Algal Research 6 (2014) 170–174

Contents lists available at ScienceDirect

Algal Research

journal homepage: www.elsevier.com/locate/algal

Harvesting *Chlorella* sp. KR-1 using cross-flow electro-filtration

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ARTICLE INFO

Article history:
Received 21 April 2014
Received in revised form 30 September 2014
Accepted 6 October 2014
Available online 22 October 2014

Keywords:
Electro-membrane
Fouling removal
Permeation flux
Harvesting microalgae
Cross-flow filtration

ABSTRACT

The purpose of the present study was to develop enhanced membrane technologies that can avoid fatal fouling problems, thus making it possible to concentrate microalgae solutions efficiently. A conductive filter called 'electro-membrane' was manufactured and then tested in a CFEF (cross-flow electro-filtration) system. In continuous mode, the applied electric field enhanced the harvesting performance by 150%, demonstrating the anti-fouling property of the synthesized electro-membrane. In discrete mode, the membrane surface, in which microalgae cells were clogged, was almost completely cleansed by the use of a periodic powerful repulsive force, resulting in flux recovery to the initial high level.

1. Introduction

Several membrane-based technologies for microalgae harvesting have been proposed to date, including submerged membrane [1,2], cross-flow filtration [3–5], and dynamic microfiltration [6,7]. Among these, the cross-flow mode warrants further investigation due to its potential for high biomass recovery and low energy consumption [4]. This cross-flow filtration technique has consistently exhibited better performance compared to the conventional dead-end filtration method due to the nature of the tangential flow, which inhibits fouling. Fouling, which causes flux reduction and performance degradation, is one major problem of any membrane-based technology. The unique microbial phenomenon of fouling is known for its notorious resilience to any prevention means. This fouling resilience is found even in the cross-flow mode, even though the tangential flow exhibits distinct effectiveness of reducing fouling under a condition of low cell concentration [3]. Typical ways of controlling fouling include optimizing process conditions (e.g., pressure, retention time, and cultivation conditions), improving system design (e.g., reactor structure and membrane surface modification), and incorporating pretreatments (e.g., mechanical washing, chemical cleaning, and chemical coagulation) [7–10]. These commonly practiced methods, however, have critical problems: e.g., mechanical washing, such as backwashing and back-pulsing, interrupts the operation [11] and chemical cleaning can gradually degrade the quality of the membrane and its operation [12]. More recently, the use of a physical force, such as shear force, sonication, and electric field, has also been used for a more dramatic effect on preventing fouling [7]. Curiously, the opposite result has been reported with the shear force generated by flow turbulence. This poor result is likely due to exopolymeric substances released from the disrupted algal cells [2]. Both ultrasonic and electric forces can also be applied in the form of a field spatially superimposed over the membrane. These powerful techniques have a distinct merit of being able to suppress fouling without interfering with the filtration itself; however, the potential to damage the membrane does exist unless the force is carefully controlled. In the case of the ultrasonic prevention, the bulky size and difficulties in integration with the membrane system are other issues regarding the scaling-up and ultimate commercialization of these anti-fouling approaches [13]. An electric field can be applied via two mechanisms: electrofiltration and electro-osmosis. Electrofiltration is theoretically based on electrophoresis, a phenomenon of charged-particle movement caused by Coulomb force in a homogeneous electric field [14]. When a direct current (DC) electric field is supplied in a filtration module, charged particles are electrostatically repelled from the surface of the electrode-coated membrane. In this way, foulants have a very limited opportunity of coming into physical contact with the membrane surface, which leads to the substantially reduced formation of fouling [14–18]. Electro-osmosis, a phenomenon where electrical potential forcefully pushes liquid to be transported through non-movable porous media, such as membranes and even fouling layers, may increase the membrane flux [18–21]. One critical disadvantage of these potent techniques is the requirement of additional energy consumption [22]. The amount of energy consumption in algae harvesting, particularly in the electro-filtration system, depends on the cell concentration, medium conductivity, and ohmic efficiency of the electrode-coated membranes, also known as electro-membranes. In this study, therefore, we synthesized ohmically efficient yet physically stable electro-membranes by means of

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http://dx.doi.org/10.1016/j.algal.2014.10.004
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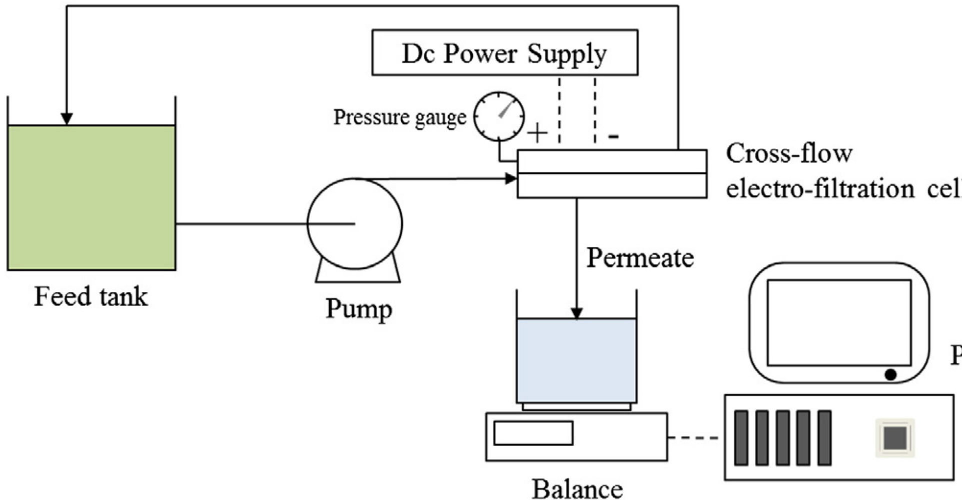

Fig. 1. Cross-flow membrane electro-filtration system.

modifying carbon electrode material. We then used this material for the purpose of improving the efficiency of the conventional cross-flow membrane filtration.

