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An ultra-low energy method for rapidly pre-concentrating microalgae

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HIGHLIGHTS

- ECF uses Ni electrodes and 4 s treatment time with pulsed or continuous DC.
- Algae rapidly separate from suspension with input energy density of 0.03 kWh/m^3.
- Max separation after 2 h is 97%; max separation effectiveness is ~30%/(kWh/m^3).
- Rapid separation occurs even if untreated algae are mixed with treated saltwater.
- Process does not cause significant cell damage.

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ABSTRACT

This study demonstrates that *Nannochloropsis* sp. can be effectively separated from its growth medium (0.2–0.3 g/L) using electro-coagulation–flocculation in a 100 mL batch reactor with nickel electrodes and a treatment time of only 4 s. Minimum energy density input for effective separation is 0.03 kWh/m^3. Both energy input and treatment time are much smaller than reported elsewhere. The process results in rapid separation of microalgae (over 90% in 120 min) with minimal damage to algal cells (>90% still alive after processing). At around 4 V input, algae can be effectively separated even in very low concentrations. Pulsing is equally effective in separating microalgae as continuous direct current of same magnitude and total exposure time. Algae can separate from their growth medium even if the suspension itself is not treated, but is mixed with treated saltwater with same conductivity. The described method has significant advantages including applicability to continuous processing and water reuse.

1. Introduction

Microalgae have a potential to become a renewable resource for fuel production that does not compete with food crops and does not use large amounts of fresh water, energy, or land. Half of biodiesel needs in the US can be supplied with microalgae grown on only 2.5% of the total cropland, compared to 24% of cropland needed for the same amount of biodiesel from palm oil (Chisti, 2007). Microalgae can also be used to produce or supplement a wide variety of fuels, including gasoline and kerosene. In addition, microalgae can be used to produce animal feeds, fertilizers (Demirbash, 2011), food, and many other chemicals (Zeng et al., 2011; Chisti, 2007; Spolaore et al., 2006a) currently produced from crude oil.

Presently, production volumes of microalgae are very low and costs of growing and processing are prohibitively high, limiting the commercialization of algae based biofuels (Cheng and Timilsina, 2011). For microalgae to become commercially viable it is imperative to reduce costs in all phases of the algae-to-fuel life-cycle. Processing of microalgae to fuels and other products typically requires harvesting, dewatering, and extraction of fuel precursors, i.e., oils and carbohydrates (DOE, 2010), or other chemicals. All of these processes are extremely resource intensive and unsustainable for large-scale production (NRC, 2012). In particular, the small sizes of the microalgae, usually ranging from one to ten micrometers, and low densities in the growing ponds, on the order of 1 g/L, present significant challenges to the harvesting and dewatering processes.

Microalgae harvesting and dewatering are currently accomplished through centrifugation, flocculation, sedimentation or filtration. Centrifugation is commonly used and is estimated to consume 8 kWh/m^3 of microalgal suspension (Danquah et al.,

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2009), although recently a commercial developer claims to have made a centrifuge that operates at 1 kWh/m^3 (Evodos, 2013).

Flocculation requires the use of expensive chemicals but the process itself may demand zero or very little external energy input (Uduman et al., 2010). Gravity sedimentation requires large amounts of land to accommodate very slow batch processing. Filtration and screening require at least 0.4 kWh/m^3 for a low-vibrating screen filter, and increased operation costs for periodic replacement of the screens (Uduman et al., 2010). Alternative coagulation methods use sonication or electrolysis. Zhang et al. (2009) report significant algal removal rates with sonication-enhanced coagulation using as little as 0.1 kWh/m^3. However, Zhang et al. (2006) report that when ultrasound is used alone, without added coagulants, the minimum energy input to achieve significant removal rate is several orders of magnitude higher.

The work presented in this paper focuses on electro-coagulation–flocculation (ECF) for low-energy dewatering or pre-concentrating of microalgae. Poelman et al. (1997) showed that electrolytic flocculation can remove 95% of the algae from suspension by consuming as little as 0.3 kWh/m^3 and without added coagulants. Other researchers, including (Alfafara et al., 2002; Emamjomeh and Sivakumar, 2009; Aragon et al., 1992; Azarian et al., 2007; Vandamme et al., 2011; Gao et al., 2010; Uduman et al., 2011) have also reported success using ECF. In published papers, the exposure times of algae mediums to direct current are between 2 and 90 min using batch processing. These short processing times are advantageous from the applications standpoint. Pearsall et al. (2011) applied this process to a continuous flow device and reported success using flow rates below 5 mL/s. Continuous-flow processing was also attempted by Kim et al. (2012). Most processes use aluminum electrodes, magnetic stirrers to enhance mixing, and most have been applied to freshwater algae. Vandamme et al. (2011) demonstrated that power consumption needed for ECF is lower for marine than for freshwater microalgae and concluded that is due to higher conductivity of the marine medium. The lowest power consumption reported by Vandamme et al. (2011) is 0.2 kWh/kg of recovered algal biomass. While all of the abovementioned processes can remove at least 80% of the algae from a medium, even the best of these processes are still far too energy, water and nutrient intensive to make microalgae based biofuel a viable fuel alternative, as concluded by NRC (2012). The design of a device that separates microalgae and its growth medium, has ultra-low energy consumption, and allows reuse of water is a necessary step and is yet to be developed.

