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Harvesting of *Scenedesmus obliquus* using dynamic filtration with a perforated disk

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ABSTRACT

Dynamic filtration adopting the rotation of a perforated disk was applied to harvest *Scenedesmus obliquus*. The highest rotation speed of the disk was found to give rise to 464 and 454 L/m^2/h of plateau permeate flux for microfiltration (MF) membrane and ultrafiltration (UF) membrane, respectively, which were approximately 9 and 11 times higher than those with no rotation. This marked performance improvement for both filtration methods, with the UF exhibiting lower irreversible fouling, was attributed to the reduction of not only cake fouling (up to 97%) but also adsorption fouling (up to 71%) by way of high shear stress on the membrane surface. At the high rotation speed in which fouling was effectively suppressed, flux was linearly increased by trans-membrane pressure; at low speeds where fouling formation remained less disrupted, on the other hand, it reached a certain limit. Besides, fouling built and worsened particularly by high amounts of extracellular polymeric substance (EPS), which was as in the case of the seawater-supplemented culture, was effectively alleviated by fast rotation. The dynamic UF based on the rotation of the perforated disk was indeed a promising and suited means of harvesting *S. obliquus*, especially cells grown under economical yet EPS-inducing cultivation conditions.

1. Introduction

Membrane filtration technology is a clean and well-established method for concentrating the ever-promising and yet very diluted biomass of microalgae [1,2]; it has distinctive advantages, such as high harvesting efficiency, possible medium reuse, no need of chemical addition, simple and continuous operation, and easy scaling-up [3,4]. This seemingly ultimate means of algae harvesting, however, has a critical issue of membrane fouling which causes permeate flux to decline and consequently performance and energy efficiency to drop. To control this fouling, three general approaches have been employed: namely, modification such as feed pretreatment [5] and membrane functionalization [6], fluid dynamics such as dynamic filtration [7,8] and electro-membrane filtration [9], and operational manipulation such as optimization [10] and membrane cleaning [11].

Dynamic filtration is unique in that it is able to generate high shear stress on the direct surface of membrane and thereby to result in slowing down fouling formation and prolonging overall filtration performance [12]. The dynamic filtration had substantially higher permeate flux than the conventional cross-flow filtration even at the same shear rate [13]. In spite of elevated electricity consumption for rotating disks, the dynamic filtration was reported to be economically competitive: high resulting permeate flux permits a smaller unit, which can well compensate for the extra burden [8]. Thus far, three types of dynamic filtration module have been proposed for the purpose of harvesting microalgae: rotating disk membranes for marine microalgae (*Nannochloropsis gaditana*, *Chaetoceros calcitrans*, and *Phaeodactylum tricornutum*) [8], vibrating membrane for marine microalgae (*N. gaditana* and *P. tricornutum*) [3,7] and freshwater microalgae (*Chlorella vulgaris* and *C. pyrenoidosa*) [3,14,15], and rotating disk on the fixed membrane for *Chlorella* sp. [13,16–18]. Module and disk structure were found to greatly affect the effectiveness of the

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dynamic filtration.

Microfiltration (MF) and ultrafiltration (UF) are the membrane of choice when it comes to algae harvesting. The long-termed permeate flux is typically better with the UF than with the MF, though pure water flux is opposite [19]. This rather counter-intuitive phenomenon is mainly due to the fact that large pores of the MF tend to more strongly attract foulants that cause irreversible fouling [20]. Algae in themselves, their species, growth conditions, and harvesting phase, seem to be another decisive factor for harvesting efficiency even for the dynamic approach [7]. *Scenedesmus obliquus*, a green freshwater algal species, is widely cultivated in the mass cultivation facility: high biomass productivity and lipid content can easily be obtained with no significant inhibitory effect on growth [21]. Besides, it is tolerant to high salinity and thus has great potential to make use of seawater as a source of water and chemical ingredients for its cultivation [22,23]. Unfortunately, however, the high salinity appears to stimulate the production of extracellular polymeric substances (EPS) to a substantial degree, which induces autoflocculation [22,24]. Though this trait can somehow be taken advantage of, it is detrimental to the membrane filtration: EPS is the cause of membrane fouling [25–27].

The purpose of this study was therefore to investigate whether the dynamic filtration using rotation of a perforated disk with MF and UF membranes could well handle membrane fouling caused by *S. obliquus* grown on the freshwater- and seawater-based media and if that would be the case, how much impact the EPS had on the dynamic filtration. To this end, the MF and UF of *S. obliquus* were conducted with rotation speed and trans-membrane pressure (TMP) varied.

2. Materials and methods

2.1. Microalgae, experimental set-up, and membranes

Freshwater microalga *S. obliquus* (UTEX-393) was obtained from UTEX (Algae Cultural Collection Center) at the University of Texas (Austin, TX, USA). They were grown in the standard BG11 medium ($NaNO_3$, 1.5 g/L; KH_2PO_4, 40 mg/L; $MgSO_4 \cdot 7H_2O$, 75 mg/L; $CaCl_2 \cdot 2H_2O$, 36 mg/L; citric acid, 6 mg/L; ferric ammonium citrate, 6 mg/L; $NA_2EDTA \cdot 2H_2O$, 1 mg/L; Na_2CO_3, 20 mg/L; H_3BO_3, 2.86 mg/L; $MnCl_2 \cdot 4H_2O$, 1.81 mg/L; $ZnSO_4 \cdot 7H_2O$, 222 μg/L; $Na_2MoO_4 \cdot 2H_2O$, 390 μg/L; $CuSO_4 \cdot 5H_2O$, 79 μg/L; $Co(NO_3)_2 \cdot 6H_2O$, 49.4 μg/L). *S. obliquus* was cultivated in 2-L culture flasks containing each medium with 3% CO_2 at 25 °C under a light intensity of 100 μmol photon m^{-2} s^{-1}. Fresh cultures in the stationary growth phase were harvested at 8 days. For fair comparison, all of the experiments were carried out with the same culture concentration of 1.17 ± 0.01 g/L.

