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Parametric Study of Photosynthetic CO_2 Conversion for Thermophilic Cyanobacterial Growth in a Novel Membrane-based Photo Bioreactor

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Abstract:A novel, laboratory-scale, membrane-based photo bioreactor was used to investigate the feasibility of CO_2 removal from flue gas of coal-fired power plants using the photosynthetic conversion of CO_2 in terms of algal biomass productivity (g m^{-2} day^{-1}). The experiments employed atmospheric CO_2 and CO_2-enriched air concentrations of 0.5% and 10% under light intensities of 75±10 µmol m^{-2} s^{-1}, with gas and water temperatures of 50±3 ˚C. An initial mass of thermophilic cyanobacterial was grown on a 2'x1' vertical growth surface for a 16-day period. The culture media flowed vertically down the growth surfaces while a CO_2-enriched air stream was circulated horizontally across and parallel to the surfaces. The productivities of algal biomass growth in atmospheric CO_2, 0.5% and 10% CO_2 were approximately 1.20, 1.82, and 1.86 g m^{-2} day^{-1}, respectively. The result showed insignificant difference in gained algal biomass between 0.5% and 10% CO_2.

Keywords: membrane-based photo bioreactor, photosynthetic conversion, thermophilic cyanobacterial, algal biomass productivity, culture media, growth surfaces

I. INTRODUCTION

Photosynthesis is the natural means of CO_2 recycling, converting ambient CO_2 to biochemical substances using sunlight and water. A main source of CO_2 emission is human activities, especially combustion of fossil fuels. World energy consumption is predicted to increase 49% from 2007 to 2035, resulting in a 43%increase of CO_2 emission over the projection period [1]. Such predictions have motivated researchers and scientists to consider methods for mitigating CO_2 emissions.

The improvement of natural photosynthetic conversion of CO_2 has been widely investigated in various configurations and applications[2]. Microalgae are ubiquitous photosynthetic organisms that can grow rapidly under various conditions, which means they have a higher potential to remove CO_2 than terrestrial plants[3].

For the purpose of this paper, research focuses on the use of cyanobacteria to photosynthetically process CO_2, because cyanobacteria possess properties that facilitate commercial production, including ability to adapt to changing environments, ability to grow in high temperature, formation of mats or chain that facilitate dewatering, and advantageous nitrogen fixation capacity[4].
Further, cyanobacteria have shown the ability to process a variety of CO_2 concentrations from ambient air (0.04%) to 100% volume-by-volume [2, 5].

Thomas et al. [6] stated that Synechocys it is and Anabaena could grow well up to 40% CO_2 concentration and Plectonema showed active growth under 100% CO_2.Kurano and Miyachi[7] reported that Chlorococcumlittorale could grow using 60% CO_2-enriched air and the growth under 10% CO_2 was double from Chlorella regularis in their culture collection. Although some microalgal species could have active growth under high CO_2 concentrations, there is insignificant increase in algal biomass productivity compared to low CO_2 concentrations. For example, Scenedemussp. could grow under 80% CO_2, but the maximum cell mass was observed at 10-20% CO_2 (maximum productivity) and Chlorella species did not show the active growth at exceeding 5% CO_2 conditions [8]. In contrast, introducing high CO_2-enriched air concentrations could increase acidity of the media, which could result in adverse impacts for the photosynthetic mechanisms and other metabolism reactions.
Thermophilic cyanobacterial have provided various productivities with a wide range of CO_2-enriched air concentrations and temperatures of 42-75 ˚C [9]. This wide range has stimulated the research groups to employ thermoplilic cyanobacterial for the application of CO_2 mitigation from the waste gas stream of the coal-fired power plants.
Miyairi[10] stated that thermoplilic cyanobacterial Synechococcuselongatushad doubling times of the cells of

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4.7 and 3.3 hours under air and 2% CO_2-enriched air during the growth for the first 12 hours. In addition, this cyanobacterium showed a faster growth rate in the laboratory culture media under the growth conditions of 2% CO_2-enriched air, pH of 7.5, temperature of 52 ˚C, and light intensity of 50 µE $m^{-2}s^{-1}$, (1 µE $m^{-2}s^{-1}$ = 1 µmol $m^{-2}s^{-1}$ = $6.02x10^{17}$ photons$m^{-2}s^{-1}$), 50 µmol $m^{-2}s^{-1}$.

