ABSTRACT

This exploratory project investigated the possibility of fixing CO₂ in flue gas emitted from a coal-fired power plant using micro-algal species. CO₂ serves as a carbon nutrient for algae to grow and secondary materials of economic value can be extracted out of algae as by-products via this process. For example, some algal oils like DHA, a supplement widely used in infant formula, have found applications in food and health care industries; other algae oils are the feedstock for biodiesel production. Revenues from these by-products could partially offset the cost of CO₂ capturing processes. As a result, the use of algae for CO₂ fixation will have much broader benefits beyond the reduction of greenhouse gas emissions.

This research work has focused on two areas. The first is developing a novel high-throughput photo-bioreactor screening system. Phototrophic algal strains that can utilize sunlight as the energy source to convert CO₂ into biological molecules are the cultures of choice in this investigation. However, Mother Nature has produced thousands of phototrophic algal species and it usually takes days or weeks for many algal strains to double their cell populations. As a consequence, a photo-bioreactor system was developed that allows simultaneous monitoring of the growth of twenty or more strains in the laboratory, which speeds up the screening process to uncover algal strains that are most suitable for fixing CO₂ from coal flue gases. The second is initiating screening work via examining four algae strains that can produce significant amounts of algal oils or antioxidant chemicals. The effect of CO₂ concentrations in the air on algal cell growth rates was found in some species. This proof-of-concept study has concluded that CO₂ could serve as the only carbon source for some algae to grow and produce valuable chemicals.

Progress was made in this preliminary investigation, especially the design, fabrication and testing of an in-house, high-throughput screening system, that will pave the way for screening a much broader spectrum of algal species for CO₂ fixation in the near future.
EXECUTIVE SUMMARY

It is estimated that more than 40% of CO\textsubscript{2} emissions in the U.S. come from coal-fired power plants. A ruling from the U.S. Supreme Court that carbon dioxide (CO\textsubscript{2}) is a pollutant and that the Environmental Protection Agency (EPA) has the right to regulate CO\textsubscript{2} emissions has paved the way for new environmental legislation from Congress in the coming months and years. Thus, there is immediate urgency for novel technologies that can capture and sequester CO\textsubscript{2} efficiently and economically. The employment of algae to capture CO\textsubscript{2} in the flue gas emitted from a power plant has generated a great deal of research interest during recent years. However, the practical application of a CO\textsubscript{2} capturing algae strategy will largely depend on the technology feasibility and the economy of the whole process. This exploratory research work has been focused in those two areas.

First, we worked on the design, fabrication and testing of a novel photo-bioreactor for high-throughput screening of algal species on their ability and efficacy of taking and converting CO\textsubscript{2} into oils. To this end, we built a system consisting of twenty clear PVC tubes as incubation vessels under a CO\textsubscript{2} environment. The amount of CO\textsubscript{2} inside the system can be adjusted to match flue gas CO\textsubscript{2} composition. These PVC tubes are under broad-spectrum desk fluorescent lights mimicking sunlight with 14 hours on, 10 hours off scheduling. The whole system was stringently sterilized and samples of algal cultures were taken out at fixed time intervals for microscopic examination of cell growths. We believe that a high-throughput photo-bioreactor screening system is of particular importance to present and future CO\textsubscript{2} capturing algae projects. It usually takes days or weeks for most algae to reach a concentration of $10^6$-$10^8$ cells/mL in an incubator. Screening algal species individually is not a practical approach and a high-throughput approach is needed for selecting the best candidates from a large pool of algae. Our system allows us to screen twenty or more species simultaneously, which will significantly speed up our research progress. Such a system can potentially be upgraded and many more PVC tubes can be incorporated for even higher throughput capacity.

Second, we initiated proof-of-concept work on culturing algae using CO\textsubscript{2} as the only carbon nutrient. Four algal species were selected for initial studies, all of which were known to grow by-products with commercial value. This was desirable because the success of any industrial process is eventually determined by its economics. Capturing and fixing CO\textsubscript{2} in algae bears costs for water, algae nutrients (e.g., fertilizers, metals), and operational expenditures. Incomes from algal by-products could help compensate some of those costs.

We started our screening work by examining the growth of four algal strains under 15%
CO$_2$ in the air. Media used have only CO$_2$ as the carbon nutrient. The algae species we studied are: *Botrococcu braunii* (BB), *Chlorella vulgaris* (CV), *Haematococcus pluvialis* (HP), and *Euglena gracilis* (EG).

