significant challenges to CO₂ sequestration for smaller fossil units. The potential for low-cost control could be critical for smaller units, where capital cost per megawatt could be substantial for CO₂ control. For coal to remain

competitive, especially in the rapidly emerging distributed-generation market and to ensure future fuel diversification, low cost marginal control systems, such as photosynthetic systems, must be developed.

Despite the large body of research in the area of photosynthesis for carbon sequestration, little work has been done to create a practical system, one that could be used with both new and existing fossil generating units. For example, use of raceway cultivators ignores land availability limitations at many existing fossil generation plants. Few existing smaller generation units could find 1000+ acres of suitable land for siting and constructing a microbial pond. Additionally, how would the CO₂ be introduced to the photosynthetic agents? Would such a system need expensively separated CO₂ (not direct flue gas) for sparging, thus vastly increasing the system cost? Would local stack emissions restriction prevent dispersion of flue gas at ground level? In addition, questions exist about supply and distribution of light. For example, in a pond, only organisms near the surface would receive sufficient photons for photosynthesis due to the high degree of reflection and attenuation caused by the water. If organisms had to exist at the surface (and outside), would cold weather have a negative impact on their performance? Further, to keep any such system operating at maximum carbon uptake rate, mature and dead organisms would need to be harvested. How would that be accomplished and at what rate? Finally, although numerous post-harvesting uses exist, what would be the optimal use with respect to the specific application and host site? These questions – questions directly related to practical application – must be addressed before deploying such a photosynthetic system.

The concept behind engineered photosynthesis systems is straightforward. Even though CO₂ is a fairly stable molecule, it is the basis for the formation of complex sugars (food) by green plants through photosynthesis. The relatively high content of CO₂ in flue gas (approximately 14% compared to the 360 ppm or 0.0036% in ambient air) has been shown to significantly increase growth rates of certain species of microalgae. Therefore, application is ideal for contained systems, engineered to use especially selected (but currently existing) strains of microalgae to maximize CO₂ conversion to biomass, absorbing greenhouse gases (Brock, 1978; Ohtaguchi et al., 1997). In this case, the microalgal biomass is the carbon sink.

For example, assuming that the composition of "typical" microalgae (normalized with respect to carbon) is CH_{1.8}N_{0.17}O_{0.56}, then one mole of CO₂ is required for the growth of one mole of microalgae. Based on relative molar weights, the carbon from 1 kg of CO₂ could produce increased microalgal mass of 25/44 kg, with 32/44 kg of O₂ released in the process, assuming O₂ is released in a one-to-one molar ratio with absorption of CO₂. Therefore, a photosynthetic system provides critical oxygen renewal along with the recycling of carbon into potentially beneficial biomass.

Enhanced natural sinks could provide an economically competitive and environmentally safe carbon management option because they do not require pure CO₂ and they do not incur the costs of separation, capture, and compression of CO₂ gas (Kajiwara et al., 1997; Hirata, et al., 1996). Among the options for enhanced natural sinks, the use of existing organisms in an optimal way in an engineered photosynthesis system is lower risk, lower cost, and benign to the environment. This contrasts with the use of ocean-based sinks, which could present problems (Bacastow and Dewey, 1996). Large amounts of iron must be added to the ocean to promote additional CO₂

fixation. As a result, there may be little control over resulting growth. “Weed” plankton, the most likely organisms to grow, would not provide sufficient nutrients for the food webs, generating a high probability of negative environmental impact (Cooksey et al., 1995).

An engineered photosynthesis system could be placed at the source of the emissions to allow measurement and verification of the system effects, rather than being far removed from the emissions source, as is the case with forest-based and ocean-based natural sinks. The power source is natural and abundant. And the energy is converted to byproducts –biomass– that could be used as fuel, fertilizer, feedstock, or source of hydrogen (Fisher, 1961). And even though some carbon is eventually released from biomass through decomposition, bioconversion is the fastest and safest method to add carbon to natural terrestrial sinks. Further, the process described in this paper also requires relatively small amounts of space, estimated to be 1/10th of a comparable raceway cultivator design. Because the organisms are grown on membrane substrates arranged much like plates in an electrostatic precipitator, there is little pressure drop. The system described here could be used at virtually any power plant with the incorporation of translating slug-flow technology to create favorable conditions, such as reduced temperatures and enhanced soluble carbon concentration. Finally, engineered photosynthesis systems will likely benefit from current research into enhancing the process of photosynthesis, either genetically or via photocatalytic reactions.