Kajiwara et al. [11] studied the feasibility of Synechococcus PCC7942 for CO_2 fixation under various CO_2 concentrations and reported that the optimal CO_2 concentration was at 5% CO_2 under light intensity of $8x10^3$ lmm^{-2}, which is equivalent to 108 and 240 µmolm^{-2} s^{-1} for cool white fluorescent and plant growth fluorescent, respectively. In addition, this microalgae showed an improved growth rate between 10% to 30%CO_2, which indicates that cyanobacteria could be employed in the photobioreactor to reduce CO_2 content from an exhausted stream from coal-fired power plants containing aprroximately 10 - 20% CO_2 [5].

This study was conducted to examine growth rate of thermophilic cyanobacteria in a membrane-based photobioreactor for CO_2 concentrations of ambient air, 0.5% and 10%. Further, the collected data would be used to assist in examining the feasibility of CO_2 mitigation using thermophilic cyanobacteria for conversion of CO_2 in a membrane-based photo bioreactor under controlled growth conditions.

II. MATERIALS AND EXPERIMENTAL APPARATUS

A. Strain and Medium

The thermophilic cyanobacterial species employed for this study was originally isolated by Drs. Igor Braun and Keith Cooksey at Montana State University. Thermophilic cyanobacterium has been cultured in culture tanks at temperatures of 50±5 °C, pH of 7.0±0.5, continuous light from a traditional light bulb and bubbling 0.3% CO_2-enriched air. The BG-11 was initially adjusted its pH to 7.6-8.0. Chemical compositions of BG-11 are illustrated in Table 1. The growth media was a volumetric combination of 50% BG-11 and 50% RO water

Table 1 Compositions of BG-11

Chemicals	g/L-RO water	g/RO water	
		15 gal	25 gal
1. $NaNO_3$	0.500	28.500	47.500
2. K_2HPO_4	0.040	2.280	3.800
3. $MgSO_4$	0.075	4.275	7.125
4. $CaCl_2$	0.036	2.052	3.420
5. Citric Acid	0.006	0.342	0.570
6. Fe ammonium citrate	0.006	0.042	0.570
7. EDTA	0.001	0.057	0.095
8. Na_2CO_3	0.002	1.140	1.900
9. Hepes	1.787	101.325	170.000

B. Membrane's Fabric and Manufacture

A membrane made from microfiber glass material (Omnisil) and measuring approximately 2.5' by 1.5' was employed as a substrate for thermophilic cyanobacteria growth. The Omnisil membrane was first neutralized by submerging in a 0.025 mMNaOH solution, rinsing using RO water and drying in the oven at 105 °C for a day. This material was then cut and sewed for a membrane in the dimensions of 2'x1'. The sewed membrane was washed of contaminants using RO water and dried out in the oven at 105 °C for two days. The membrane was then attached to a header shown in Figure 1, which consisted of a stainless steel pipe and a rectangular stainless steel rod with a shim made from a Mylar sheetto aid in the distribution of the water film on both sides of the membrane.

Fig. 1. A set of membrane (Growth surface)

C. Experimental Setup and Conditions

Figures 2showed the actual novel membrane-based photo bioreactor.

Fig. 2.The novel membrane-based photo bioreactor

The growth conditions for this investigation were temperatures of 50±5 °C, pH of 7.0±0.5, light intensities of 75±10 µmol m^{-2} s^{-1} and three CO_2 concentrations: atmospheric CO_2, 0.5% and 10% CO_2-enriched air. The dimensions of a photosynthetic conversion chamber of CO_2 were 24" wide, 48" long and 19" high and consisted of two internal and two external light panels made from acrylic.

