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Microfiltration of algae: Impact of algal species, backwashing mode and duration of filtration cycle

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ABSTRACT

The objective of this study was to investigate and compare the microfiltration characteristics of mixed algal cultures containing two species of green microalgae: *Chlorella vulgaris* and *Chlamydomonas reinhardtii*. Submerged membrane filtration experiments with 300 mg L^{-1} suspensions of pure algal cultures indicated that while membrane fouling potential was comparable in both cases, *Chlorella vulgaris* had a lower cake formation potential. Filtration experiments were carried out with 1000 mg L^{-1} suspensions of mixed algal culture over several 12-h cycles with backwashing, either in the on-line or off-line mode. While on-line backwashing caused more fouling, this did not significantly affect the flux through the membrane, which was controlled by the cake formation on the membrane. The algal mixed culture was also filtered over many 3-h cycles with on-line backwashing. Lower cycle duration resulted in lower average cake resistance and hence allowed more membrane throughput, but at the cost of more frequent backwashing. Chemical washing of the membrane could remove the fouling resistance only partially. Thus, despite periodic chemical washing, the intrinsic membrane resistance increased consistently with cumulative throughput through the membrane.

1. Introduction

The algal based technologies have garnered increasing attention in past decade or so because of their dual applications in wastewater treatment and biofuel production [1–3]. However, the simultaneous achievement of these objectives is critically dependent on the efficiency of algal harvesting and dewatering [4]. This is often a complex proposition because of the very nature of algal cells, viz. small cell size, low density and concentrations in growth medium [5]. Due to these inherent challenges with microalgal cultures, conventional processes for harvesting, such as centrifugation and flocculation, are highly energy intensive, and often control the economics of biofuel production and other downstream utility for valuable compounds, viz., proteins, pigments, etc. [4]. The recent investigations into algal biorefinery are predominantly focused on maximizing the product output from harvested algal biomass in order to achieve sustainability and offset the higher harvesting and dewatering costs [6–8].

Recent efforts on membrane microfiltration of algal cultures have demonstrated this to be a feasible alternative due to relatively low energy inputs and simplicity, while achieving nearly 100% biomass recovery [9,10]. The role of membrane technology for harvesting the algal biomass has also been investigated by various researchers in algal biorefineries [11]. These also allow for recirculating of permeates without any chemical build-up [5]. Gerardo et al. reduced the energy requirements and associated cost of membrane microfiltration of *Scenedesmus* sp. from 2.23 kWh m^{-3} and \$0.282 kg^{-1} of harvested microalgae to 0.90 kWh m^{-3} and \$0.058 kg^{-1} of microalgae harvested by optimizing the process itself [9]. Similar process optimization for *Chlorella minutissima* reduced the energy consumption to 1.27 kW kg^{-1} biomass from initial 2.86 kW kg^{-1} biomass [12]. Also, Chu et al. demonstrated long term applicability of dynamic membrane for *Chlorella pyrenoidosa* [13]. Similar investigations have been carried on applicability of membrane microfiltration with other microalgal species, viz. *Chlorella vulgaris* [14], *Chlorella sorokiniana* [15], *Scenedesmus* sp. [16], *Nannochloropsis oculata* [17].

The roles of different process parameters, such as critical flux, transmembrane pressure, membrane characteristics, mode of operation, etc., have also been investigated by various researchers [4]. Recently, Marbelia et al. investigated the role of membrane porosity and surface charge on the membrane fouling by many algal species [18]. Their results show increase in fouling with increasing porosity. Also, negatively charged membranes showed reduced fouling for many algae and was found to be dependent on exopolymer particles [18]. The effect of temperature on membrane fouling was investigated by Chu et al. who reported higher critical flux with higher operating temperature [19]. The lowering in water viscosity was partly suggested to be the reason for

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this. Another recent study investigated the role of axial vibration of ultrafiltration membrane in lowering the membrane fouling [20]. The membrane performance during wastewater treatment is also affected by the presence of generated extracellular polymeric substances (EPS) [21,22]. Their major effect is due to the accumulation on the membrane surface forming an impervious layer, and thus reducing the flux throughput with operation. Further, the mechanism for such fouling is highly complex and depends, among other factors, on the concentration and composition of EPS (e.g., proteins, polysaccharides, lipids etc.), and the presence of other fouling agents [21]. Wang et al. reported better correlation of fouling with loosely-bound EPS than tightly-bound EPS [23].

The role of membrane filtration during actual wastewater treatment using microalgae has also been investigated by many researchers. Praveen et al. compared the performance of forward osmosis and microfiltration for tertiary wastewater treatment in a membrane photobioreactor [24]. Luo et al. reviewed the applicability of membrane filtration in submerged membrane photobioreactors for biomass cultivation and wastewater treatment [25] and showed the process feasibility with different wastewaters including real secondary treated effluent [26], treated industrial effluent [27], and agriculture wastewater [28]. Marbelia et al. also demonstrated similar applicability of membrane filtration for integrated cultivation and nutrient removal in membrane photobioreactors [29].