The conceptualized process, shown in Figure 1, begins after the flue gas has passed through suitable particulate control device(s) so that the gas will be substantially free of solid impurities. The cooled flue gas passes through the bioreactor, which houses vertically suspended growth membranes growing thermophilic organisms, arranged to minimize pressure drop of the flue gas throughout the reactor. The growth substrate, which is a woven fibrous membrane, must be resistant to wear in the harsh environment of the flue gas and corrosive potential of the growth media and, because of the vertical position, offer a high degree of adhesion with the microalgae. However, the degree of adhesion can be too high, becoming problematic for harvesting.

OBJECTIVES

The objectives of this study were: (1) to build a pilot-scale prototype of the membrane-based photobioreactor; (2) to demonstrate its operation and performance using a thermophilic strain of *Chlorogleopsis* isolated by Dr. Keith Cooksey of Montana State University; and (3) to characterize the growth and CO₂ assimilation of *Chlorogleopsis* at different light levels.

RESULTS AND DISCUSSION

Pilot-Scale Bioreactor Prototype

Growth Media Transport System

The growth media transport system consists of two distinct parts – a circulating fluid system and liquid distribution system. The circulating fluid system is a closed-looped, pump-and-gravity-fed transmission system where water containing defined levels of nutrients and soluble carbon (or void of soluble carbon), is delivered to the membrane support for the organisms. The water then

flows through distribution headers and then into the fibers by gravity-assisted capillary action. A view of the capillary transport of water on a populated substrate is seen in Figure 2.