The size of the light panel was approximately 4.25" wide, 38.25" long and 17.25" high. Therefore, there were three rectangular channels for three sets of membranes. The rectangular channel was approximately in the dimensions of 5.00" wide, 38.25" long and 17.00" high. A membrane was placed in the membrane's holder located in the middle of the rectangular channel. A side of the growth surface, the growth area, was approximately 2' long and 1' high, resulting in approximately 1 m^2 for three membranes.

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A horizontal and two vertical vanes located at the front of the chamber were used to distribute and adjust air flow to the three channels. The investigated CO_2 stream was composed of a mixture of compressed air from the building, bottled CO_2 and combustion of natural gas. Compositions of atmospheric CO_2, 0.5% and 10% CO_2, respectively were employed.This stream flowed horizontally through the photosynthetic conversion chamber using an in-line centrifugal fan model FX8XL from Fantech. The air speed was calculated based on the average of four air-speed measurements taken on each side of the growth surface at 4" and 8" deep down from the top of the membrane's height and at 0" and 18" long from the air entrance of the membrane's width using an AirdataMultimeter ADM-850L Electronic Micromanometer from Shortridge Instruments, Inc. The desired air speed for all measurement points was 0.4 – 1.4 m s^{-1}.

Temperature of the CO_2-enriched air stream was controlled using two in-line fin-strip heaters installed in the circulation air duct. These fin-strip heaters were automated to maintain the air-stream temperature in the range of 50±3 ˚C using a series 93-temperature controller from Watlow.

When 10% CO_2 was employed, a Bunsen burner was used to combust a blend of natural gas and compressed air. The burner components consisted of a Bunsen burner, a set of a thermocouple, snap disks, a pilot, a solenoid valves and control. The combustion of a gas mixture not only gave a high CO_2 content but also provided heat to the CO_2-enriched air stream. Heat from the combustion was sufficient to maintain the temperature of the air stream in the desired range. Although the main need required from the combustion was a high CO_2 level, at a steady state condition a gaseous CO was monitored and maintained below 40 part per million (PPM); a high CO content might harm the growth.Therefore, CO was selected as a key for the data acquisition to turn off the natural gas when the CO level rose beyond the setting value. A gas analyzer model 375 WP from NOVA was a major device used to monitor the present concentrations of CO, CO_2, and O_2 in the air stream.

The growth media was collected in an approximately 64 L conical growth tank. Approximately 64 L of the media was a combination of 34 L of fresh media and 30 L of culture media containing thermophilic cyanobacteria, which was named initial algal biomass. The growth media was heated and controlled in a range of 50.0±3.0 ˚C using a combination of a 750-Watts immersion heater from Tempco and a series 93-temperature controller from Watlow. The media was pumped by a compressed-air driven diaphragm pump to the headers of the membranes at an approximately flow rate of 0.8 GPM per header, which was individually controlled by rotameters form King Instrument Company. The header generated vertical falling films of the growth media throughout on both sides of the membrane across the CO_2-enriched air stream at where CO_2 dissolved in the falling films. pH of the growth media was measured using a waterproof pHTestr 3+ from Oakton and adjusted by adding 3N NaOH every 15 minutes for the first hour. Light energy provided was from traditional light bulbs installed in the light panels. Each light panel consisted of six light bulbs providing approximately maximum light intensity of 150 µmol$m^{-2}s^{-1}$. This study employed the average light intensities of 75±10 µmol$m^{-2}s^{-1}$.

The distribution of light was gauged using a Li-190SA quantum sensor, a LI-250A light meter and a light measurement grid before and after the experiment. The 24-point measured light grid was replaced in the membrane holder at a time of measurement. This investigation employed the natural light-dark cycle: 12-12 hr light-dark cycle. This cycle was automatically controlled using a programmable wall switch model TI032 – 3/3-Way from Aube technologies for the external light panels and an ET724 Electronic In-Wall Timer from GE Consumer & Industrial for the internal light panels.

