Characterization of an aerated submerged hollow fiber ultrafiltration device for efficient microalgaee harvesting

Franziska Ortiz Tena 1 | Karolína Ranglová 2 | David Kubač 2 | Christian Steinweg 1 | Claudia Thomson 3 | Jiří Masojídek 2,4 | Clemens Posten 1

1 Institute of Process Engineering in Life Sciences Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
2 Laboratory of Algal Biotechnology, Centre Algatech, Czech Academy of Science, Institute of Microbiology, Třeboň, Czech Republic
3 iSeaMC GmbH, Bremen, Germany
4 Faculty of Science, University of South Bohemia, České Budějovice, Czech Republic

Correspondence
Franziska Ortiz Tena, Institute of Process Engineering in Life Sciences, Karlsruhe Institute of Technology (KIT), Fritz Haber Weg 2, 76131 Karlsruhe, Germany.
Email: franziska.ortiz-tena@kit.edu

Funding information
Horizon 2020 Framework Programme, Grant/Award Number: Sabana 727874

Abstract
The present work characterizes a submerged aerated hollow fiber polyvinylidene fluorid (PVDF) membrane (0.03 μm) device (Harvester) designed for the ultrafiltration (UF) of microalgal suspensions. Commercial baker’s yeast served as model suspension to investigate the influence of the aeration rate of the hollow fibers on the critical flux (CF, \(J_c\)) for different cell concentrations. An optimal aeration rate of 1.25 vvm was determined. Moreover, the CF was evaluated using two different Chlorella cultures (axenic and non-axenic) of various biomass densities (0.8–17.5 g DW/L). Comprably high CFs of 15.57 and 10.08 L/m²/h were measured for microalgae concentrations of 4.8 and 10.0 g DW/L, respectively, applying very strict CF criteria. Furthermore, the \(J_c\)-values correlated (negative) linearly with the biomass concentration (0.8–10.0 g DW/L). Concentration factors between 2.8 and 12.4 and volumetric reduction factors varying from 3.5 to 11.5 could be achieved in short-term filtration, whereat a stable filtration handling biomass concentrations up to 40.0 g DW/L was feasible. Measures for fouling control (aeration of membrane fibers, periodic backflushing) have thus been proven to be successful. Estimations on energy consumption revealed very low energy demand of 17.97 kJ/m³ treated microalgal feed suspension (4.99 × 10⁻³ kWh/m³) and 37.83 kJ/kg treated biomass (1.05 × 10⁻² kWh/kg), respectively, for an up-concentration from 2 to 40 g DW/L of a microalgal suspension.

Keywords
energy, filtration, harvesting, membrane, microalgae
INTRODUCTION

The term microalgae usually refers to photosynthetic microorganisms, both prokaryotic and eukaryotic, forming single cells, filaments, or aggregates. A great variety of species has been discovered to date, revealing various biochemical compounds and possible applications [1]. The fields of food and feed application, wastewater treatment, biofuel, or fertilizer production are just some examples for possible microalgal utilization [2]. As a consequence, dewatering of microalgae is gaining more and more interest as an important part of downstream processing. Cultivating microalgal biomass in outdoor units usually results in dilute suspensions with low biomass densities (measured as dry weight [DW]) of about 1–3 g DW/L (assuming a water content of 90% in the cells this means 10 g/L “solids” correspond to 1–3% w/w total solids [TS]). These values are more than 10 times lower than those achieved in classic heterotrophic cultivation processes. The separation of water from biomass, especially of small single-celled microalgal strains, thus requires costly processing of large water volumes, representing one of the major challenges of microalgal downstream processing [3–5].

The majority of microalgal cells are characterized by their small size (range of 1–10 μm [6]) and cell density similar to water (marine algae: 1030–1100 kg/m³, freshwater algae: 1040–1140 kg/m³ [7]), both resulting in slow settling velocities according to Stokes’ law [8–10]. In some cases, high lipid content in the cells and high salt content in the medium can even reduce density difference to zero. These cell properties make especially centrifugation rather inefficient. However, even though it is cost and energy demanding, centrifugation is the most commonly used method for harvesting large volumes [4, 5]. It is suitable for most types of microalgae—except fragile species—but mainly applied when high-value products are required. Disk stack centrifuges (like for yeasts) offering very small sedimentation paths are the device of choice, furthermore special designs have been developed for microalgal harvesting (see a recent review [11]). Filtration—as the major alternative—has its drawbacks as well. The small cell size makes an even thin filter cake in dead-end filtration practically impermeable. Elasticity of the outer layer of microalgal cells can block the gussets between the particles leading to a so-called compressible filter cake. In such cases, higher transmembrane pressure (TMP) increases the filter cake resistance but not the flow. Frequently occurring suspended macromolecules make employment of alternative approaches with active filter cake or clogging removal necessary. These could be crossflow filtration, for example, in the construction form of dynamic crossflow filtration [4, 12]. The use of filter aids like in yeast filtration is not applicable. At the end, the produced slurries may contain still too much water for subsequent processing steps. Pre-concentration steps like floatation or flocculation (per flocculants or auto-flocculation per pH-shifts) are only applicable in medium scale. For the purpose of feed and food additives, wastewater treatment, pharmaceuticals, and bioactive compound production, the application of contaminating substances (like coagulants) that ease the harvesting process is not allowed [3, 4, 9].