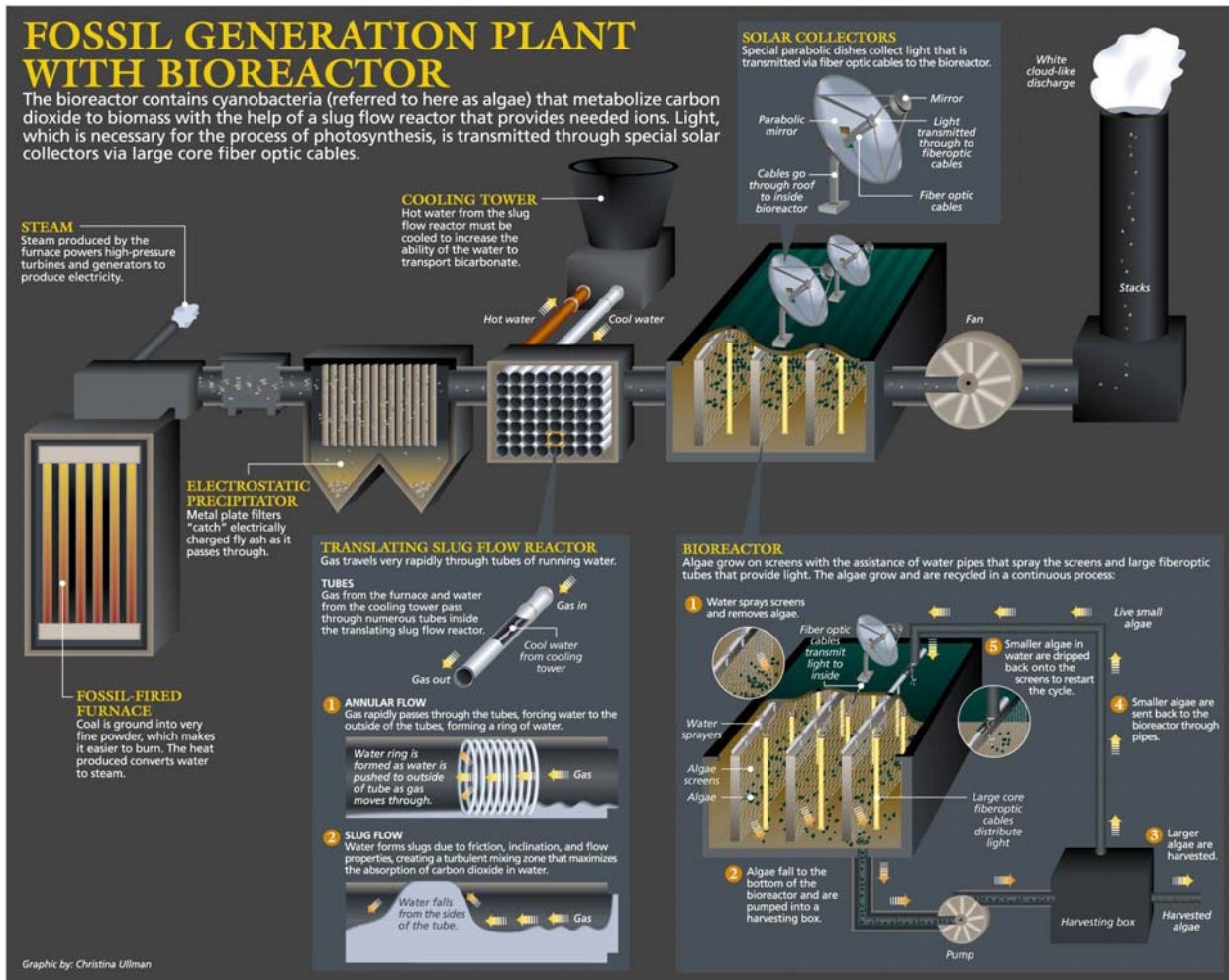


Figure 1. Artist's concept of the bioremediation process.

One of the more significant engineering challenges of this project is nutrient enhancement and delivery to the photobioreactor. Microalgae often more easily fix carbon and inorganic nitrogen in soluble form. Translating slug flow technology, developed at Ohio University's Institute for Corrosion and Multiphase Processes, not only increases concentrations of nutrients in the aqueous phase by directly removing them from the flue gas, but also lowers flue gas temperatures (Jepson, et al., 1993). Slugs create zones of greatly enhanced gas-liquid mass transfer, putting CO₂ and NO_x into soluble form for the microalgae. Such transfer would greatly speed up the natural process of photosynthesis, which in large-scale bioreactors, may be limited by the rate of diffusion of the carbon through the organism membranes.

Photon Collection and Delivery

Solar photons are the energy source of the system and one of the primary factors determining system efficiency. In order to utilize solar photons at maximum efficiency, the light delivery subsystem must deliver a sufficient quantity and quality of photosynthetic photons deep within the bioreactor and minimize the light loss due to reflection and adsorption. Direct, filtered sunlight is collected and delivered into the bioreactor, via collection optics and large-core optical fibers. As seen in Figure 1, the collector would be mounted outside the bioreactor, preferably on top of the reactor. The actual installed collector for the pilot-scale reactor is shown in Figure 3.



Figure 2. Populated substrates showing capillary transport of water.



Figure 3. Solar Collector mounted above pilot-scale bioreactor.

The visible light from the sun reflected from collector dish and secondary optics is launched into an array of optical fibers. These large core fiber optic cables then supply photons necessary to support photosynthesis, using special distributors located between the vertical growth membranes (Figure 4).

By controlling attenuation through the fiber optic cables and using especially designed distributor plates made from similar materials, a uniform distribution of photons may be supplied, typically at a rate between $60\text{-}120 \mu\text{mols m}^{-2} \text{s}^{-1}$. This distribution is a key element in reactor design. The sunlight, originally collected by tracking mirrors (optimizing solar collection) will provide over $2000 \mu\text{mols m}^{-2} \text{s}^{-1}$ of suitable photons throughout the day. However, at that rate, most photons would be wasted, as photosynthesis in thermophiles occurs at much lower levels of light.