Our preliminary study has suggested that it is possible to utilize CO$_2$ as the only carbon nutrient for algae to grow and produce secondary by-products. In particular, we found that CV is a good candidate for converting CO$_2$ into algal oils that can be subsequently converted into biodiesel. We systematically studied the growth rate of CV under 15% CO$_2$ in the air, which is similar to CO$_2$ composition in flue gases. Continuous work has been planned to further investigate this species.

An attempt was made to extract algal oils out of CV and BB using hexanes as an extraction solvent. However, the amount of biomass collected from each incubation experiment was insufficient for oil extraction. Thus, the effect of NO$_x$ and SO$_x$ in flue gas on algae growth and hydrocarbon production could not be evaluated. Future work is planned to examine means for immobilization of algal cells allowing for easier collection and more efficient extraction of algal oils.
OBJECTIVES

This project had the following two objectives:

(1) Investigate effects of CO₂ concentrations in air on algal growth rates, biosynthesis of algae oils, and the quality of algae biodiesel;

(2) Examine what effect the presence of NOₓ and SOₓ in the CO₂-air mixture has on algae growth, hydrocarbon (alga oil) production, and the quality of resultant biodiesel fuels.

INTRODUCTION AND BACKGROUND

A recent U.S. Supreme Court ruling¹ and pending legislation in Congress² have added urgency for coal-fired power plants and scientific research communities to find new technologies to efficiently and cost-effectively capture and sequester CO₂ from flue gases. The use of algae for capturing greenhouse emissions could become a practical solution to the CO₂ emission problem.³ Our exploratory research has been focusing on finding answers to the following fundamental questions:

(1) Will algae species utilize CO₂ as the only carbon nutrients for growth?

(2) Will algae tolerate a CO₂ concentration as high as 15%? (Flue gas from a coal-fired power plant typically contains about 15% CO₂.)

(3) To make CO₂ reduction economically feasible, can chemicals and materials of commercial value be extracted from algae to offset some costs of this greenhouse gas reduction practice given estimations that capturing and sequestering flue gas CO₂ will potentially lead to a 30% cost increase for power plants?

In addition, a high-throughput screening system needs to be designed, synthesized and tested for screening a large pool of algae species in various culture media for their ability to efficiently fix CO₂ molecules. Because it usually takes days for algae species to grow⁴, examining algae species one at a time is not a practical approach for screening hundreds and thousands of algal strains available in nature for capturing CO₂. Unfortunately, uncovering an algal strain that can efficiently uptake CO₂ molecules is required before more detailed studies (e.g., genetic and proteomic investigations) can be performed. As a result, our experimental design focused on building a high-throughput photo-reactor for culturing microalgae as well as proof-of-concept studies on the use of concentrated CO₂ (15 v/v%) as the only carbon source for algae growth.
EXPERIMENTAL PROCEDURES

All chemicals, biochemicalls and reagents mentioned in this report were purchased from either Sigma-Aldrich (Milwaukee, WI) or Fisher Scientific (Waltham, MA) and used without further purification. Milli-Q water was produced using a water purification system supplied from Millipore Corporation (Billerica, MA). Algal strains mentioned in this report were purchased from UTEX, an algal culture collection facility at the University of Texas at Austin (Austin, TX), which is partially supported by the National Science Foundation. Materials and parts used for construction of the photo-bioreactor were purchased from a local Lowe’s store in Carbondale, IL. A light meter used for measuring light intensities was purchased from Fisher Scientific and a Varian Gas Chromatography (model 3900) equipped with a TCD detector was utilized for determining the concentration of CO₂ in the air mixture. A Micromaster® I microscope from Fisher Scientific was used for counting cells. CO₂ and compressed air were supplied from Airgas America (Benton, IL) and all glassware mentioned in this report was purchased from Chemglass Life Science (Vineland, NJ).

Creation of Algae Culturing Media

For purposes of accurate scientific research, the medium used for culturing algae must be controlled. The following four media were created for this project: modified Bold 3N, Bristol, proteose, and MES-volvox. The techniques used can be found in the literature and are described below.

Modified Bold 3N Medium: for 1 L total with pH of 6.2.

(1) To approximately 850 mL of H₂O, add each of the components in the order specified in Table 1 (except vitamins) while stirring continuously.

(2) Bring total volume to 1 L with H₂O. (*For 1.5% agar medium, add 15 g of agar into the flask; do not mix.)