Due to these obstacles, dewatering of microalgae can be technology, energy and cost demanding [10] and can make 20–30% of the biomass production costs [3]. At present, microalgal processing requires a high net energy ratio (energy required to produce dry biomass [DBM] vs. energy content) and carbon balance reducing the application of microalgal biomass mostly to high-value products (> $10,000 t⁻¹) [9]. To be able to set up an economically viable and environmentally sustainable microalgal process, a low-energy harvesting method is therefore required. Most important, microalgal dewatering processes should be highly effective for most of all microalgal strains generating high biomass concentrations at its recovery. Besides, operation, energy and maintenance costs need to be moderate while handling of large volumes is possible.

Up to now, no universal harvesting technique has been found that meets all requirements. To decrease harvesting costs, dewatering processes are often set up as two step concentration procedures: first step—preconcentration (thickening) and the second step—dewatering. Often, a typical microalgal harvesting process combines membrane filtration followed by centrifugation. Usually, the microalgal slurry is thickened during the first step to 2–7% total suspended solids (TSS) before it is dewatered to a “cake” (paste) of 25% TSS (concentration factor up...
This procedure combines membrane filtration as a low energy step for high water throughput and a high energy centrifugation step to achieve high product concentrations. Preconcentration of, for example, a factor 10 from 3 to 30 g/L and a subsequent centrifugation step from 30 to 300 g/L reduces energy demand in the centrifuge by about 90% compared to centrifugation alone.

Especially in wastewater treatment by microalgae additional tasks have to be accomplished. Low light conditions can lead to low growth rates where the cells cannot take up all nutrients. On the other hand, low biomass concentrations caused by low nutrient availability lead to inefficient light usage. Together with the typical not controllable continuous flow, this requires a controllable biomass recycle or retention. If possible, this should be done with the same filtration device as the preconcentration step. Membrane filtration is—especially for the first concentration step—a dewatering method for microalgae biomass that has several advantages. It is suitable for diluted suspensions with initial concentrations \( \leq 10 \text{ wt./vol.}% \) and can yield up to 40% TSS with a microalgae removal of more than 95%. Furthermore, cell damage is minimal due to reduced shear stress, making this generally low-energy technology also ideal for shear sensitive species. Nevertheless, membrane fouling is the major drawback of this rather slow microalgae harvesting method. Periodic membrane cleaning and/or replacement can increase process costs and reduce the overall process efficiency [3, 8, 9]. It was shown, that energy demand of the two-step process (first step: membrane filtration, second step: centrifugation) can be effectively reduced by up to 90.4% per m\(^3\) and 96.9% per kg harvested biomass, respectively [13].

In this work, a prototype of a low-energy, submerged, aerated hollow fiber membrane filtration unit designed for microalgae harvesting was developed and characterized. The so-called Harvester has been designed to process microalgae cultures of low biomass densities, which should be effectively concentrated. Membrane fouling is minimized by periodic backflushing and due to air bubbling inducing moderate shear on the membrane surface to minimize a cake build-up and pore blocking. Several variables were evaluated in this study to characterize the membrane performance: membrane permeability and compressibility, critical fluxes (CFs) for various biomass concentrations of unicellular microalgae Chlorella. A model organism (yeast Saccharomyces cerevisiae) served as control to differentiate between biological and procedural effects.

The Harvester described in this study can be regarded as a way to solve the problem of high energy costs of microalgae dewatering during biomass downstream processing.

# MATERIALS AND METHODS

## 2.1 Microalgae cultivation and biomass preparation

### 2.1.1 Microalgae

Two different Chlorella microalgae strains (both cultivated phototrophically) with a cell size between 2 and 10 \( \mu \text{m} \) were used for the determination of the CF (see Section 2.3). Chlorella vulgaris H14 (further abbreviated as Chlorella A) was cultivated axenically in TAP-Medium (acetate-free, pH 7.5) in a closed 28 L photobioreactor (pH 7, 5, 25°C, 1.1vvm, 1% CO\(_2\)) with internal lightening and light intensities up to 500 \( \mu \text{mol/m}^2/\text{h} \).

The microalgae C. vulgaris R-117 (CCALA 1107, Culture Collection of Autotrophic Organisms, Institute of Botany, Treboň, Czech Republic; further abbreviated as Chlorella B) was cultivated non-axenically in inorganic medium [14–17] during July 2020 at Centre Algatech, Treboň (GPS coordinates – 48° 59’15″ N; 14° 46’40.630″ E) using an outdoor thin-layer cascade (650 L). Automatic regulation of CO\(_2\) supply kept pH at 8.0 ± 0.2.

### 2.1.2 Yeast

Commercial baker’s yeast S. cerevisiae (DHW, Vital Gold) was used as a model organism of a spherical cell shape with diameter of 5–10 \( \mu \text{m} \) similar to most microalgae species. The yeast experiments allowed defining a preliminary range of operation for the characterization of the filtration device using a microalgae biomass.

The yeast material was dissolved in phosphate-buffered saline medium (PBS, NaCl 8 g/L, KCl 0.2 g/L, KH\(_2\)PO\(_4\) 1.44 g/L, Na\(_2\)HPO\(_4\) 0.24 g/L, pH 7.4), a non-toxic buffer for cells that protects the cells from osmotic pressure. For CF experiments, two yeast suspensions of different biomass densities of 3.0 and 15.0 g DW/L were used.