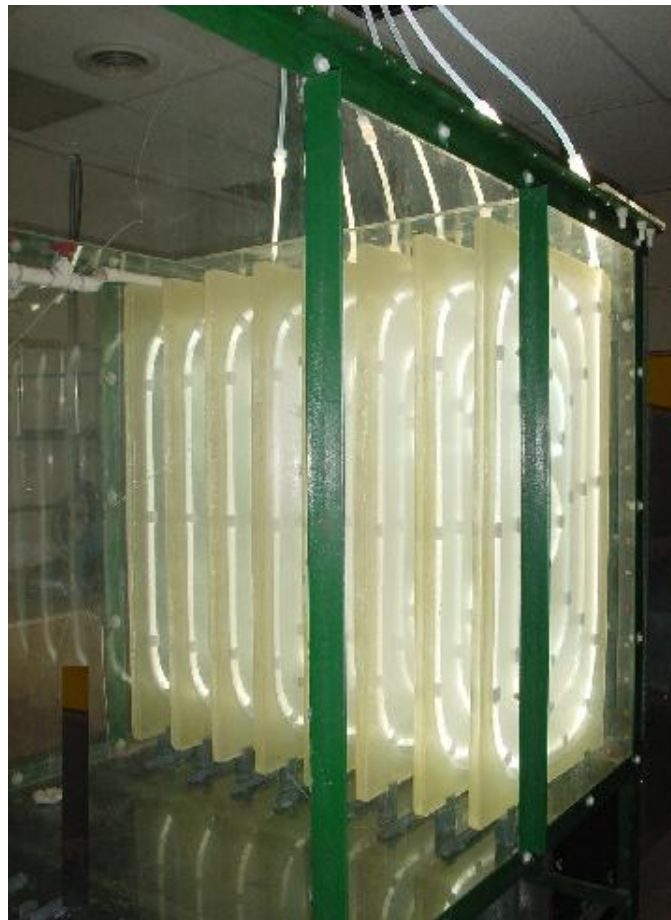


Figure 4. Lighting panels with fiber optic leads.

A further point of interest is that sunlight contains wide spectra of energy; some is useless to the photosynthetic organisms, such as infrared, and some is harmful, such as certain ultraviolet spectra. Filters remove unwanted portions of the solar spectra and allow it to be used for thermal photovoltaic production of electricity needed to power the auxiliary components of the system.

Organism Harvesting and Repopulation

The harvesting system provides a way to remove mature organisms, or reduce cell density to promote further cell division, as well as repopulate the membranes with developing organisms, thus maximizing carbon uptake. Preliminary tests indicate that microalgae, removed in "clumps" from the growth strata, are easily agitated into a diffuse state. Mature microalgae (organisms with a low potential for carbon utilization) can be removed and microalgae that are maturing, (organisms with a high potential for carbon utilization), can be repopulated on the growth strata.

The harvesting for the experimental bioreactor is done using the water distribution system to minimize needs for additional components. By increasing the water pressure to the distribution header, a great flow of water per unit area of membrane is achieved, creating a gentle washing effect. This gentle washing is critical, so as not to shock the organisms and delay continued growth. Further, the gentle washing process is generally 30-40% effective (on a mass basis) in removing organisms from the membrane substrate, which is needed to maintain cell density to sustain continued cell division. Illustrations of the membranes before and after washing are shown in Figures 5 and 6.



Figure 5. Membrane populated with microalgae.



Figure 6. Membrane washed with the harvesting system.

Bioreactor Performance

Sustainability tests with approximately 30 gallons of specially isolated strain of *Chlorogleopsis* and two Omnisil membranes were performed to quantify the growth of cyanobacteria in the bioreactor. After completing the initial mass determination, which enabled the quantification of the cyanobacterial growth over the course of the experiment, the system was allowed to reach steady conditions (five days) before experimentation.

The daily yield of cyanobacteria was determined by harvesting each night. The harvested cyanobacteria were pumped through a 5 micron filter, which was dried for 7 days in a convective oven at 90°C. The mass results of the daily harvesting are shown in Figure 8. Also shown in Figure 7 is the average (daily) solar flux during the experiment.