(3) Cover and autoclave medium.

(4) When cooled add vitamins. (*For agar medium, add vitamins, mix, and dispense before agar solidifies.)

(5) Store at refrigeratator temperature.
### Table 1. Modified Bold 3N Medium

<table>
<thead>
<tr>
<th>Item</th>
<th>Component</th>
<th>Amount</th>
<th>Stock Solution Concentration</th>
<th>Final Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NaNO₃</td>
<td>30 mL/L</td>
<td>10 g/400 mL H₂O</td>
<td>8.82 mM</td>
</tr>
<tr>
<td>2</td>
<td>CaCl₂.2H₂O</td>
<td>10 mL/L</td>
<td>1 g/400 mL H₂O</td>
<td>0.17 mM</td>
</tr>
<tr>
<td>3</td>
<td>MgSO₄.7H₂O</td>
<td>10 mL/L</td>
<td>3 g/400 mL H₂O</td>
<td>0.30 mM</td>
</tr>
<tr>
<td>4</td>
<td>K₂HPO₄</td>
<td>10 mL/L</td>
<td>3 g/400 mL H₂O</td>
<td>0.43 mM</td>
</tr>
<tr>
<td>5</td>
<td>KH₂PO₄</td>
<td>10 mL/L</td>
<td>7 g/400 mL H₂O</td>
<td>1.29 mM</td>
</tr>
<tr>
<td>6</td>
<td>NaCl</td>
<td>10 mL/L</td>
<td>1 g/400 mL H₂O</td>
<td>0.43 mM</td>
</tr>
<tr>
<td>7</td>
<td>P-IV metal solution</td>
<td>6 mL/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Soilwater</td>
<td>40 mL/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Vitamin B12m solution</td>
<td>1 mL/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Biotin solution</td>
<td>1 mL/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Thiamine vitamin solution</td>
<td>1 mL/L</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Bristol Medium**: for 1 L total.

1. To approximately 900 mL of H₂O add each of the components in the order specified in Table 2 while stirring continuously.

2. Bring total volume to 1 L with H₂O. (*For 1.5% agar medium, add 15 g of agar into the flask; do not mix.)

3. Cover and autoclave medium.

4. Store at refrigerator temperature.

### Table 2. Bristol Medium

<table>
<thead>
<tr>
<th>Item</th>
<th>Component</th>
<th>Amount</th>
<th>Stock Solution Concentration</th>
<th>Final Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NaNO₃</td>
<td>10 mL/L</td>
<td>10 g/400 mL H₂O</td>
<td>2.94 mM</td>
</tr>
<tr>
<td>2</td>
<td>CaCl₂.2H₂O</td>
<td>10 mL/L</td>
<td>1 g/400 mL H₂O</td>
<td>0.17 mM</td>
</tr>
<tr>
<td>3</td>
<td>MgSO₄.7H₂O</td>
<td>10 mL/L</td>
<td>3 g/400 mL H₂O</td>
<td>0.3 mM</td>
</tr>
<tr>
<td>4</td>
<td>K₂HPO₄</td>
<td>10 mL/L</td>
<td>3 g/400 mL H₂O</td>
<td>0.43 mM</td>
</tr>
<tr>
<td>5</td>
<td>KH₂PO₄</td>
<td>10 mL/L</td>
<td>7 g/400 mL H₂O</td>
<td>1.29 mM</td>
</tr>
<tr>
<td>6</td>
<td>NaCl</td>
<td>10 mL/L</td>
<td>1 g/400 mL H₂O</td>
<td>0.43 mM</td>
</tr>
</tbody>
</table>
Proteose Medium: for 1 L total with pH of ~6.8.

(1) Add proteose peptone to Bristol medium in proportions shown in Table 3. (*For 1.5% agar medium, add 15 g of agar into the flask; do not mix.

(2) Cover and autoclave medium.

<table>
<thead>
<tr>
<th>Table 3. Proteose Medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>

MES-Volvox Medium: for 1 L total.

(1) To approximately 950 mL of H₂O, add each of the components in the order specified in Table 4 (except vitamins) while stirring continuously.

(2) Adjust the pH to 6.7.

(3) Bring total volume to 1 L with H₂O. (*For 1.5% agar medium, add 15 g of agar into the flask; do not mix.)

(4) Cover and autoclave medium.

(5) When cooled add vitamins. (*For agar medium, add vitamins, mix, and dispense before agar solidifies.)