## 2.2 Biomass quantification

Biomass density was determined by measurement of the optical density (OD) of microalgae and yeast at 750 and 500 nm, respectively, using a VIS-spectrophotometer (V-1200, VWR/Perkin Elmer, Lambda 35).

The measurement of DBM concentration (in g DW per L) was performed as previously described [17–19]. Culture samples (5 mL) were collected on preweighed glass microfiber filters (GC-50). The cells were washed twice with deionized (DI) water, the filters were dried in an oven.
at 105°C for 8 h, and finally transferred to a desiccator and weighed (precision of ±0.01 mg).

2.3 Filtration device Harvester

2.3.1 Description of the ultrafiltration device Harvester

For microalgae harvesting, a pilot-scale ultrafiltration (UF) device (Harvester 1.0, designated as Harvester) was designed and constructed (Figure 1). The commercially available membrane module (Puron Hollow Fiber Rows, Koch Membrane Systems) used in the Harvester consists of three bundles of aerated submerged polyvinylidene fluoride (PVDF) hollow fibers with a nominal pore size of 0.03 μm, the total membrane surface of 1.31 m² and a pure water permeability of about 490 L/m²/h·bar at 22°C. The permeate is collected on the inner side of the fibers (outside-in application). The fibers can be aerated using a controllable mass flow controller (Type 1579, mks) for fouling reduction. The driving force for the filtration process is a TMP, which is applied by a vacuum pump (Drive: MCP-Z Process ISM918A, Pump head: Z-201, MI0023, Ismatec) and monitored online using a pressure transmitter (MS – 10663, WIKA). Both constant flux and constant pressure are feasible to generate a permeate flux. A turbidity sensor (Turbimax CUS50D, Endress & Hauser) was used to measure the concentration of the cell-containing suspension online, fed to the Harvester using a peristaltic pump.
TABLE 1 Starting fluxes and flux-step heights for the CF experiments of various species and aeration rates

| Microorganism | Starting flux $J_{Start}$ | Flux-step height |
|---------------|---------------------------|------------------|
| *S. cerevisiae* | 9.16 L/m²/h               | 2.30 L/m²/h      | (Aeration 0.00 and 1.25 vvm) |
|               | 13.75 L/m²/h             | 2.30 L/m²/h      | (Aeration 2.50 vvm) |
| *Chlorella A*  | 10.30 L/m²/h             | 1.16 L/m²/h      | (DBM 1.0 g DW/L) |
|               | 13.70 L/m²/h             | 2.30 L/m²/h      | (DBM 0.8 g DW/L) |
| *Chlorella B*  | 9.16 L/m²/h              | 0.90 L/m²/h      | (All biomass concentrations tested) |

(Flowmaster FMT300 - ISM 1020, Ismatec) from a coupled photobioreactor (PBR in case of microalgae) or a feed tank (yeast). The concentrated cell suspension—retentate—can be pumped out of the *Harvester* via a peristaltic pump (Drive: Ecoline VC-Easy-Load - ISM 1077A, pump head: Masterflex L/S - 7518-10, Ismatec). Cell recycling to the cultivation unit as well as collection in a retentate tank is possible. All fluxes applied (feed, retentate, and permeate) were quantified online using flowmeters (Optiflux 5000, Krohne). The temperature (AT 001, autosen GmbH) and turbidity (Turbimax CUS50D, Endress & Hauser) inside the *Harvester* as well as its filling height (via hydrostatic pressure sensor (AC 004 Niveau, autosen GmbH)) were measured online. Periodic backflushing with tap water was applied to reduce membrane fouling.

2.3.2 Membrane resistance

Prior to the filtration experiments, the membrane was conditioned filtering DI-water at a constant permeate flux for 45 min. The water-flux ($J_W$ in L/m²/h) of the clean membrane was measured afterwards for a minimum of 10 min. The membrane resistance $R_m$ of the clean membrane could be calculated using the applied TMP (in mbar) and temperature-dependent viscosity of water ($\mu(T)$) in Pa·s according to Equation (1) [20].

$$R_m = \frac{\text{TMP}}{J_W \cdot \mu(T)}$$

2.3.3 Determination of the critical flux

The critical Flux $J_c$ was described by Field et al. in 1995 [21] who stated a threshold flux—the so-called CF—below which fouling does not occur. To date, more classifications (e.g., strong/weak form of the CF) have been defined [22], but those will not be distinguished in this work. The term “critical flux” here refers to the maximum permeate flux, above which a measurable increase in pressure ($d\text{TMP}/dt$) occurs at a constant pressure filtration.

Several methods for the measurement of the CF have been used [23]. In the present study, the method described by Diez et al. [24] was applied. The “modified flux-step method” uses backflushing to remove fouling built-up during the individual flux steps. In each step, the constant flux was set up for a period of 10 min, within which the TMP was recorded. For evaluation of each interval, the pressure increase ($d\text{TMP}/dt$) of each flux step was determined via linear regression. A critical TMP-increase of 10 Pa/min was chosen analogously to van der Marel et al. [25].

The starting flux and flux-step height for the various species tested are listed in Table 1. Only the ascending phase was taken into account, as both ascending and descending phases have been proven to identify the same value for the CF (data not shown).

