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Review article

Application of membrane dewatering for algal biofuel

Weiwei Mo [a,*], Lindsay Soh [b], Jay R. Werber [c], Menachem Elimelech [c], Julie B. Zimmerman [c,d]

[a] Department of Civil Environmental Engineering, University of New Hampshire, Durham, NH 03824, United States
[b] Department of Chemical and Biomolecular Engineering, Lafayette College, Easton, PA 18042, United States
[c] Department of Chemical and Environmental Engineering, Yale University, New Haven, CT 06520, United States
[d] School of Forestry and Environmental Studies, Yale University, New Haven, CT 06520, United States

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ABSTRACT

Microalgae dewatering is one of the major process bottlenecks in terms of energy and cost, hindering further development of microalgae biofuels. Membrane filtration has the potential to overcome many drawbacks of conventional dewatering technologies. The major focus of this review is to evaluate the current state-of-the-art of membrane filtration technologies as well as to identify the factors that affect efficiency. The major metrics pertaining to system performance have been identified and compared across four membrane system configurations — cross-flow, submerged, dynamic, and forward osmosis. Previous reported life cycle impacts of various algae dewatering technologies were also examined and compared. The review revealed that trade-offs exist between different membrane configurations, yet there is limited understanding on the mechanisms, performance, and environmental implications of these algae dewatering systems. Further experimental and life cycle assessment studies are necessary to draw conclusions as to the most preferable configurations. The field would also greatly benefit from consistency in research and reporting frameworks.

Contents

* Corresponding author at: Department of Civil and Environmental Engineering, University of New Hampshire 35 Colovos Road, 334 Gregg Hall, Durham, New Hampshire 03824, United States.
E-mail address: Weiwei.mo@unh.edu (W. Mo).

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1. Introduction

Microalgae biofuels have recently garnered tremendous attention as a potential renewable energy feedstock with high efficiencies of carbon and nutrient fixations [1,2], but the significant production energy, water, and/or economic demands have limited their commercialization [3,4]. Based on current technologies, a net negative energy balance has generally been calculated for microalgae biofuel production; that is, the production process consumes more energy than that produced by combusting the resulting biofuel [5]. This production process consists of three distinct process steps: (1) microalgae cultivation, (2) harvesting and/or dewatering, and (3) extraction/conversion to produce biofuels, such as biodiesel and biocrude [2,3]. Dewatering, that is separating and concentrating the biomass from the algae culture, is one of the most energy intensive steps, accounting for approximately 20–40% of the energy demand [3].

Due to the diluteness of algae culture, many of the currently commercialized dewatering technologies, such as centrifugation, flocculation, and belt and chamber press filtration require either prohibitive energy demands or harmful chemical addition. Meanwhile, membrane filtration has been gaining attention due to potential advantages in terms of performance, energy usage and cost [6,7]. Membranes serve as a selective barrier, allowing passage of water while retaining algae to increase the concentration of algae solution [8]. Microfiltration (MF; 0.1–10 μm pores) and ultrafiltration (UF; 1–100 nm pores) are the most commonly studied membrane types for microalgae filtration, allowing for almost complete retention of biomass while preserving the structure, properties and motility of the collected cells [9]. It also potentially disinfects the residual growth medium via removal of microorganisms bigger than the nominal pore sizes, allowing for reuse of the permeate including remaining nutrients and water [10]. Furthermore, no addition of chemicals is required, thus preventing contamination of the end products [11–13]. Elimination of chemical addition also simplifies downstream processes such as extraction, conversion, refining, and the use of the residual algal biomass after oil extraction (e.g., as animal feed) [10,14,15]. Table 1 summarizes the advantages, disadvantages, and energy use of various algae dewatering technologies, including centrifugation, chemical flocculation, air flotation, electrolytic methods, press or belt filtration, and membrane filtration. A comparison of energy intensities of different microalgae dewatering technologies provided in Table 1 shows that membrane filtration can be very competitive. In algae biofuel production, it is important to select the most appropriate technology based on factors such as downstream processes, end products, energy consumption, and costs. Given the unique traits of membrane filtration, it is important to understand whether and how it can be applied for energy and cost efficient algae dewatering.

In recent years, a number of review studies focusing solely or partly on algae dewatering have been published [9,10,22,25,27–33]. Many of these studies outline potential algae dewatering technologies and investigate their efficiencies in terms of cost and energy consumption; however, limited discussion has been provided on the current research and issues related to using membrane filtration as a means of algae dewatering [9,10,22,31,33,34]. For example, Uduman et al. (2010) reviewed the merits and drawbacks of a myriad of algae dewatering technologies including one membrane filtration system (cross-flow filtration), but did not offer much detail regarding the limiting factors, performances, and on-going research of this membrane filtration system [22]. In another review of multiple technologies, Kim et al. (2013) briefly introduced cross-flow, submerged, and dynamic membrane filtrations as possible approaches for algae dewatering [10]. Jaffrin (2008), on the other hand, provided a comprehensive review of various dynamic filtration systems for a variety of industrial applications, but not specifically microalgae dewatering, limiting the transferability of the findings to this application [35]. A recently published review by Gerardo et al. (2014) introduced membrane uses in algae cultivation, dewatering, and downstream processing, but did not offer a robust discussion on algae dewatering [27]. Pore size and membrane materials were considered the main causes of varied membrane performance in the Gerardo et al. paper, while other factors, such as algae species, and hydrodynamic characteristics were neglected. These previous studies do not offer a means by which to comparatively evaluate different membrane configurations. This review seeks to understand the key variables affecting membrane performance and to provide metrics for evaluating membrane performance, enabling comparisons of algae dewatering efficiency and effectiveness across various system configurations. Further, insights are offered on membrane system configurations, life cycle energy and costs, research gaps and future directions.

Table 1
Advantages, disadvantages and energy requirements of various algae dewatering technologies.

Technology	Energy use[a] (kWh/m^3)	Advantages	Disadvantages	References
Centrifugation	0.5–8	Commercially established for valuable microalgae products such as nutraceuticals or nutrient supplements	Energy and cost intensive; often needs to be combined with other pre-concentration steps	[3,7,16–19]
Chemical flocculation	0.1–14.8	Generally considered energy efficient (yet to be firmly proved); established in water and wastewater treatment	Life cycle impacts of flocculant production; efficacious for certain species under limited pH and ionic strength ranges; potential to contaminate biomass limits end use applications	[3,18,20–23]
Air flotation	1.5–20	Increased efficacy of microalgae removal compared with natural sedimentation	Small bubbles are more effective but more energy intensive; often requires pre-flocculation	[16,23–25]
Electrolytic methods	0.33–2	Generally energy efficient	Electrodes are costly and require frequent replacement	[22,25,26]
Press or belt-filtration	0.5–5.9	No chemical inputs or biomass contamination	Inadequate to recover small microalgae cells; filters have to be cleaned or replaced regularly; relatively lower biomass recovery	[16,18,23,25]
Membrane filtration	0.17–2	Potentially better performance, energy requirements, and costs; allows for reuse of permeate; no chemical inputs or biomass contamination	Requires further development and testing; data gaps for many relevant system conditions; membrane fouling and pressure losses at high biomass concentrations	[10,11,16,17,20,27]

[a] Energy consumptions in this column include all electricity used during dewatering operation, but do not include energy associated with manufacturing and producing equipment and chemicals. Initial algae concentrations of the studies that reporting energy consumptions vary from 0.2 to 8 g/L.