(6) Store at refrigerator temperature.

<table>
<thead>
<tr>
<th>Table 4. MES-Volvox Medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
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<tr>
<td>3</td>
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<tr>
<td>4</td>
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<tr>
<td>5</td>
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<tr>
<td>6</td>
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<tr>
<td>7</td>
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<tr>
<td>8</td>
</tr>
<tr>
<td>9</td>
</tr>
</tbody>
</table>
Culture Conditions

In a typical incubation experiment, pre-cultures were carried out in 250 mL conical flasks on a shaker with the following conditions:

1. Temperature of 25°C,
2. Shaking at 100 rpm,
3. Light flux density of 40,000 lux,
4. Light-dark rhythm of 14 hours-10 hours, and
5. 15% (v/v) CO₂-air.

A sample of 1 mL was taken out at fixed time intervals for examination of cell populations under a light microscope. For a comparison study, compressed air without the CO₂ blend was utilized for cell cultures.

RESULTS AND DISCUSSION

Reactor Design

Figure 1 shows our design of a high-throughput photo-bioreactor with only four PVC tubes. CO₂ gas and compressed air are mixed inside a gas reservoir (a round-bottomed flask). The ratio of the mixed air can be adjusted by controlling the flow rates of both CO₂ and compressed air via tuning the gas regulators of both gas tanks. A 10 μL air sample can be withdrawn from the reservoir flask by using an air tight syringe for a Gas Chromatography experiment to calibrate the CO₂ composition in the air mixture. To establish an aseptic condition, we installed a UV chamber in the gas line before the PVC tubes for killing airborne bacteria. Air sterilization in combination with the disinfection of all materials used for constructing the photo-bioreactor (e.g., ethanol rinsing and autoclave) can minimize contamination, resulting in more precise experiments free of potential variables caused by unwanted microorganisms. An air bubbler is also installed in line for maintaining the inside air pressure at one atmosphere.
Figure 1. Schematic Representation of Photo-Bioreactor

We have chosen clear PVC tubes with an inside diameter (ID) of one inch and a height of twelve inches as the host for incubating microalgae. PVC materials have been utilized for storing and transferring microorganisms and are known to have no significant interference with the growth of algae cultures. Clear tubes are selected over colored materials to minimize the absorption of photo-energy from our desk lamps. Although PVC is the material of choice when we constructed our photo-bioreactor, clear glass tubes can also be adopted for a photo-bioreactor. However, the higher cost of glass materials over PVC will become a disadvantage once our laboratory investigation is moved into a large-scale pilot test for commercial production.

Bright Effects® daylight CFL broad-spectrum fluorescent light bulbs (20 watts) were adopted as our photo-light source. Fluorescent light has a wide spectrum, closely resembling sunlight, that contains UVA, UVB, UVC, visible light and infrared. The outdoor illuminance in Carbondale is about 120,000 lux for direct sunlight at noon. We found that our desk lamps can deliver roughly 40,000 lux to the surface of the PVC tube under our laboratory setting.

A sample outlet has been installed on the top of each PVC tube for taking a small amount of cultures (~ 1 mL) out of the reactor. Algal strain growth is monitored by counting the cells of the culture sample under a light microscope at a fixed time interval. To minimize contamination, we use a rubber septum to seal the sample outlet. Only a sterilized needle with a syringe can be used for piercing the septum for sample collection.
At the present time, we have assembled 20 PVC tubes in line for simultaneous incubation and investigation of 20 species/culture media. The amount of CO\textsubscript{2} inside the system can be adjusted from 0-100% by controlling the inflow of CO\textsubscript{2} gas and compressed air. More PVC tubes can be installed in the future if we need to screen a larger number of algal species in different media.

\textit{Culturing Microalgae and Incubation Media}

Algae strains can be biosynthesized via either phototrophic production where bio-energy inside algal cells is supplied via light such as sunlight and electric lights or heterotrophic production where algal bio-energy is supplied from a biological carbon molecule. For example, glucose can be utilized as a feedstock for heterotrophic production of algae strains. The bio-energy in glucose will simply be transferred into the bio-energy of algal biological molecules (e.g., algal oils).

The goal of our present research project is to capture and convert CO\textsubscript{2} molecules into organic carbon molecules inside an algal cell. As a result, phototrophic production of algae is the process of choice. The bio-energy generated in algal cells should be from sunlight that is readily available in nature.