In addition to microalgae, researchers have also investigated on the filterability of algae and bacteria mixed cultures [30]. However, studies with detailed investigations into the multiple algal systems, the membrane filterability of individual species, and their contribution towards filterability characteristics of the system are rare; and most such efforts are limited to mono algal and axenic systems. This limits their scalability to the mixed algal suspensions, which are often encountered in treatment plants [31]. In order to establish the applicability of membrane microfiltration for the real systems with mixed algal species, it is important to gain the information about the filterability of individual species and their synergistic behaviour in mixed suspension. Further, it is also important to identify the critical parameters affecting their synergy.

Hence, the objectives of the present study were to explore the microfiltration characteristics of algal suspensions; first, to compare filtration rate and development of membrane resistance during microfiltration of pure cultures of *Chlamydomonas reinhardtii* and *Chlorella vulgaris*; second, to assess the impact of backwashing mode on the filtration characteristics of a mixed algal suspension containing the above algal species; third, to study the impact of the length of filtration cycle on filtration rate and development of membrane resistance for the same mixed algal suspension; and, finally to determine the efficiency of chemical washing in removing fouling resistance of the membrane. We selected these two species since both, *C. vulgaris* and *C. reinhardtii* have previously demonstrated good potentials for nutrient removal [32–36] and lipid accumulation for biofuel [37–42]. Also, since these are often observed as dominant species in treatment plants and high rate algal ponds (HRAP) treating domestic wastewater [43], investigations into the harvesting of their mixed culture with membrane microfiltration are required.

2. Materials and methods

2.1. Preparation of algae culture

A monoculture of *C. vulgaris* was purchased from Indian Agricultural Research Institute, New Delhi. This was supplied on the solidified slanted agar media. Stock culture was prepared by picking some algal cells from the agar slant using a sterilized loop and then suspending them in Mineral Salt Medium (MSM) [44].

A monoculture of *C. reinhardtii* was commercially unavailable; hence the pure culture was prepared from a sample containing mixed algal culture obtained from an oxidation pond in IIT Kanpur by subsequent subculturing using the streak plate method. The sample was streaked on nutrient rich solidified agar surface. Well separated colonies of algae were observed after 24 h of incubation at 30 °C. Cells of *C. reinhardtii* were transferred from the agar plate to MSM media. After one week of growth in the MSM media, cells were again streaked on the agar plate. This process was repeated five times. Isolation of a pure culture of *C. reinhardtii* was confirmed by light microscopy. Stock culture was prepared by picking some algal cells from the agar plate and suspending them in MSM as before.

Stock cultures were maintained in mixed conditions in a light chamber with alternate 16 h of light and 8 h of dark period at light intensity of ~150 μmol m^{-2} s^{-1}. A portion of the culture was removed periodically and replaced with equal volume of MSM. The axenic condition of the cultures was checked regularly under microscope. A fluorescence microscope (EC LUMAM-RPO, LOMO PLC, Russia) was used for this purpose.

Algae concentration in algal suspensions was measured gravimetrically; 10 mL volumes of algal suspensions (in triplicate) were filtered using pre dried and pre weighed filter paper (Millipore, USA; 0.22 μm pore size, 47 mm diameter). The filters were dried in a hot air oven at 105 °C for 24 h, cooled in desiccator and weighed using an analytical balance (Model AB 135-S, METTLER TOLEDO, USA). Algae concentration is expressed as mg (dry weight) L^{-1}.

2.2. Membrane

A hollow fiber membrane with pore size of 0.1 μm was used. Specifications of the membrane are given in Table 1. As suggested by the manufacturer, the new membrane was dipped into 70% isopropyl alcohol for 1 h to convert membrane surface to a hydrophilic condition. The membrane was operated in submerged mode by dipping it completely in the solution to be filtered while permeate was collected inside the hollow fibers through suction (i.e., outside-inside mode).

2.3. Reactor setup

Schematic of the reactor setup is shown in Fig. 1. The reactor consisted of cylindrical plastic container of 0.4 m diameter and 0.2 m liquid height, with liquid volume of ~25 L. One hollow fiber membrane module was submerged in it. Mixing was provided continuously by using a rotor operating at 105 ± 10 rpm. Filtration through the membrane module was achieved by attaching a suction pump to the outlet of module. Trans-membrane pressure (TMP) was determined by observing the suction pressure using a vacuum gauge. A flexible perforated plastic pipe connected to an air compressor was placed around the membrane module for aeration purposes. Compressed air was constantly supplied at a rate of 15 L min^{-1} in the form of coarse bubbles through the perforated pipe. In some cases, the filtrate from membrane module was collected in a 5 L tank, for use in backwashing purposes. All other filtrate was recycled back to the reactor.

Table 1
Specifications of the membrane used during microfiltration of algal suspensions.

Parameter	Value
Material	Polypropylene
Pore size (μm)	0.1
Length (mm)	750
Fiber external diameter (μm)	310 ± 15
Fiber wall thickness (μm)	33 ± 3
Number of fiber per module	1400
Surface area (m^2)	0.94
Maximum trans-membrane pressure (TMP) (kPa)	100
Manufacturer	Zena
Model	P5S