Membrane filtration was carried out using a dynamic filtration module, a FMX B-class (bench scale) commercial equipment equipped with a perforated disk (BKT Co. Ltd., Korea). A membrane and a rotational disk were installed on the bottom of the module and rotating shaft at the center of the module connected to a rotor, respectively (Fig. 1(a)). The effective filtration area was 1.46×10^{-2} m^2. While microalgal culture in the feed tank was pumped into the module and recirculated back into the feed tank, the permeate passing through the membrane was collected for calculating permeate mass flow rate using a load cell connected to a computer and then sent back into the feed tank so that the initial biomass concentration in the feed tank remained constant (Fig. 1(b)). All of the experiments were conducted at temperatures between 25 and 30 °C. Details of the equipment and system were previously reported [18]. A commercial MF membrane (0.2 μm), polyvinylidene fluoride (PVDF) (Microdyn-Nadir, Germany), and an UF membrane (150 kDa), polyethersulfone (PES) (Microdyn-Nadir, Germany), were used throughout the experiment. Their respective membrane permeabilities, as measured by pure-water filtration, were 4728.4 ± 352.7 and 780.1 ± 57.5 L/m^2/h/bar. Rejection of microalgae cells by a membrane was determined by optical density (OD) at 680 nm of the feed and permeate and it was found to be 99.9 ± 0.1% regardless of membrane and rotation speed.

2.2. Filtration procedure

In order to examine the effect of rotation speed on filtration performance, filtration experiments with microalgal cultures were carried out at four rotation speeds of 0, 400, 800, and 1600 rpm, a constant TMP of 100 kPa, and a feed flow rate of 8 L/min for 120 min. After filtration, cake layer on the membrane surface was washed out by deionized water and water permeability of the fouled membrane was measured.

To find out how much permeate flux changed according to TMP stepping at different rotation speeds, TMP was increased in a stepwise manner from 20 to 140 kPa with 20 kPa of TMP interval, each TMP step at 20, 40, 60, 80, 100, 120, and 140 kPa lasted 10 min, and the corresponding permeate flux measured every 2 min. Each TMP stepping was carried out at three rotation speeds of 400, 800, and 1600 rpm and a feed flow rate of 8 L/min.

To examine the effect of seawater-supplemented cultivation on filtration performance, *S. obliquus* was grown in a seawater-supplemented BG11 (SBG) medium. The SBG medium was prepared by adding 10% (SBG 10%) and 20% (SBG 20%) of volume percentage of seawater to the BG11 medium without $MgSO_4$, $CaCl_2$, or Na_2CO_3. Details of the SBG medium were previously reported [22]. The final biomass concentrations for SBG 10% and SBG 20% were 1.05 ± 0.02 and 0.76 ± 0.01 g/L, respectively. Each filtration experiment with different microalgae cultures grown in BG11 and SBG media was carried out at four rotation speeds of 0, 400, 800, and 1600 rpm and a constant TMP of 100 kPa and a feed flow rate of 8 L/min for 120 min

2.3. Analytical and calculation methods

Biomass concentration of a microalgal culture was determined as follows. A microalgal suspension was filtered through a pre-dried and pre-weighed 0.45 μm cellulose nitrate membrane filter (Whatman, USA) and the remaining biomass weighed after drying at 105 °C for 24 h. ODs of the feed and permeate were measured at 680 nm using a UV–Vis spectrophotometer (UV-1800, Shimadzu, Japan). Total carbohydrate concentration for the analysis of main EPS components in the cultivation medium was analyzed by the phenol-sulfuric acid method using glucose as a model sugar (Sigma-Aldrich, USA) as a standard [28].

Rejection (%), flux decline (FD, %), permeability loss (PL, %), and resistances of membrane, total filtration, fouling, cake, and adsorption were calculated as follows:

$$\text{Rejection} = 100 \times (1 - OD_{permeate} / OD_{feed})$$

$$FD = 100 \times (1 - J_{plateau} / J_{initial})$$

$$PL = 100 \times (1 - J_{w,\,fouled} / J_{w,\,new})$$

$$J_{w,\,new} = TMP / \mu R_m$$

$$J = TMP / \mu R_t = TMP / \mu (R_m + R_f) = TMP / \mu (R_m + R_c + R_a)$$

$$J_{w,\,fouled} = TMP / \mu (R_m + R_a)$$

where $OD_{permeate}$ and OD_{feed} are OD of the permeate and feed, respectively, $J_{plateau}$ (or J) and $J_{initial}$ are the permeate fluxes (L/m^2/h) at the plateau (where no large change of permeate flux occurs) and the initial state during microalgae filtration, respectively, $J_{w,}$