D. Estimation of Initial Algal Biomass

Thermophilic cyanobacteria were generally inhomogeneous in various clusters' sizes in the culture tanks. In order to make it homogeneous and suitable sizes as possible to decrease clogging on the shim inside the header, 31 L of the culture media with thermophilic cyanobacteria were experientially collected, filtered and grinded through a 0.5 mm traditional strainer.

A liter of possible homogeneity in 31 L was collected, filtered using a 15 cm diameter glass microfiber model 934-AH and Bunn vacuum pump model 400 – 200 and dried out in the oven at 105 °C for 20 minutes. This dried algal biomass was used to calculate for the algal biomass of the rest 30 L, which was in the range of 8 – 10 g and named the initial algal biomass of the experiment.

E. Experiments and Harvests

The 30 L of the media with the initial algal biomass was added in the conical growth tank. The experiments of each CO_2 concentration were maintained for a 16-day period. There were four harvests for the entire experimental period: three periodic harvests and a final harvest. A periodic harvest was operated through the harvesting unit and a Swagelok nozzle model SS-43S4 through the holes on the lid for approximately 45 minutes every four days.

The nozzle was applied on each surface for approximately 2 minutes to spray on and ideally half remove the layer of thermophilic cyanobacteria from the growth surfaces at a flow rate of approximately 1.5 GPM and a pressure of 25 psi from a 3-phase Grundfos pump model CRI-5. The harvested algal biomass accumulated in a harvesting tank was circulated and captured by a 0.5 and 100 µm filters.

The filters were dried out in the oven at 105 °C for 2 days. For the final harvest, the membrane was removed from its frame and dried out in the oven at 105 °C for two days. The net dried algal biomass was used to calculate for the productivity in terms of g m^{-2} day^{-1}.

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III. RESULTS

A. Investigation for the best growth period

10% CO_2-enriched air was selected to determine the best productivity in various growth periods under the mentioned growth condition. The layer's color of thermophilic cyanobacteria on the screen turned to dark green at the end of third day by observing its change in color on the vertical screens.

Change of color could possibly specify the peak growth phase. The harvest was performed every specific growth period shown in Table 2. The original designed harvesting technique was a high pressure up to 90 PSI and flow rate of RO water at 17 GPM.

However, the ineffective result showed in harvesting No. 1; a spray nozzle was employed as a major harvesting device for the consequent harvests and experiments. The harvested algal biomass was calculated for the productivity in terms of g m^{-2} day^{-1} as the following formula.

$$\psi = \frac{M_f}{A(t)} \qquad (1)$$

Where M_f= dry harvested algal biomass in g
M_i = initial algal biomass in g
A = area of six 2'x1' vertical growth surfaces, approximately 1 m^2
t = growth period in day

Table 2 Productivity from Various Growth Periods

Harvesting No.	Growth Period (day)	Algal Biomass (g)	Average Productivity ($gm^{-2}day^{-1}$)
1	9	2.46	0.27
2	5	14.39	2.88
3	7	9.63	1.38
4	8	7.98	1.00
5	7	10.93	1.57
6	7	17.17	2.45
7	5	11.43	2.29
8	3	8.50	2.83
9	4	9.42	2.36

B. Productivity of atmospheric CO_2, 0.5% and 10% CO_2-enriched air

Thermophilic cyanobacterium was grown under atmospheric CO_2, 0.5% and 10% CO_2. The accumulated algal biomass of thermophilic cyanobacteria of each investigated CO_2 concentration was used to calculate the average productivity in terms of g m^{-2} day^{-1} as the following formula.

$$\psi = \frac{M_{total} - M_i}{A(t)} \qquad (2)$$

Where M_{total}= accumulated algal biomass from four harvests in g
M_i = initial algal biomass in g
A = area of six 2'x1' vertical growth surfaces, approximately 1 m^2
t = growth period in day

The results were shown in Table 3.