2. Methods

2.1. Electro-membrane synthesis and characterization

Commercial carbon cloth (Toray, Japan) was used as the base membrane for synthesizing the electro-membranes. The carbon cloth, which has pores that are too wide to be used for algae harvesting, was first treated before use as follows. 15 g of polyvinylidene fluoride (PVDF, average Mw ~180,000, Sigma Aldrich, USA) and 6 g of polyethylene oxide (PEO, average Mw 100,000, Sigma aldrich, USA) dissolved in 85 g of N-methyl-2-pyrrolidone (NMP, Sigma aldrich, USA) are each prepared as a casting solution. The solution was cast manually to a thickness of 250 μm on a clean glass plate using a casting roller. The surface morphologies of the electro-membrane before and after harvesting were revealed using a field emission scanning electron microscope (FE-SEM, SIRION-100, FEI, USA). The porosity of the membrane was calculated according to Eq. (1):

$$\varepsilon = \frac{(W_w - W_d)/\rho_w}{(W_w - W_d)P_w + W_d/\rho_p} \tag{1}$$

where, W_w is the wet membrane weight (kg), W_d is the dry membrane weight (kg), ρ_w is the water density (kg/m^3) and ρ_p is the polymer density (1.78 kg/m^3). Each value was estimated in triplicate.

2.2. Cross-flow membrane electro-filtration system and harvesting process

A homemade electro-membrane was placed and tested in the cross-flow electro-filtration system (Fig. 1). In order to cause water electrolysis during filtration, a platinum plate with an active area of 14 cm^2 was placed on the opposite side of the electro-membrane with 5 mm distance and served as the counter anode (Fig. S1.). A 2 L volume of microalgae culture was introduced under a trans-membrane pressure of 200 kPa and at a cross-flow velocity of 1 m/s. A freshwater microalgae species (*Chlorella* sp. KR-1, Fig. 2a) locally isolated in South Korea [23], with a cell size of 2–4 μm (Fig. 2b) and at a concentration of 1.2–1.4 g/L, was used for the present study. The effective filtration area of the membrane was 14 cm^2, and the flux of permeate water through the membranes was automatically measured in a programmable computer connected with a balance. Prior to the measurement, the electro-membranes were submerged in deionized water at a 200 kPa for 20 min. After membrane compaction, the membranes were flushed with deionized water for 10 min. Then, pure water flux was estimated according to Eq. (2):

$$J_w = \frac{Q}{A\Delta t} \tag{2}$$

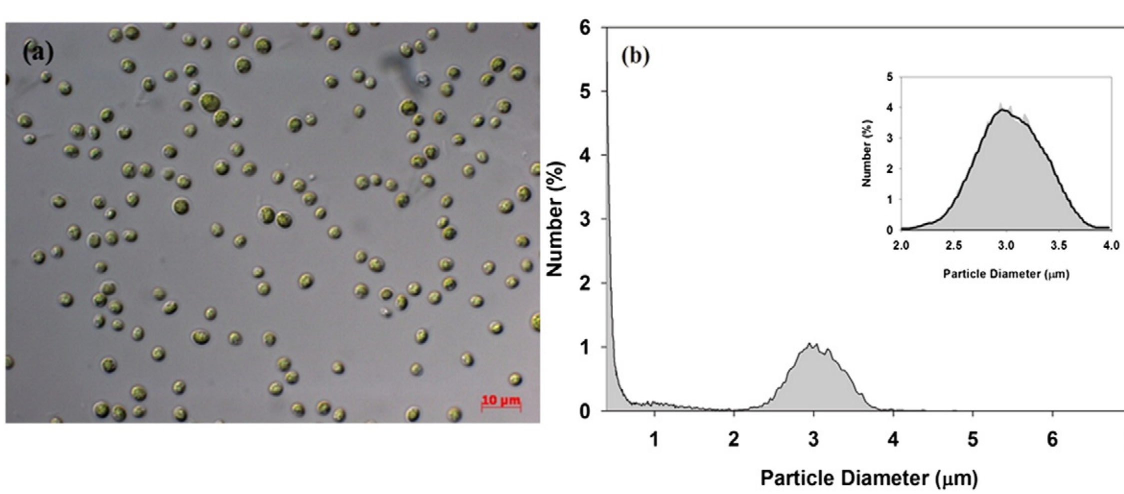

Fig. 2. Freshwater microalga *Chlorella* sp. KR-1: (a) microscopic image and (b) size distribution.