Another important factor in our selection of algal strains for our proof-of-concept study is the economic consideration of our process. Algae culture media usually contain metals like Na and K as well as other co-enzymes such as B12 and biotin. Culture media significantly contributes to the final cost of algal growth. Chemicals and materials isolated out of algal cells that have commercial values will help offset the cost of algae production.

BB, CV and EG were known to generate significant amounts of algal oils that could be converted into transportation fuels. For example, up to 86% of BB’s dry weight is composed of long chain hydrocarbons that can be directly used as feedstock for hydrocracking in an oil refinery for the creation of standard gasoline (octane), kerosene and diesel. EG has a lipid (oil) content of 14-20% by dry weight. The HP strains were known to produce astaxanthin, a powerful antioxidant that can be used as a food supplemental.

All four algal strains were cultured under 15% (v/v) CO\textsubscript{2}-air, a ratio typically found in flue gases from coal-fired power plants. After every 12 hours, a sample was taken out from the incubator for counting algae cell populations. A comparison study has also been carried out to examine the effect of CO\textsubscript{2} on the growth of algal cells by utilizing compressed air without the blending of CO\textsubscript{2} for culturing algal cells. Our preliminary study is summarized in Tables 5-7.
Table 5. Growth Curve for CV

<table>
<thead>
<tr>
<th>Day</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Number (x 10^4 mL^-1)</td>
<td>0% CO2</td>
<td>0.3</td>
<td>0.6</td>
<td>0.9</td>
<td>1.1</td>
<td>1.7</td>
<td>2.2</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>15% CO2</td>
<td>0.3</td>
<td>1.1</td>
<td>3.62</td>
<td>8.73</td>
<td>29.4</td>
<td>89.9</td>
<td>231.6</td>
</tr>
</tbody>
</table>

Table 6. Growth Curve for BB

<table>
<thead>
<tr>
<th>Day</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Number (x 10^4 mL^-1)</td>
<td>0% CO2</td>
<td>1.2</td>
<td>1.4</td>
<td>1.5</td>
<td>2.3</td>
<td>2.7</td>
<td>2.7</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>15% CO2</td>
<td>1.2</td>
<td>2.14</td>
<td>4.62</td>
<td>11.8</td>
<td>20.5</td>
<td>33.8</td>
<td>35.7</td>
</tr>
</tbody>
</table>

Table 7. Growth Curve for EG

<table>
<thead>
<tr>
<th>Day</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Number (x 10^4 mL^-1)</td>
<td>0% CO2</td>
<td>0.81</td>
<td>1.5</td>
<td>2.66</td>
<td>4.7</td>
<td>8.43</td>
</tr>
<tr>
<td></td>
<td>15% CO2</td>
<td>0.81</td>
<td>0.6</td>
<td>0.63</td>
<td>0.4</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Modified Bold 3N medium was used for culturing both BB and CV while MES-volvox medium was employed for HP. EG was grown in proteose medium. Table 5 shows a remarkable CO2 effect on the growth of CV: the CV strain grows slowly in the medium under compressed air while it grows much faster under 15% CO2-air. Modified Bold 3N medium contains NaNO3, a nitrogen source for algal biosynthesis of amino acids, peptides, and proteins that have α-amino groups. K2HPO4 and KH2PO4 provide necessary phosphate groups as a component of DNA, RNA and other phosphated molecules of algal cells. Vitamin B12, biotin and thiamine are the non-metabolized co-enzymes required in algae’s foods for maintaining its bio-activities. Other components in the medium are to supply algae with Ca, Mg, K, and Na metals. Thus, CO2 in the air blend is the only carbon source that can be utilized by algae for the biosynthesis of organic carbon materials like algal oils and carbohydrates. Compressed air consists of only 0.03% CO2. When compressed air is used for culturing algae, CV is under carbon starvation and thus, the growth of CV under compressed air is very slow. In contrast, a higher CO2 concentration (15 v/v%) will supply the CV strain with abundant carbon nutrients leading to the much higher growth rate shown in Table 5.

Table 6 suggests that CO2-concentrated air also facilitates the growth of BB since CO2 is the only carbon nutrient available to BB in a modified Bold 3N medium. However, BB cells grow much slower than CV. This might be attributed to its accumulation of hydrocarbon oils outside of the cell wall. To our surprise, CO2 showed a negative effect on the EG strain. At 15% CO2 concentration, the EG culture maintained a steady cell
population. A higher CO$_2$ ratio in the air may lead to lower pH in the medium and some algae species are more sensitive to the environmental pH. Our preliminary investigation on HP has also been carried out and a negative CO$_2$ effect was also found for HP. However, more detailed studies are currently under way for these species. Proteose medium used for culturing HP contains peptone leading to bacterial contamination in our preliminary investigation of HP.