2.3.4 Evaluation of the filtration process

To evaluate the harvesting efficiency of the complete process, a volumetric reduction factor (VRF) as well as a concentration factor $F_C$ were defined according to Equations (3) and (4) [26], using the initial ($V_0$) and final ($V_f$) volumes as well as the final ($C_f$) and initial ($C_0$) microalgae concentrations.

$$\text{VRF} = \frac{V_0}{V_f}$$

$$F_C = \frac{C_f}{C_0}$$

The harvesting efficiency ($\eta$) was used to evaluate the quality of the permeate generated by the membrane. It refers to the decrease of the OD of the feed suspension (OD$_{feed}$) due to biomass present the permeate (OD$_{permeate}$) in percent. A value of 100% means a full retention of any solid particles by the membrane.

$$\eta = \frac{\text{OD}_{feed} - \text{OD}_{permeate}}{\text{OD}_{feed}}$$

2.3.5 Mass balance for the *Harvester*

The filtration device *Harvester* can be used as a tool for the up-concentration of a microalgae culture. Furthermore, it
can be coupled to a photobioreactor to control the biomass concentration by cell recycling (R) or discharge (D). A mass balance for the Harvester revealed the following relation (Equation (5)):

\[ c_{x, \text{retentate}} = \frac{V_{\text{feed}}}{V_{\text{retentate}}} \cdot c_{x, \text{feed}} \] (5)

where \( V_{\text{feed}} \) is the feed flux into the Harvester in L/min, \( c_{x, \text{feed}} \) is the biomass concentration (g DW/L) of the feed suspension, \( V_{\text{retentate}} \) the retentate flux out the Harvester, and \( c_{x, \text{retentate}} \) the biomass concentration (g DW/L) of the retentate.

### 2.3.6 Energy consumption

To evaluate the energy consumption of the filtration unit Harvester, the pumping of the feed suspension (feed pump), permeate (permeate pump) as well as the concentrated retentate stream (harvest pump), together with the energy needed for membrane aeration have to be considered. For various biomass concentrations (start/end), the VRFs, and concentration factors, the energy demand for different scenarios could be evaluated and compared. A theoretical set-up with a given feed flux of 100 m³/h, an aeration rate of the membrane fibers of 1.25 vvm, and an operational permeate flux set to a sub-critical value of 19.5 L/m²/h (representing 85% of the CF predetermined for representative biomass concentrations) were considered.

Using the above-mentioned frame conditions, the energy required to perform a biomass concentration to a certain level per 3 permeate (\( E_v \) in kJ/m³ and kWh/m³) was calculated. Furthermore, the energy consumption per kg DW of the harvested biomass \( E_w \) (in kJ/kg and kWh/kg) could be determined.

The actual power demand of all three pumps \( P_S \) was calculated by dividing the theoretical demand \( P_{th} \) by the pump-specific efficiency factor \( \eta \) (Equation (8)):

\[ P_S = \frac{P_{th}}{\eta} \] (8)

The energy required for the aeration of the membrane fibers \( P_a \) was calculated using Equation (9), including the aeration rate (\( \dot{V}_{air} \)) in m³/s together with the hydrostatic pressure above the gas outlet (\( p_{hydro} \)) due to the water column.

\[ P_a = \dot{V}_{air} \cdot p_{hydro} \] (9)

### 3 RESULTS AND DISCUSSION

#### 3.1 Membrane characterization

##### 3.1.1 Critical flux experiments using baker’s yeast

Prior to the start of each filtration experiment, DI-water was filtered at 23 L/m²/h for 45 min. The filtration data was used to calculate the membrane resistance \( R_m \) for every approach according to Equation (1) (see Supporting Information Figure S1).

Five sets of experimental conditions regarding DBM concentration and aeration rates of the membrane fibers were applied to determine the \( J_c \) value for yeast suspensions (see Table 2). In line with other studies [23, 27–
Critical flux experiments with microalgae

Prior to each filtration experiment, DI-water was filtered at 20–23 L/m²/h for 45 min. The filtration data were used to calculate the membrane resistance $R_m$ for every approach according to Equation (1) (see Supporting Information Figure S1).

Figure 2 demonstrates a typical permeate-flux and TMP time profile (Chlorella B, 10.0 g DW/L, 1.25 vvm) for the CF experiments conducted applying the flux-step method. An increase in TMP of >10 Pa/min at a constant permeate flux was used as CF criteria.

Microalgae biomass grown in any medium contains—apart from cells—cell debris as well as small soluble molecules (extracellular organic matter, EOM) produced by the microalgae metabolism. Several studies have revealed the fouling propensity of all constituents of such suspensions [20, 26, 40]. EOM has been identified as to cause irreversible fouling, resulting in a permanent blockage of the membrane pores. Cells alone are responsible for the build-up of reversible filter cakes on the membrane surface that can be nearly totally removed by back-flushing. The consortium of cells, cell debris and EOM can create dense filter cakes on the membrane surface that increase the filtration resistance but help to reduce irreversible fouling effects [34, 35, 39]. Compared to the model culture (yeast) in the previous section, the filtration of Chlorella cultures resulted in higher rates of pressure-increase (dTMP/dt) and lower CFs due to the presence of EOM and cell debris (see Tables 2 and 3).

