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Harvesting microalgal biomass using a magnetically induced membrane vibration (MMV) system: Filtration performance and energy consumption

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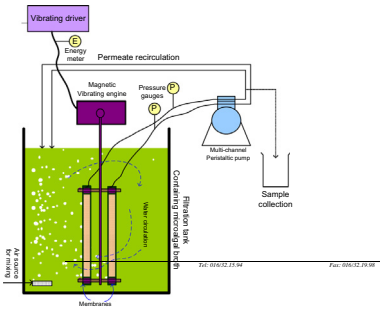
HIGHLIGHTS

- A vibrated membrane (MMV) was applied to up-concentrate microalgal broths.
- Filterability of both broths was assessed and compared.
- Membranes with higher porosities offer better performances.
- The MMV offers good fouling control and proved to be economically attractive.
- The MMV showed a low energy consumption in microalgae harvesting.

GRAPHICAL ABSTRACT



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ABSTRACT

This study was performed to investigate the effectiveness of submerged microfiltration to harvest both a marine diatom *Phaeodactylum tricornutum* and a *Chlorella vulgaris* in a recently developed magnetically induced membrane vibrating (MMV) system. We assess the filtration performance by conducting the improved flux step method (IFM), fed-batch concentration filtrations and membrane fouling autopsy using two lab-made membranes with different porosity. The full-scale energy consumption was also estimated. Overall results suggest that the MMV offers a good fouling control and the process was proven to be economically attractive. By combining the membrane filtration (15× concentration) with centrifugation to reach a final concentration of 25% w/v, the energy consumption to harvest *P. tricornutum* and *C. vulgaris* was, respectively, as low as 0.84 and 0.77 kW h/m^3, corresponding to 1.46 and 1.39 kW h/kg of the harvested biomass.

1. Introduction

Harvesting microalgal biomass from cultivation broths is one of the major challenges that limits the widespread and full-scale application of microalgae as raw material for many different end-products, especially biofuel (Greenwell et al., 2010). Microalgae-based-products are currently only economically feasible on a limited scale, primarily for high-value products, such as food supplements, natural pigments and polyunsaturated fatty acids (Raja et al., 2008). When aiming at the biomass, harvesting is normally the bottleneck of the downstream processing. However, when just some of the desired components (mostly high value products) need to be extracted from the biomass, the extraction procedure and efficiency is of a more vital interest (Šoštarič M, 2012). The most common harvesting technique is centrifugation, but few others are also suggested because of economical reason, including flocculation, electro-coagulation-flocculation and membrane filtration.

Micro- and ultrafiltration have been proven to be effective to harvest microalgae, both in cross-flow and submerged configura-

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tion (Rossignol et al., 1991; Zhang et al., 2010; Bilad et al., 2012). Membrane filtration has many advantages in this context: an almost complete retention of biomass, potential disinfection via removal of microorganisms bigger then the nominal pore sizes, limited addition of chemicals into the system, thus preventing them from accumulating in the system, and a low energy consumption (Mouchet and Bonnelye, 1998; Judd and The, 2006). The cross-flow filtration offers a high productivity (high applied fluxes) due to the high cross-flow velocity and high shear rates exposed onto the membrane surfaces. However, this consumes considerable amounts of energy due to the sometimes high applied pressures and liquid velocities, especially for ultrafiltration membranes (Le-Clech et al., 2006). In addition, over-exposure of microalgal biomass to shear, especially in the intake and pumping systems, may break microalgal cells to form smaller particles, colloids and algal organic matters (AOMs) or promote release of exopolymeric substances (EPS) (Babel and Takizawa, 2010; Ladner et al., 2010). Furthermore, cell breakage may also lead to the loss of targeted products from the cell interior. On the other hand, the submerged aerated system applies lower pressures, brings limited exposure of microalgal cell to enhanced shear rates (hence reducing EPS release), and thus offers a lower energy consumption and reduced investment cost than the cross-flow system (Judd and The, 2006; Le-Clech et al., 2006; Babel and Takizawa, 2010). However, these membrane processes also have some disadvantages, such as the relatively low fluxes that increase the capital costs, when large volumes have to be treated. Membrane scouring via air bubbling is less effective than cross flow operation, thus increasing the maintenance cleaning frequency and down-times (Mouchet and Bonnelye, 1998).

The required shear at the membrane surface in a submerged system is generally provided by coarse air bubbles which can, in the case of algae cultivation, also act to supply the required carbon dioxide (CO_2) from the air. However, this approach produces a relatively weak shear rate, so that only moderate membrane fluxes can be applied. It is also often difficult to ensure a homogeneous bubble distribution and a "plateau" in terms of flux improvement is reached beyond which no further improvement can be achieved by increasing the bubbles flow (Cui et al., 2003; Genkin et al., 2006).

