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Microalgae cultivation for carbon dioxide sequestration and protein production using a high-efficiency photobioreactor system

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ABSTRACT

Pilot-scale algae photobioreactors (APBs) were used to culture microalga *Chlorella vulgaris* 395 on flue gas from the T.B. Simon Power Plant at Michigan State University. The flue gas was pumped directly into the APBs to provide a carbon source for the culture. Various photosynthetic photon flux densities (PPFD) (31, 104, 177, 531 μmol m^{-2} s^{-1}) and harvest ratios (20% and 30 %v/v) were applied on the photobioreactor to study their effects on algal growth. The results suggested that increasing PPFD significantly enhanced biomass production in terms of productivity, biomass concentration, and total dry weight at both harvest ratios. The highest biomass productivity of 0.40 g L^{-1} d^{-1}, along with corresponding biomass concentration of 1.30 g L^{-1} and biomass dry weight of 40.0 g d^{-1} APB^{-1}, were achieved at the PPFD of 531 μmol m^{-2} s^{-1} with the 30% harvest ratio. A photovoltaic (PV) powered APB was then simulated to carry out a techno-economic analysis. The mass balance analysis concluded that a one-metric-ton unit with 224 m^2 PV panels can generate 0.4 kg of dry algae biomass with 51% protein content and sequester about 0.8 kg of CO_2 per day. The economic analysis indicated that a net positive revenue of $55,353 per year could be achieved for a system with an effective reactor volume of 100 m^3 and the corresponding PV panels of 22,400 m^2.

1. Introduction

Carbon dioxide (CO_2), a major greenhouse gas, is a leading contributor to climate change [1]. Roughly 39% of CO_2 emissions in the U.S. (> 2200 million metric tons of CO_2) originate from electrical power plants [2]. Using microalgal based CO_2 sequestration to reduce power plant flue gas emissions is a sustainable solution for CO_2 control. It has been reported that growing 1 kg of microalgal biomass can fix approximately 1.83 to 1.88 kg of CO_2 [1,3]. Compared to terrestrial plants, microalgae have high protein, lipid and carbohydrate content, and represent one of the most promising feedstocks for chemical and biofuel production without negative impacts on arable land [4]. Year-round production and superior biomass productivity are the main advantages of phototrophic algae compared to land crops [1].

Phototrophic microalgae require CO_2, light and nutrients (nitrogen, phosphorus, and minerals) to convert CO_2 into carbohydrates, lipids and proteins. Flue gas from power plants is rich in CO_2 and can be used as a carbon source for algal growth. Many algal species including *Chlorella* sp., *Chlamydomonas reinhardtii*, *Scenedesmus* sp., *Nannochloropsis* sp., and *Nannochloris* sp. have been studied to sequester CO_2 from flue gas [5,6]. Among the species studied, microalgae *Chlorella* were considered as one of the best performers in terms of CO_2 utilization efficiency [3]. Therefore, we used *Chlorella vulgaris* in this study.

Delivering a sufficient amount of light to the algae cells is a critical factor for algal biomass accumulation, particularly for large-scale algal cultivation. Lighting strategies may rely on sunlight penetration to transfer photons to algal cells in culture medium. However, using sunlight for algae cultivation has intrinsic problems as it is influenced by geographic location, daytime period, and weather conditions [6]. Artificial light sources can be a good alternative to provide controllable high-density illumination to enhance algal growth. Both fluorescent lights and light-emitting diodes (LEDs) have been used as such alternatives [7]. Compared to fluorescent lights, LEDs represent a more efficient lighting source by providing specific photosynthetic absorption spectra and dissipating less energy as heat [8]. These artificial lights require electricity to power them, and renewable energy sources can be used to develop a technically sound and economically feasible lighting strategy. Therefore, photovoltaic (PV) panels as the renewable power source were incorporated into the economic analysis for the studied

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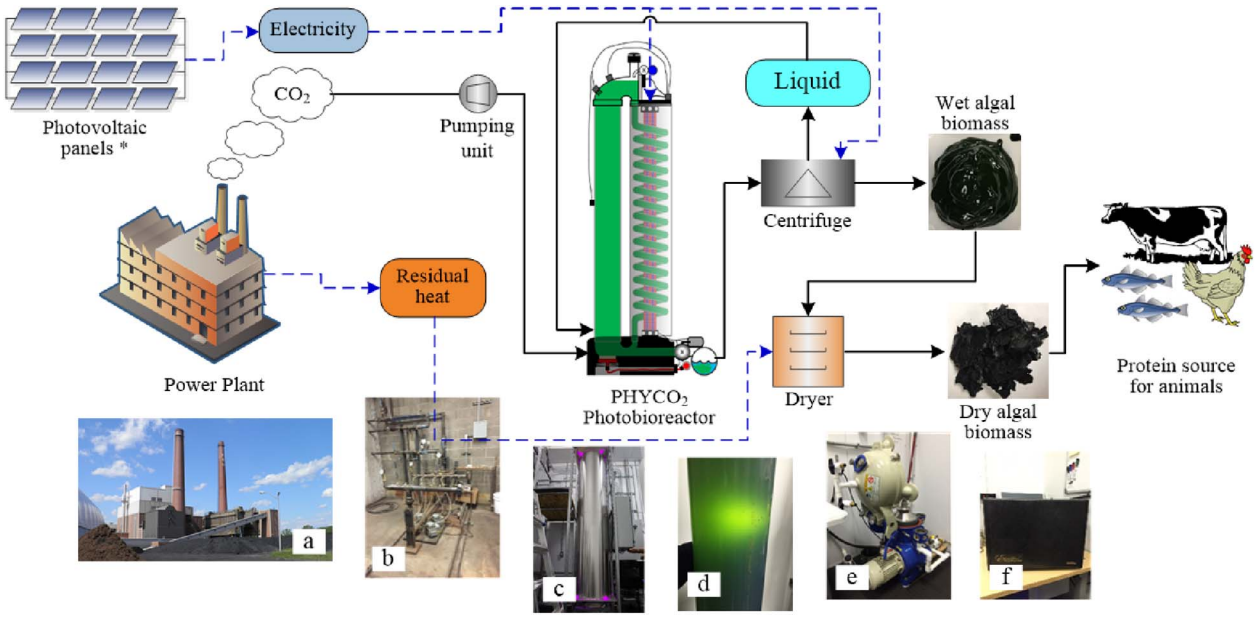