We noted that the productivity for the following day tracked the average solar flux for the previous day's growth very well (correlating to over 98%). While not confirmed in this work, it seemed intuitive that if the solar collector/distributor system is tuned to produce an optimal photon flux (100-200 $\mu\text{molm}^{-2}\text{s}^{-1}$) that reducing the daily photon exposure would correspondingly reduce biomass productivity.

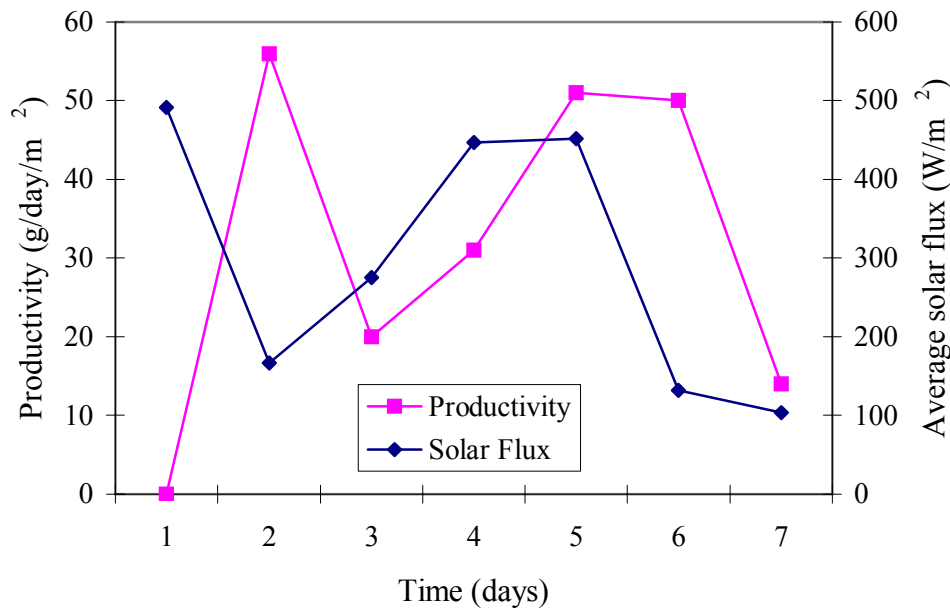


Figure 7. Preliminary Productivity Data

The tests were repeated for cyanobacterial growth over a period of 10 days following an acclimation period of seven days. The results, shown in Figure 8, were slightly lower than the results presented in Figure 7, especially when normalized to the average solar flux from the day before. This was likely because the solar collector experienced significant loss of reflective coating between May and July. However, these results were significant because they showed that the cyanobacteria have a considerable ability to grow once acclimated to the membrane substrate.