The enhancement of membrane shear-rates has long been recognized as one of the most efficient factors for fouling control. It is implemented either by moving the fluid or the membrane. The membrane can be moved in a circular rotation, a torsional vibration or in vertical and horizontal oscillation systems (Jaffrin, 2008; Bilad et al., 2012). Application of a rotating disk system for algal harvesting, recently reported by Frappart et al. (2011) and Rios et al. (2011), showed that it almost doubled the membrane productivity compared to a reference cross-flow system, ascribed to the high shear-rates at the liquid-membrane interface. However, Ladner et al. (2010) found a very significant impact of enhanced shear on the microalgal cells. The AOM released from sheared microalgal cells caused increased membrane pore blocking. This phenomenon was not observed in the other studies (Frappart et al., 2011; Rios et al., 2011), probably due to different types of microalgae (cell wall), type of pumps, filtration experimental designs (shorter time-frame), etc. Therefore, a process that would maintain a high shear-rate only at the liquid-membrane interface, and not in the whole bulk, would be beneficial to achieve an efficient filtration process.

In this study, we applied a magnetically induced membrane vibrating (MVM) system to harvest both a marine diatom *P. tricornutum* and a *C. vulgaris*. Both are promising species for the production of microalgal biomass for food, feed, or fuel, and are currently intensively studied (Greenwell et al., 2010; Raja et al., 2008). Their sizes are also large enough to be retained by the applied membranes.

The effect of membrane porosity is also investigated here by testing two lab-made polyvinylidene fluoride (PVDF) membranes. The filtration performances are evaluated using the improved flux-step method (IFM) (van der Marel et al., 2009) and fed-batch concentration filtrations. The membrane fouling was evaluated by observing scanning electron microscopy (SEM) images. The energy consumption for a full-scale MVM application in algae harvesting was also tentatively estimated by extrapolating the data obtained from a related full-scale submerged MBR for wastewater treatment.

2. Methods

2.1. Cultivation and characterization of microalgae

The tests were conducted using two different microalgal broths namely a *Phaeodactylum tricornutum* and *Chlorella vulgaris*. A small contamination during the experiment of the latter broth was observed under light microscopy by *Scenedesmus* sp. However, the degree of contamination was assumed to be too small to affect the results. Both broths were cultivated using a 25 L lab-scale photobioreactor operated in batch-wise. The growth media are given in Table 1. The photobioreactor design and operation are given by Vandamme et al. (2011). The filtration experiments were performed for one week within the stationary growth phase, which was achieved after 7 days of cultivation. The fresh biomass concentrations were 0.25 and 0.21 g/l for *P. tricornutum* and *C. vulgaris*, respectively. All feeds for each broth were produced in one batch cultivation to avoid discrepancies that often occur on the feed properties among different batches.

2.2. Membrane preparation, properties and module potting

Two different flat-sheet membranes with different porosity were prepared from 9% and 12% w/w PVDF, (Mw∼534,000)/N,N-dimethylformamide (DMF) solutions by phase inversion using 3% w/w of polyvinylpyrrolidone (PVP, Mw∼10,000) as an additive. The solutions were cast on a polypropylene non-woven support (Novatexx 2471, kindly supplied by Freudenberg, Germany) with a 250 μm wet thickness and casting speed of 2.25 cm/s, and then

Table 1
The growth media for the microalgae cultivation. The solutions were dissolved in demineralized water for the *C. vulgaris*. Marine salts (NaCl) were added for *P. tricornutum*.

Component	Concentrationin the final medium (M)
Tris buffer	3.78×10^{-3}
$NaNO_3$	1×10^{-3}
$CaCl_2{\cdot}2H_2O$	2.5×10^{-3}
$MgSO_4{\cdot}7H_2O$	1.5×10^{-4}
NaHCO3	1.5×10^{-4}
$Na_2SiO_3{\cdot}9H2O$	1.00×10^{-4}
K_2HPO_4	5.00×10^{-5}
Trace metals solution	
$Na_2EDTA{\cdot}2H_2O$	3.78×10^{-3}
$FeCl_3{\cdot}6H_2O$	1×10^{-3}
$CuSO_4{\cdot}5H_2O$	2.5×10^{-3}
$ZnSO_4{\cdot}7H_2O$	1.5×10^{-4}
$CoCl_2{\cdot}6H_2O$	1.5×10^{-4}
$MnCl_2{\cdot}4H_2O$	1.00×10^{-4}
$Na_2MoO_4{\cdot}2H_2O$	5.00×10^{-5}
H_3BO_3	1.65×10^{-5}
Vitamins solution	
Thiamine HCl (vitamin B_1)	2.96×10^{-7}
Biotin (vitamin H)	2.05×10^{-9}
Cyanocobalamin (vitamin B_{12})	3.69×10^{-10}