The ECF process described in this paper attempts to address some of the shortcomings currently associated with other ECF processes. It is different than its precursors in several aspects:

1) Microalgae suspension is subjected to direct current for only a few seconds, where the current is either pulsed or applied continuously. The short processing time is favorable for continuous flow processing and desirable for commercial applications.
2) The process does not use stirrers during electrolysis. This is an advantage because overall energy input is reduced.
3) The process has a high ratio of electrode surface area to algae suspension volume. This increases the areas for electrochemical reactions and is conducive to self-induced mixing.
4) Electrodes are made from pure nickel.
5) The process is applied directly to microalgae suspended in its growth medium at various concentrations, and to pure saltwater prior to mixing with algae suspension.
6) The process does not require that any external coagulant chemicals are added during the process.
7) The process uses a simple device design that can be adapted to continuous flow processing in commercial applications.

This paper describes the equipment and process used to separate marine microalgae, *Nannochloropsis* sp., from their growth medium, and presents results of varying operational parameters, including voltage, initial algae concentration, electrode material, current pulsing scheme, and treated suspension, and how these changes affected the efficiency of the process and cell viability.

2. Methods

2.1. Experimental setup and equipment

A schematic of the experimental setup is shown in Fig. 1. The setup consists of four major components: an algae reactor, power electronics, a control computer, and separation-monitoring equipment.

The algae reactor is a batch reactor with a 100 mL capacity and four electrode pairs. The reactor walls are made out of acrylic for easy viewing. Outer dimensions of the acrylic housing are 6 cm × 6.5 cm × 9 cm. The electrodes are slid into and held in place by milled grooves on the inside surfaces of the acrylic walls. The eight electrodes have surface dimensions of 5.0 cm by 7.6 cm and have alternating offsets at the top for electrical contact. Nickel alloy 200 electrodes (>99% pure nickel) were used for all but one experiment and stainless steel 316 electrodes were used in a single experiment.

Power for the reactor is supplied by a DC power supply rated at 40 V and 128 A (Hewlett Packard 6684A 0-40V/0-128A). Power from the supply is controlled using a high power MOSFET (IXFN180N25T) and driver (27425). The MOSFET is configured as a switch to control the voltage supplied to the reactor electrodes.

A computer equipped with a National Instrument data acquisition card and LabView software controls the MOSFET drivers and monitors the resulting power to the reactor. Power to the reactor is controlled by pulsing the voltage to the reactor plates with pulses that are rectangular. The computer controls the pulse duration, duty cycle and total number of pulses. Pulse amplitude is controlled by setting the output on the DC power supply. Current was measured using a Fluke i30 DC/AC Current Probe. Voltage was measured directly using the data acquisition card and a voltage divider. A Fluke 196 ScopeMeter was used to independently verify the current and voltage values and shape of the pulses.

Algae density was measured using Thermo Scientific Scanning 10 UV spectrophotometer at 440 nm. This wavelength was found to give peak absorbance during a wavelength scan performed with

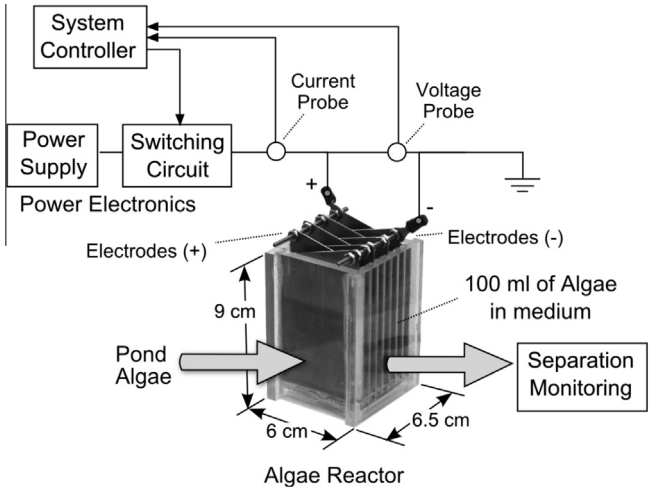

Fig. 1. Schematic of the experimental equipment with a photo of the algae reactor.