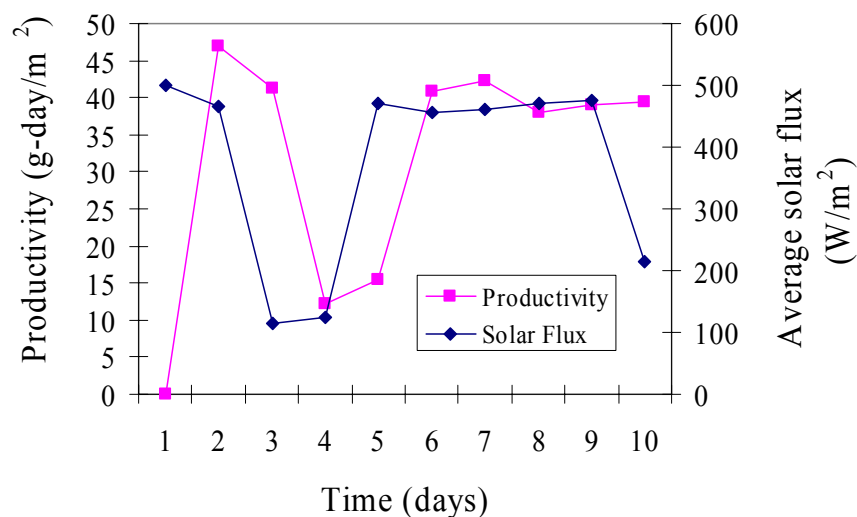


Figure 8. Repeated Productivity Results

Performance of *Chlorogleopsis* at Different Light Levels

A time profile of the growth of the thermophilic *Chlorogleopsis* over 28 days at an elevated temperature of 50°C, at an elevated CO₂ concentration of 5% (v/v supplemented), and at a light intensity of 250 μmol m⁻² s⁻¹ is shown in Figure 9. The resulting growth profile, achieved using flask experiments, was exponential, with an average specific growth rate (μ) of 0.14 d⁻¹ for the first 18 days, and 0.018 d⁻¹ day from days 18 to 28, the latter suggesting the start of growth saturation. The maximum dry weight observed was 1.24 g/L on day 28.

To determine how the growth rate of the cyanobacteria will vary with light intensity, three light intensities (250 [average 246], 200 [average 203] and 100 [average 100] μmol m⁻² s⁻¹) were tested. For all treatments, a four-day lag period followed by the exponential growth phase was observed (Figure 10). The average specific growth rates for the whole eight-day period were 0.22, 0.28 and 0.22 d⁻¹ for 250, 200 and 100 μmol m⁻² s⁻¹, respectively. Excluding the four-day lag period, the resulting average specific growth rates were 0.341, 0.516 and 0.382 d⁻¹ for 250, 200 and 100 μmol m⁻² s⁻¹, respectively. The final dry weight observed at 200 μmol m⁻² s⁻¹ significantly exceeded those for 250 and 100 μmol m⁻² s⁻¹. Thus, the optimal light intensity based on the three light treatments was 200 μmol m⁻² s⁻¹.

The carbon-assimilation rates of *Chlorogleopsis* were also estimated based on dry-biomass data and carbon content of the cyanobacteria. The carbon content of dried *Chlorogleopsis* biomass was measured at 41.1%, with standard deviation of 1.3% (n=6). Figure 11 shows the calculated carbon-assimilation rates for combinations of three light intensities (250, 200 and 100 μmol m⁻² s⁻¹) and three CO₂ conditions (ambient CO₂, elevated CO₂ [5%] delivered at a high flow rate of 0.0104 l gas l⁻¹ medium min⁻¹, and elevated CO₂ [5%] delivered at a low flow rate of 0.002 l gas l⁻¹ medium min⁻¹). The resulting maximum carbon-assimilation rate was 20.4 mg C/L-day, which

corresponded with the light intensity of $200 \mu\text{mol m}^{-2} \text{s}^{-1}$ and 5% CO_2 delivered at low flow rate. It is noteworthy that elevated CO_2 improved the carbon-assimilation rates.

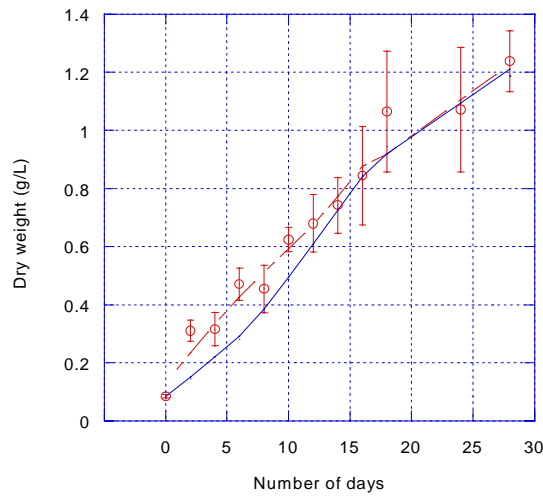


Figure 9. Dry weight changes over time of *Chlorogleopsis* at 5% (v/v) CO_2 -supplemented condition with light intensity of $250 \mu\text{mol m}^{-2} \text{s}^{-1}$. Flow rate of the CO_2 gas was $0.002 \text{ l gas l}^{-1} \text{ medium min}^{-1}$. Data were based on average of three samples. Error bars show standard deviations. Solid line shown is estimation based on an S-curve model.