Consistent with the results in Section 3.1.1, a decrease of the CF was measured with increasing cell concentration.
In all cases, a negative linear correlation of DBM (of 1.0–10.0 g DW/L) and $J_c$ was found ($R^2 = 0.97$), which is in line with other studies [29, 41]. Contrary to those findings, $J_c$ stagnated for higher cell concentrations (10.0 and 17.5 g DW/L), which was accompanied by a lower pressure increase ($dTMP/dt$, Table 3) measured for the highest biomass concentration. In contrast to these findings, the time profiles of the permeate flux and TMP showed an obviously higher fouling occurring for the higher concentrated microalgae culture: a stable permeate flux above 15 L/m²/h could not be achieved for this culture despite higher setpoints (see Supporting Information Figure S2).

A flux decrease could be observed, although the TMP is increasing constantly up to 150 mbar. Preliminary experiments revealed that the membrane used is compressible resulting in a pressure-dependent membrane resistance $R_m$ (Equation (10), $R^2 = 0.98$, see Supporting Information Figure S3):

$$R_m = 4.135 \times 10^{11} + 2.004 \times 10^{10} \cdot \text{TMP}^{0.6648} \quad (10)$$

In consequence, the membrane pores were “squeezed” together and therefore the membrane resistance was increased, which led to a decrease of the flux at a specific
TMP. In this case, the CF was not suitable to depict the differences in fouling behavior between the two suspensions with the biomass concentration of 10.0 and 17.5 g DW/L.

A higher increase of the pressure with time (dTMP/dt, see Figure 2) was observed for the denser Chlorella B cultures (non-axenic, 4.8 and 10.0 g DW/L) compared to the low cell concentrations (0.8 and 1.0 g DW/L). This can be attributed to the increased biomass concentration as already discussed. Nevertheless, other factors need to be considered, namely microalgaes species, culture variability, and cultivation conditions.

**Microalgae species:** As indicated by the microscopic pictures, the cell size of both *C. vulgaris* strains was within the range of 2–10 μm, as previously reported [42]. The differences in filtration performance have usually been attributed to cell surface characteristics, which can influence the interaction of cell and membrane surface together with the amount and varieties of EOM produced by the microalga metabolism. Small molecules like EOM can enhance interactions between solid particles as well as with the membrane enhancing membrane fouling [35, 39, 43]. Without further investigation, no clear conclusion can be drawn about those aspects.

**Culture composition:** Non-axenic Chlorella B culture was cultivated outdoors in an open reactor system and thus, some bacteria might be present which are absent in the axenic culture (Chlorella A). It is well known that the structure and density of filter cakes on membrane surfaces are influenced by the composition of the cultures to be filtered [35, 39]. Small solid particles usually cause high filtration resistances whereas larger particles create high porous filter cakes. Furthermore, the size distribution of solid particles influences the structure of the filter cake occurring: Consortia with large particle size distributions tend to increase the packing density of the building-up filter cake structure and thereby its additional resistance to filtration. Voids between larger particles within the cake are filled by smaller particles resulting in a high cake density [44, 45]. The cell size distribution in the Chlorella B culture was wider compared to the Chlorella A culture due to the presence of bacteria, which are usually smaller than microalgal cells [1]. Therefore, an influence of the cell size distribution to the increase of the TMP (dTMP/dt) cannot be neglected.

**Culture conditions:** The culture conditions of the two Chlorella cultures used were different. The culture of Chlorella A originates from a large-scale laboratory reactor with controlled conditions. In contrast, Chlorella B was grown outdoors under natural conditions (concerning temperature and light). The microalgae cultures were thus exposed to an unstable and not-optimized environment. Unfavorable conditions like low temperatures or high irradiance can lead to cell stress accompanied by an increased content of cell debris and/or a higher production of EOM resulting in higher membrane fouling.

To conclude, the results showed a linear increase of the CF with increasing biomass concentration up to 10.0 g DW/L equivalent accompanied by rising membrane fouling. Higher cell concentrations lead to more pronounced fouling but cannot be simply detected by the $J_c$ due to the necessity of high forces leading to a membrane compressing. Additionally, the variation in the culture composition and conditions can be considered to explain higher dTMP/dt rates of Chlorella B cultures compared to Chlorella A.

An overview of several studies measuring the CF of various microalgae, mostly Chlorella species using microfiltration (MF) and UF membranes is shown in Table 4. Various microalgal species have been tested, whereas Chlorella occurred the most. The data illustrates several differences and trends concerning membrane pore size, cell size, and biomass concentration influencing the CF.

| Microalgae species | Biomass concentration (g DW/L) | Aeration (vvm) | $J_c$ (L/m²/h) | dTMP/dt at $J_c$ (Pa/min) |
|-------------------|-------------------------------|---------------|----------------|--------------------------|
| Chlorella A       | 0.8                           | 1.25          | $J_c > 32.06$ | 6.95                     |
| Chlorella A       | 1.0                           | 1.25          | $J_c > 22.93$ | 12.11                    |
| Chlorella B       | 4.8                           | 1.25          | 15.57          | 14.45                    |
| Chlorella B       | 10.0                          | 1.25          | 10.08          | 18.04                    |
| Chlorella B       | 17.5                          | 1.25          | 10.08          | 15.27                    |
TABLE 4  Comparison of CFs for various microalgae species and biomass concentrations using submerged microfiltration (MF) and ultrafiltration (UF) membranes. The CF criterion is an important factor for the evaluation of \( J_c \), which is mainly influenced by the pore size of the membrane and the biomass concentration of the suspension applied.

