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The role of physical and chemical parameters on forward osmosis membrane fouling during algae separation

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ABSTRACT

Forward osmosis (FO) is an emerging membrane separation process, and it has recently been explored for microalgae separation, one of the key steps in algal biodiesel production. The current study systematically investigated the physical and chemical parameters affecting FO flux performance during microalgae separation. To the best of the authors' knowledge, this is the first study reporting FO fouling by microalgae as well as the effect of solute reverse diffusion on FO fouling. FO fouling was more severe at greater draw solution concentrations and in the active-layer-facing-the-draw-solution orientation, which can be partially attributed to the corresponding higher flux levels under these conditions. Indeed, a critical flux phenomenon was observed for the concentration driven FO process, where significant relative flux reduction occurred only when the water flux level exceeded some threshold value. The presence of Mg^{2+} in the feed water had detrimental effect on algal fouling, with more dramatic flux loss at greater Mg^{2+} concentration in the feed. Despite that $MgCl_2$ had superior FO performance (higher water flux and lower solute reverse diffusion) when compared to NaCl as draw solution in the absence of foulants, the use of $MgCl_2$ as a draw solution nonetheless promoted significant flux loss as a result of severe fouling when algae was present. This was likely caused by the reverse diffusion of Mg^{2+} from the draw solution into the feed water, which led to an unfavorable interaction between the divalent ion and the algal biomass in the feed water. Such reverse-diffusion-induced fouling should be explicitly considered for draw solution selection.

1. Introduction

Separation of microalgae cells from source water has gained a resurgence of research interest in recent years [1]. Microalgae convert carbon dioxide and sunlight into algal biomass—a promising biofuel source [2,3]. Engineered algae photobioreactors may also be used for carbon dioxide removal and thus reducing greenhouse gas emission (e.g., flue gas from coal fired power plants) [3–5] as well as for wastewater treatment [6,7]. In these applications, algal biomass separation from effluent is a critical aspect for subsequent biofuel production as well as for maintaining a stable reactor operation. In parallel, it is also well known that seasonal algal bloom can have severe adverse impacts on surface water qualities. In some severe cases, the release of algal toxin and the production of unpleasant color and odor can even make the water unsuitable as a drinking water source [8,9]. Once again, microalgae removal is important from drinking water production perspective.

Conventional methods, such as coagulation, flocculation, floatation and centrifugation, have been traditionally used for microalgae separation. In parallel, membrane filtration (e.g., microfiltration (MF) and ultrafiltration (UF)) has received increased attention due to its high separation efficiency and easy operation [10,11]. For example, Zhang et al. [11] used a UF process to harvest and dewater algal cells, where cross-flow filtration and air-assisted backwash were used to maintain a high water flux. Unfortunately, these pressure-driven MF and UF membrane processes are prone to fouling and are relatively energy intensive. The search for an ideal algae separation technology with high separation efficiency and low energy input is an ongoing research topic.

Recently, forward osmosis (FO) has emerged as a promising alternative membrane separation technology [12]. Driving by the concentration difference across a solute-rejecting dense membrane, FO does not require an external applied pressure. A pure water flux is established spontaneously across the FO membrane from a low concentration feed water (FW) to a high concentration draw solution (DS) under the chemical potential gradient [12].

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Compared to pressure-driven MF and UF processes, FO offers many advantages including (1) better separation efficiency thanks to its nonporous rejection layer [13] and (2) potentially lower power consumption (e.g., in the case where a high osmotic pressure DS, such as seawater, is naturally available). Consequently, FO may have many potential applications in water and wastewater treatment [13,14], desalination [15], food processing [16], and electricity production (i.e., osmotic power harvesting using a related osmotic membrane process—pressure retarded osmosis process) [17–19]. The National Aeronautics and Space Administration (NASA) of the United States has further proposed to implement FO in an algae photobioreactor that receives sewage for algae cultivation and subsequently biofuel production in a project named Offshore Membrane Enclosure for Growing Algae (OMEGA) [20,21]. In this project, the semi-permeable FO membrane is used to retain algal biomass as well as the nutrients required for their growth, while the contaminant-free water is extracted through the FO membrane by the high osmotic pressure seawater. Since the primary objective of the OMEGA project is for algae biomass harvesting and naturally abundant seawater is used as draw solution, the difficult task of draw solution regeneration (i.e., separation the FO permeate water from and re-concentration of the draw solution) can be avoided.

A significant challenge in FO applications is membrane fouling. Although there has not been any reported literature on algae fouling of FO membranes, algal bloom is usually linked to severe biofouling of pressure-driven membranes [22]. Despite that FO may potentially have lower fouling propensity compared to pressure-driven membranes [13,14,23], drastic flux loss can occur under certain unfavorable conditions such as high draw solution concentrations and high flux levels [24–27]. In addition, the solute reverse diffusion (i.e., the transport of draw solutes) from the high concentration DS to the feed water, a unique phenomenon in the concentration-driven FO process [24], may also have critical impact on FO fouling.