Fig. 1. The pilot algae photobioreactor (APB) cultivation system in the MSU T.B. Simon power plant **.
a. T.B. Simon power plant; b. flue gas pumping unit; c. photobioreactor; d. algae growing in the reactor; e. centrifuge; f. dryer.
*: Photovoltaic panels were not included in the current pilot operation at the MSU T.B. Simon power plant.
**: Solid black line is mass flow and the dashed blue line is energy flow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

APB units. Additionally, the length of the light path in photobioreactors plays an important role in algae biomass production. Short light paths (i.e., plate-based photobioreactors) increase light penetration and improve photosynthesis efficiency [9]. Therefore, a unique APB was designed by $PHYCO_2$ to achieve high-efficiency algal cultivation. Different from other APB designs, the $PHYCO_2$ APB uses both LED lighting and a special helical coil design to minimize energy inputs and increase illumination surface area per unit LED light, so that light illumination efficiency would be synergistically improved.

In this study, two $PHYCO_2$ APBs were installed in the T.B. Simon Power Plant at Michigan State University (MSU) to capture CO_2 in flue gas for high-efficiency algal cultivation (Fig. 1). The APBs were operated at the power plant > 12 months. Effects of CO_2 concentration, photosynthetic photon flux density (PPFD), and harvest ratio on algal production were investigated during the testing period to determine the preferred culture conditions. A techno-economic assessment including mass and energy balance and economic analyses was conducted on a scale-up production to elucidate the feasibility of the system for CO_2 sequestration and value-added protein feed production.

2. Material and methods

2.1. Algal strain and culture medium

Microalga *Chlorella vulgaris* 395 was purchased from UTEX Culture Collection of Algae (Austin, TX) and stored on Tris-Acetate-Phosphate (TAP) agar medium [10] at room temperature under constant fluorescence light. Liquid TAP medium (without agar) was used for the seed cultures. Modified TAP medium was used as photoautotrophic culture medium containing the following substances: 7.5 mmol L^{-1} of NH_4Cl, 0.34 mmol L^{-1} of $CaCl_2{\cdot}2H_2O$, 0.4 mmol L^{-1} of $MgSO_4{\cdot}7H_2O$, 0.68 mmol L^{-1} of K_2HPO_4 (anhydrous), 0.45 mmol L^{-1} of KH_2PO_4 (anyhydrous), and 1 mL of TAP trance elements solution.

2.2. Bench cultivation

The seed cultures were propagated weekly by transferring 1 mL of previous culture into 500 mL Erlenmeyer flasks containing 200 mL of fresh TAP media. All autotrophic cultures were grown in 2 L flasks with 700 mL culture medium. *C. vulgaris* seed (70 mL) was aseptically inoculated into the flask at inoculum of 10% (v/v). The flasks were placed on shakers at 20 °C with an agitation speed of 200 rpm. Four 12-inch LED light bars (J & J electronics Inc. Irvine, CA) were used to provide continuous PPFD of approximately 191.1 μmol m^{-2} s^{-1}. Each LED bar contains six red diodes and two blue diodes. The wavelength of the red light is 645–675 nm and the wavelength of the blue light is 415–445 nm. CO_2 and air cylinders were used to prepare mixed gas with four CO_2 concentrations (0.04, 5, 7 and 10% v/v). The mixed gases were filtrated by a 0.22 μm filter and then pumped into the headspace of the flasks with a fixed flow rate of 2.8 ± 0.2 L per minute. Cultivation occurred over a period of 11 days. Each cultivation has three replicates. Samples (50 mL) were taken from each flask every 1 to 3 days throughout the cultivation period.

2.3. Pilot algae photobioreactor operation

The $PHYCO_2$ APB units (US Patent #8,476,067 B2, Canada Patent #2,712,862) were used in this study (Fig. 2). Two 118 L APBs (with the working volume of 100 L) were installed in the T.B. Simon Power Plant at MSU where natural gas is the fuel source. Each APB unit consists of a vertical up-tube, a helical coil, and a light source. A gas sparger at the bottom of the up-tube acts as the flue gas delivery unit and forces the medium vertically through the up-tube, and then the medium is gravitationally circulated down through the helical coil to the bottom of the APB. The gas sparger pushes the medium back up through the up-tube again. The same LED bars used in the lab cultivation are installed in the center of the helix coil as the light source to provide required PPFD and support algal growth. There are totally eighty-four 12-inch LED bars installed for each APB unit, including fifty-six bars evenly distributed in the center of helix coil and twenty-eight bars around the up-tube. The units ran for 12 months on natural gas fired flue gas. Data used in this study were collected from March 28th, 2016 to September 8th, 2016. The flue gas, containing 7.6 ± 0.8% v/v of CO_2, was directly pumped from the stack to the APBs at a flow rate of 0.04 m^3/min.