| Membrane Configuration | Microalgae species (cell size in \( \mu \text{m} \)) | Biomass concentration (g DW/L) | CF Method CF criterion | Ref |
|------------------------|-----------------------------------------------|-------------------------------|------------------------|-----|
| Submerged, external, flat sheet | Chlorella pyrenoidosa | 0.3 | FS-IFM | [46] |
| MF PVDF 0.1 \( \mu \text{m} \) | 27 (15°C) 30 (25°C) 42 (35°C) | 20 Pa/min | 15 L/m²/h (3 L/m²/h) |
| Submerged, internal, flat sheet | Chlorella pyrenoidosa | 0.3 | FS-IFM | [47] |
| MF PVDF 0.1 \( \mu \text{m} \) | 42 | 20 Pa/min | 10–15 L/m²/h (2.5–3 L/m²/h) |
| Submerged, internal, hollow fibers | Chlorella sp. ADE4 | 1.0 | FS | [48] |
| MF HDPE 0.4 \( \mu \text{m} \) | 58.5 | 0.2 kPa/min | 42 L/m²/h (12–33 L/m²/h) |
| Submerged, external, hollow fibers | Chlorella vulgaris (2–10 \( \mu \text{m} \)) | 0.0691 | FS-IFM-R | [49] |
| UF PVDF 0.03 \( \mu \text{m} \) | 39.4 | 20 Pa/min | 10 L/m²/h (5 L/m²/h) |
| Submerged, internal, flat sheet | Phaeodactylum tricornutum (8–35 \( \mu \text{m} \)) | 0.23 | FS-IFM | [48] |
| UF PVDF 0.03 \( \mu \text{m} \)/0.05 \( \mu \text{m} \) | >50 | 20 Pa/min | 10 L/m²/h (5 L/m²/h) |
| Submerged, external, flat sheet | Chlorella vulgaris (2–10 \( \mu \text{m} \)) | 0.8 | FS | [13] |
| UF PVDF 0.03 \( \mu \text{m} \) | 1.0 | 10 Pa/min | 10 L/m²/h (5 L/m²/h) |
| Chlorella vulgaris (2–10 \( \mu \text{m} \)) | 4.8 | This study | (2.5–3 L/m²/h) |
| 10.0 | >32.06 | |
| 17.5 | >22.93 | |
| Phaeodactylum tricornutum (8–35 \( \mu \text{m} \)) | 0.25 | |
| 0.79 | >50 | |
| 1.52 | 40 | |
| 30 | |
| Submerged, external, flat sheet | Chlorella vulgaris (2–10 \( \mu \text{m} \)) | 0.21 | FS-IFM | [50] |
| UF Cellulose MWCO: 10 kDA | 0.73 | 10 Pa/min | 10 L/m²/h (5 L/m²/h) |
| Chlorella vulgaris (2–10 \( \mu \text{m} \)) | 1.43 | This study | (1.16–2.30 L/m²/h) |
| Microcystis sp. | 0.25 | D: \( J_{\text{start}} \) 9.16 L/m²/h (0.9 L/m²/h) |
| Phaeodactylum tricornutum (8–35 \( \mu \text{m} \)) | 0.79 | |
| 1.52 | >50 | |
| 30 | |
| 100 | |
| Submerged, external, flat panel | Isochrysis (3–5 \( \mu \text{m} \)) | 0.30 | FS-B/FS-R | [30] |
| UF PES-PVD 0.05 \( \mu \text{m} \) | 15 | 10 Pa/min | 10 L/m²/h (10 L/m²/h) |
| Chlorella vulgaris (2–10 \( \mu \text{m} \)) | 0.40 | This study | |
| Phaeodactylum tricornutum (8–35 \( \mu \text{m} \)) | 0.30 | |
| 0.90 | >50 | |
| 20 | |
| N. oculata (1–3 \( \mu \text{m} \)) | 1.60 | |
| 35 | |
| 10–20 | |
| 10.00 | 15 | |
| Pavlova lutheri (5–7 \( \mu \text{m} \)) | 8.86 | |
| 10.00 | |
| 15 | |
| Pavlova lutheri (5–7 \( \mu \text{m} \)) | 20 | |
| 10.00 | |
| 15 | |
| Pavlova lutheri (5–7 \( \mu \text{m} \)) | 35 | |
| 10.00 | |
| 15 | |

Internal: inside PBR; external: separate from PBR; MF: microfiltration; UF: ultrafiltration; PVDF: polyvinyliden fluoride; HDPE: high-density polyethylene; PES-PVD: polyethersulfone polyvinylpyrrolidone; MWCO: molecular weight cut-off; CF: critical flux; FS: flux-stepping; IFM: improved flux-step method; -B: backflushing; -R: relaxation.
cell size seems to inversely influence CF values: Microalgal species with smaller cell size, for example, *Isochrysis*, tends to have lower values (15 L/m²/h) as compared to species with greater cell size (e.g., *C. vulgaris*, $J_c = 50$ L/m²/h) at similar biomass concentrations (0.3–0.4 g DW/L), due to higher diffusion activities to the bulk phase and lower surface interactions with the membrane of smaller particles compared to bigger ones [23]. Microalgal cells of similar size (*Nannochloropsis oculata*, *C. vulgaris*) achieve comparable values for $J_c$ (35 L/m²/h) for analogous culture densities (1.43–1.6 g DW/L) [13, 30]. The membrane material seems to have only little influence on the CF as comparable values for similar species and biomass concentrations of different, independent studies have been shown [23].