Effects of Flue Gas Pollutants on Algae Growth and Hydrocarbon Production

While this research was successful in demonstrating the effects of CO$_2$ concentrations in air on algal growth, technical problems were encountered in the second task, which attempted to study effects from the presence of NO$_x$ and SO$_x$ in the CO$_2$-air mixture on algae growth, hydrocarbon (algae oil) production, and quality of resultant biodiesel fuels. We attempted to extract algal oils out of CV and BB by using hexanes as an extraction solvent. The technical problem encountered was that not enough biomass was collected from each incubation experiment for oil extraction. Algal cells have a density similar to that of water and thus, centrifugation, etc. had limited success in recovering algal cells from the incubation media. In the future, we will examine the use of solid beads for immobilization of algal cells. Such matrix-supported cells could be easily collected via filtration. Alternatively, cationic polymers could be introduced for flocculation of algae strains since algal cells usually have negative charges on their cell walls. However, all of these approaches may have some drawbacks. For example, the use of a cationic polymer may complicate the extraction of algal oils and the growth of algal species on a solid bead could also be slowed due to steric interactions with the host. Further investigations will be needed for efficiently extracting algal oils. To some degrees, we were a bit over ambitious in our expectations for cell isolation when the proposal was prepared.

However, we are delighted to achieve a goal that was not listed in the original proposal, which was the building of an in-house photo-bioreactor for high-throughput screening of algal species for uptaking CO$_2$ from the air. As discussed in this report, we believe that a system like ours is of particular importance to any research project on CO$_2$ capturing algae. This is due to the slow growth rate of many algal strains. A thorough investigation of tens or hundreds of algal species for their ability to uptake CO$_2$ will be needed for leads.

CONCLUSIONS AND RECOMMENDATIONS

Our preliminary investigation has confirmed that CO$_2$ molecules can be a viable feedstock (carbon nutrient) for algae growth and metabolism. A CO$_2$ concentration as high as 15% has been utilized for culturing algae. Different algal species demonstrated
different growth patterns under our laboratory settings. In particular, CV could be a promising
candidate for fixing and converting CO\textsubscript{2} into algal oils. Such oils can be
utilized for producing transportation fuels. Although it grows slower, BB could be
another choice for capturing CO\textsubscript{2} and producing algal oils. Microscopic examination of
this species has revealed that much of BB’s oils and fats are actually accumulated at the
outside of its cells giving rise to the possibility of facile extraction of oils out of its cells
in future work. Other species that are known to generate economically important
by-products have also been cultured in our laboratory.

Equally important, we have designed, fabricated and tested a high-through
photo-bioreactor for rapidly screening various algae species for their ability to uptake
CO\textsubscript{2} at a concentration of 15% or higher. One particular problem that we have dealt
with in this system is bacterial infections. A UV chamber installed in our system has
played a critical role in reducing the bacteria population in the air mixture inside the
system. In the future, we plan to upgrade our photo-bioreactor with more incubation
tubes so that more and more algae species can be examined simultaneously.

Due to the small scale of algae production in our laboratory setting, we were only able to
successfully start extracting oils and other important chemicals out of these cells at the
very end of the project. We plan to culture algae on a much larger scale (~50-100 liters)
in the future as well as examine means for immobilization of algal cells allowing for
easier collection and more efficient extraction of algal oils. Chemicals such as algae oils
and antioxidants will then be extracted using a traditional solvent extraction approach
once we collect enough biomass in the lab. These chemicals will be examined to
determine how the presence of NO\textsubscript{x} and SO\textsubscript{x} in flue gas affects algae growth rates and the
quality of resultant hydrocarbon produced by this process.

REFERENCES
3. NREL Close-Out Report: A Look Back at the U.S. Department of Energy’s Aquatic
5. Modified from: Algal Culturing Techniques, R.A. Andersen, Ed., Elsevier Inc., Hong
Kong, China, 2005.
6. Personal communication, A. Fisher.
8. Test was conducted on May 12, 2009, at 1:00 p.m. on the SIUC campus in
Carbondale, IL.
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