The objective of the current study was to investigate the effect of physical (flux level, membrane orientation, and cross flow) and chemical parameters (feed water chemistry as well as draw solution chemistry) on FO fouling during algae separation. In addition, the effect of solute reverse diffusion on FO fouling was systematically studied.

2. Materials and methods

2.1. Chemicals and materials

All the reagents and solutions were prepared with analytical grade chemicals and ultrapure water (ELGA water purification system, UK) unless stated otherwise. Sodium chloride and magnesium chloride were used as draw solutes. Both sodium chloride and magnesium chloride have been widely used as model draw solutes in the FO literature [12]. The microalgae species *Chlorella sorokiniana* (C.S.) was used as the model algae. C.S. is a unicellular green algae with an average cell diameter of ~5 μm. C.S. species grows rapidly even under extreme conditions, and it has been widely used for wastewater treatment as well as for biodiesel production [2,7]. The microalgae were cultivated with the synthetic BG 11 growth medium following the method described by Bordel et al. [28]. The microalgae were harvested when its concentration reached 2–3 g/L (on dry mass basis). This stock solution was diluted with ultrapure water to prepare the feed water (containing 100 mg/L algal biomass) for FO fouling experiments.

The flat-sheet FO membrane used in the current study was obtained from Hydration Technology Inc. (Hydrowell Filter, HTI, Albany, OR). The membrane properties have been reported by several previous studies [12,24,29,30]. Briefly, the membrane is made of cellulose triacetate (CTA) with an embedded polyester mesh for

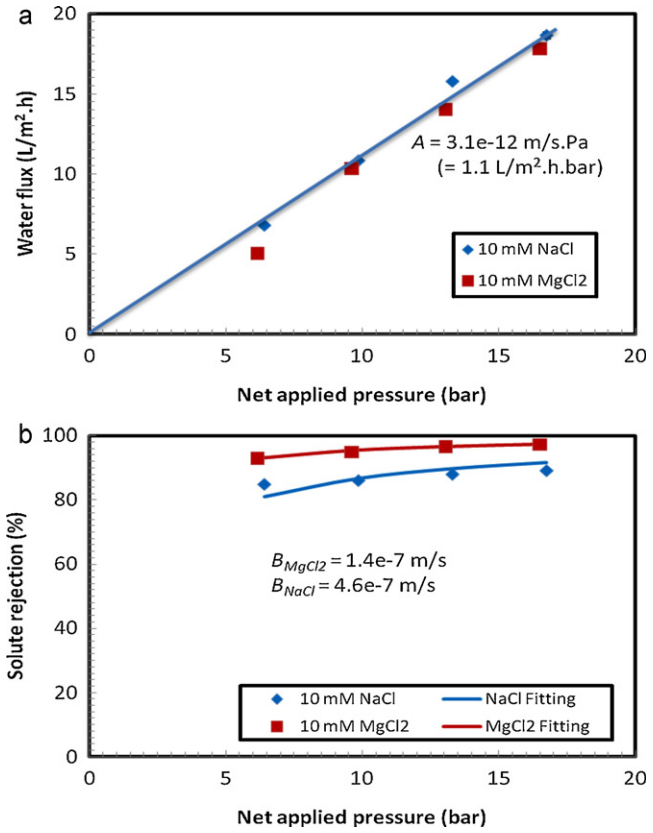

Fig. 1. Water flux (a) and solute rejection (b) as a function of applied pressure for the HTI membrane tested in RO mode.

mechanical support [12,24]. Compared to typical thin film composite RO membranes, the HTI membrane has a much thinner cross-section (<50 μm), which is presumably designed to minimize internal concentration polarization (ICP) in the porous support layer [12,24]. The water permeability and solute rejection of the membrane shows some slight batch-dependent variations [24,30]. In the current study, all the FO membrane coupons were obtained from the same batch, and they were tested in a cross flow reverse osmosis setup to measure its water flux and solute rejection over an applied pressure range of 0–17 bar (Fig. 1) in order to determine their separation properties [24]. The water permeability coefficient A was obtained from the water flux vs. applied pressure plot, while the solute permeability coefficient B was evaluated by fitting the rejection vs. pressure curve based on the following equation [24]:

$$R = \left(1 + \frac{B}{A(\Delta P - \Delta\pi)}\right)^{-1} \quad (1)$$

where R is the measured solute rejection; ΔP and $\Delta\pi$ are the hydraulic pressure difference and osmotic pressure difference across the membrane, respectively. Based on Fig. 1, the following separation properties were determined:

$A = 3.1 \times 10^{-12}$ m/s Pa = 1.1 L/m^2 h bar.
B_{NaCl} (for sodium chloride) = 4.6×10^{-7} m/s.
B_{MgCl_2} (for magnesium chloride) = 1.4×10^{-7} m/s.

2.2. FO experiments

FO experiments were performed using a bench-scale cross flow FO setup according to our previous studies (Ref. [24] and Fig. 2). For each test, a clean FO membrane coupon (~60 cm^2 active membrane area) was used in the cross flow test cell. Diamond-