It must be emphasized that the CF-criterion in this study was set rather low to 10 Pa/min. This is an important variable for the evaluation of $J_c$ and needs to be taken into account when comparing those values. Keeping this fact in mind it can be concluded that the filtration performance (as measured by the CF) of the filtration device *Harvester* presented in this study falls within this range, or even prevails comparable set-ups.

The CF defines the upper limit of the membrane performance, where a stable filtration process without severe fouling can be performed. A filtration device can never be run at its maximum as to avoid capacity overload and to guarantee its optimal efficiency. Flux values either applied for microalgal harvesting (first step of dewatering or up-concentration) or as a part of a microalgal membrane bioreactor (internal or external) are set below the threshold of the membranes used [39, 51, 52] to sub-critical values of, for example, 85% of $J_c$ [13]. Therefore, *Harvester* can be classified as suitable for both criteria addressing microalgae harvesting.

### 3.2 | Microalgae filtration tests

In order to characterize the filtration performance of the *Harvester* (“proof-of-concept”), the cultures of *Chlorella* B at four biomass densities were prepared and filtered to test the capacity of the membrane. The VRF, concentration factor ($F_c$), and the harvesting efficiency ($\eta$) were calculated according to Equations (2)–(4) in Table 5. Due to limited time, all filtration experiments were restricted to a maximum of 1–4 h.

When the culture of biomass density of 1.53 g DW/L was used a maximum $F_c$ of 12.4 and VRF of 11.5 could be achieved within the short time of testing. Furthermore, for initially denser *Chlorella* cultures, cell densities of up to 40 g DW/L (in retentate) are achievable by the *Harvester*. Fouling control (aeration of the membrane fibers and periodic backflushing) was thus effective and allowed to set up a stable filtration process even for high biomass concentrations (Figure 4). An up-concentration of the microalgae cells (e.g., from 14.20 to 40.00 g DW/L) as well as a continuous filtration of a biomass flux (14.20 g DW/L) producing a constant retentate stream of 40.00 g DW/L is feasible using the *Harvester*, as shown in Figure 4. The harvesting efficiency $\eta$ varied between 78% and 93% within the first 30 min of each trial but went up to >99% after this short starting period.

According to the mass balance (see Equation (5) in Section 2.3.5), the biomass concentration in the retentate of the filtration device ($c_{X,\text{retentate}}$) was influenced by the cell concentration in the feed/PBR ($c_{X,\text{feed}}$) as well as by the quotient of feed and retentate flux ($\dot{V}_{\text{feed}}/\dot{V}_{\text{retentate}}$). Turbidity measurements inside the *Harvester* and the PBR proved the capability of the filtration device: the calculated concentration $c_{X,\text{retentate}}$ was achieved after a short time (~20 min) with very low deviations (<1%). Furthermore, an up-concentration of the biomass of more than factor 2 (from 14.20 to 40.00 g DW/L) was reached in this experiment.

### 3.3 | Energy consumption

Table 6 summarizes the operational and device parameters used for the calculation of the energy demand of the *Harvester* for different process scenarios applying an arbitrarily chosen feed inflow of 100 m³/h. It needs to be mentioned that $P_{\text{th,feed}}$ and $P_{\text{th,retentate}}$ strongly depend on the local circumstances and are given here only as examples, while the energy used to generate the permeate flux is a central element subject of this investigation. The required pump power is calculated considering a pump efficiency factor, which was set exemplary to 0.7. This value usually varies between 0.6 and 0.8, depending on the pump used and is thus not crucial for a general idea of the plant performance. The energy needed for aeration is neglectable compared to the power requirement of the pumps (Table 6). Constructive optimizations need to be performed when applying the

| Biomass concentration (g DW/L) | Aeration (vvm) | VRF | $F_c$ |
|-------------------------------|---------------|-----|------|
| Start | End |                               |     |     |
| 1.53 | 19.00 | 1.25 | 11.5 | 12.4 |
| 2.30 | 16.20 | 1.25 | 7.7  | 7.0  |
| 5.80 | 24.60 | 1.25 | 4.5  | 4.2  |
| 14.20 | 40.00 | 1.25 | 3.5  | 2.8  |
principle of the *Harvester* in large-scale and/or long-term operation to reduce the power demand of the feed pump, which is easily feasible. The energy required to maintain the TMP ($P_{th,permeate}$, Table 6) is thus the main power sink.

Different up-concentration scenarios are considered resulting in varying values for $F_C$ and VRF (see Table 7). For this purpose, the biomass concentration in the input *Chlorella* culture ($c_{x,Start}$) is specified, as well as the desired concentration in the retentate ($c_{x,End}$).