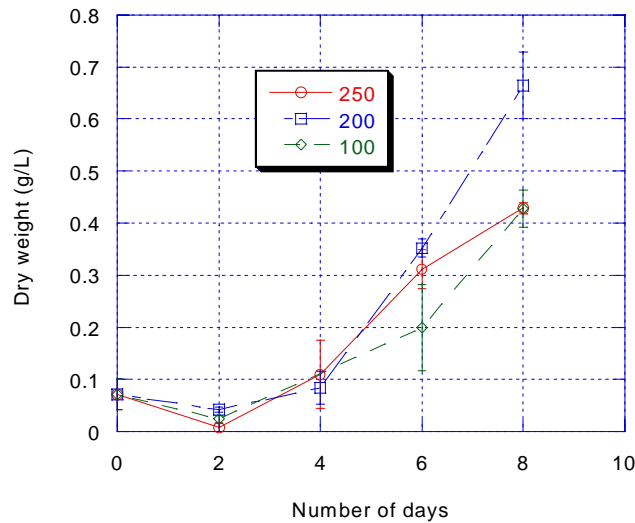


Figure 10. Dry weight changes over time of *Chlorogleopsis* at three light intensities (250, 200, and 100) in $\mu\text{mol m}^{-2} \text{s}^{-1}$. Flow rate of the 5% CO_2 gas was at $0.002 \text{ l gas l}^{-1} \text{ medium min}^{-1}$. Data were based on an average of two samples. Error bars show standard deviations.

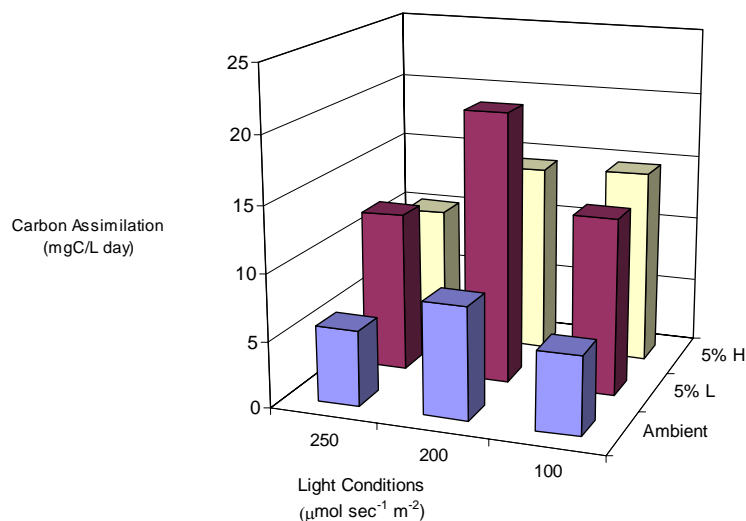


Figure 11. Carbon-assimilation rates for three light intensities (250, 200, and 100 $\mu\text{mol m}^{-2} \text{s}^{-1}$) and three CO₂ gas conditions (ambient CO₂, elevated CO₂ [5%] delivered at a high flow rate [H] of 0.0104 l gas l⁻¹ medium min⁻¹, and elevated CO₂ [5%] delivered at a low flow rate [L] of 0.002 l gas l⁻¹ medium min⁻¹). Data were based on average of two replications. Each replication had two samples.

CONCLUSIONS

The subsystem research has progressed to the point that a viable pilot-scale bioreactor is being constructed to test long-term, sustainable and continuous conversion of CO₂ to biomass using collected solar photons. Further, this photobioreactor offers numerous possibilities for not only greenhouse gas mitigation, but also to control a wide variety of pollutants, notably NO_x and ammonia slip, while producing a product that could have sustainable economic value.

The productivity data strongly indicated that the harvesting method of higher water flow did not physically stress the cyanobacterial mass that remained on the substrate. That is critical for long term sustainability. Further, the data reflected that productivity, at least in the current implementation, was a function of photon availability. Thus, it seems logical that deployment should be favored in locations with higher average incident solar flux.

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