Table 3 Experimental results from atmospheric CO_2, 0.5% and 10% CO_2-enriched air

CO_2 Concentrations	Average Productivity (g m^{-2} day^{-1})
Atmospheric CO_2	1.20
0.5% CO_2	1.82
10% CO_2	1.86

IV. DISCUSSION AND RECOMMENDATION

Thermophilic cyanobacteria grew very well at 0.5% and 10% CO_2-enriched air under temperatures of 50 ± 3 °C, light intensities of 75 ± 10 µmol m^{-2} s^{-1}, and pH of 7.0 ± 0.5. Based on observation, the layer's color of thermophilic cyanobacteria on the growth surface changed from light green to dark green by the end of the third day. This change could indicate the peak growth of thermophilic cyanobacteria. The experimental result showed in Table 2 for investigation the possible peak growth period; thermophilic cyanobacteria were grown under 10% CO_2 and harvested at different growth periods.

A pressure of 90 PSI and flow rate of 17 GPM of RO water were applied for harvesting No. 1. However, this method was ineffective to harvest a half layer of thermophilic cyanobacteria on the growth surface, resulting in low productivity of harvesting No. 1. The spray nozzle was employed for the consequent harvests resulting in better efficiency. Although the spray nozzle was effectively, it was very difficult to maintain the consistent amount of thermophilic cyanobacteria on the growth surface for the consequent growth. The average productivity for the first two harvests and harvesting No. 5 and 6 was 1.58 and 2.01 g m^{-2} day^{-1}, respectively. Inconsistency in algal biomass for the consequent growths could result in variation of the productivity.

Microfiber glass from Omnisil fell off the membrane during harvesting. This resulted in adding up periodically accumulated algal biomass and decreasing in a final mass of the membranes. Therefore, both consequent amounts and microfiber glass affected the productivity. Although mass of the membranes decreased because of losing microfiber glass, which was uncountable, the result of harvesting No. 9 was not much difference from the 3-day growth period. Therefore, the 4-day growth period was selected for the investigation of CO_2 mitigation using thermophilic cyanobacteria.

pH of the growth media dropped and reached saturated pH very fast for the experiments with CO_2-enriched airs of 0.5% and 10%, especially with 10% CO_2.

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Therefore, change in pH was focused and adjusted in the first hour. During a 16-day experimental period, average light intensity approximately decreased 10 µmol $m^{-2}s^{-1}$. This decrease could be a result of stains on the light cases from the spray nozzle during harvesting.

For investigating of using thermophilic cyanobacteria for the application of CO_2 mitigation, microalgae were grown under atmospheric, 0.5% and 10% CO_2 for the 16-day period. Thermophilic cyanobacteria grew well under 0.5% and 10% CO_2; however, Table 3 showed that the growth compared to atmospheric CO_2 was only in factors of 1.52 and 1.56 for 0.5% and 10% CO_2, respectively. According to the study of Miyairi [10] with the same cyanobacteria, but different CO_2-enriched air concentrations, the productivity was significantly different between ambient air and 0.3% CO_2. In contrast, there was insignificant difference in growth between 0.3% CO_2 and 5% CO_2; moreover, a concentration of 60%CO_2 reduced the growth compared to 0.04% and 0.3% CO_2.This indicated that a high CO_2 concentration does not support the growth of thermophilic cyanobacteria for the setup in this study. On the other hand, this result could guide to a transitional CO_2 concentration for the growth, which could be somewhere from atmospheric to 0.5% CO_2 and has been investigated for the next publication. In addition, a better technique of harvest and control in pH, gas concentration and temperature has been employed for the investigation of the transitional CO_2 concentration for the current work.

Therefore, feasible commercialization of the novel membrane-based photo bioreactor would require additional photosynthetic considerations when accounting for the CO_2 concentration in power plant flue gases.

V. CONCLUSION

The results of this study were concluded as follows: (1) thermophilic cyanobacterial grew well at both 0.5% and 10.0% CO_2-enriched air; (2) there was no significant difference in the productivity between 0.5% and 10.0% CO_2-enriched airs; (3) the best growth period in terms of g m^{-2} day^{-1} was unclear yet.

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BIOGRAPHY

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