Compared to other studies [13, 53], a low energy demand was calculated for all scenarios considered (Table 7). Even for a rather high up-concentration from 2 to 40 g DW/L, the energy demand does not exceed $1.05 \times 10^{-2}$ kWh/m$^3$ permeate or $4.99 \times 10^{-3}$ kWh/kg harvested microalgae.

**TABLE 6** Operational and plant parameters used for calculation of energy consumption of the *Harvester*

| Membrane aeration rate | Membrane surface $m^2$ | Permeate flux $L/m^2h$ | Transmembrane pressure $Pa$ | Feed flux $m^3/h$ |
|------------------------|------------------------|------------------------|-----------------------------|------------------|
| 1.25 vvm               | 1.31                   | 19.5                   | 13635                       | 100              |
| $2.5 \times 10^{-4}$ m$^3$/s | 7.1 $\times 10^{-6}$ m$^3$/s | 2.8 $\times 10^{-2}$ m$^3$/s | $P_{th,permeate}$ (kJ/s) | $P_{th,feed}$ (kJ/s) | $P_{th,retentate}$ (kJ/s) | η pumps (all) | Power demand aeration (kJ/s) |
| 0.303                  | 0.332                  | 0.023                  | 0.70                        | 1.194 $\times 10^{-3}$ |

**FIGURE 4** Permeate-flux, TMP, and DBM time profiles for different modes of operation (A: up-concentration $c_{Harvester} = 14.2 \rightarrow 40$ g DW/L, B: continuous filtration $c_{Harvester} = 40.0$ g DW/L) for the *Chlorella* B culture.
TABLE 7  Energy consumption by the filtration device *Harvester*: energy required per m³ permeate (*E_v*) and per kg of DBM in retentate (*E_w*) for different concentration scenarios

| Concentration proportion | C_v,Start → C_v,End (g DW/L) | F_C | VRF | E_v (kJ/m³) | E_w (kJ/kg) | E_w total (kJ/m³) | E_v total (kJ/kg) | Red.-% |
|--------------------------|-------------------------------|-----|-----|-------------|-------------|-------------------|-------------------|--------|
| 2 → 10                   |                               | 5   | 5   | 42.35       | 1.18 × 10⁻² | 16.94             | 4.71 × 10⁻³       |        |
| 3 → 30                   |                               | 10  | 10  | 39.17       | 1.09 × 10⁻² | 11.75             | 3.26 × 10⁻³       |        |
| 2 → 40                   |                               | 20  | 20  | 37.83       | 1.05 × 10⁻² | 17.97             | 4.99 × 10⁻³       |        |

Scenario I: direct up-concentration to desired DBM concentration only using centrifugation, Scenario II: two-step up-concentration using the *Harvester* as first step (fivefold concentration) followed by centrifugation as second step, Scenario III: two-step up-concentration using the *Harvester* as first step (20-fold concentration) followed by centrifugation as second step. Red.-%: relative energy reduction of two-step harvesting using membrane filtration compared to direct up-concentration only using centrifugation.

TABLE 8  Energy consumption for microalgae harvesting for three scenarios combining filtration and centrifugation (for two preconcentrations factors *F_C*) or solely centrifugation (*C_v,Start*: 2 g DW/L, *C_v,End*: 250 g DW/L). The energy required per m³ permeate (*E_v*) and per kg of DBM in retentate (*E_w*) are compared for a continuous algae feed of 100 m³/h.

| Scenario | F_C (kWh/m³) | E_v (kWh/m³) | E_w (kWh/kg) | E_v total (kWh/m³) | E_w total (kWh/kg) | Red.-% |
|----------|--------------|--------------|--------------|-------------------|-------------------|--------|
| I        | –            | 125          | 7.99         | 3.99              | 7.99              | 0.00   |
| II       | 5            | 1.18 × 10⁻²  | 4.99 × 10⁻³  | 0.16              | 1.61              | 94.87  |
| III      | 20           | 0.01         | 9.48         | 0.15              | 99.62             |

Summing up, using the *Harvester*, a microalga suspension can effectively be up-concentrated as first step in the downstream process of microalgae biomass, which can then be followed by centrifugation to maintain high cell concentrations, as demonstrated in Tables 7 and 8. Membrane filtration can thus reduce the energy demand per kg DBM significantly (up to about 99%, Table 8) when coupling it to centrifugation [30]. Furthermore, the low energy demand allows the *Harvester* to be applied for cell recycling in continuous microalgae cultivation, for example, for the production of low-cost biomass or wastewater remediation.

4  CONCLUSION

The present study revealed the suitability of the submerged aerated PVDF membrane UF device *Harvester* for microalgae harvesting. Comparable high fluxes (10.08 to >32.06 L/m²/h) can be realized for different biomass concentrations (0.8–17.5 g DW/L). Optimal operational conditions (fouling control via membrane aeration and backflushing) allow a stable filtration handling high biomass concentrations (up to 40.0 g DW/L) efficiently. The very low energy demand makes the *Harvester* an ideal tool for the first up-concentration step in microalgae downstream processing. Further, it can be used for external cell recycling in continuous microalgae cultivation, e.g., deployed for wastewater treatment.
**NOMENCLATURE**

| Symbol | Units | Explanation |
|--------|-------|-------------|
| V      | L/min | Volumetric flow rate |
| $\mu(T)$ | Pa s | Temperature-dependent viscosity |
| -B     |       | Backflushing |
| C      | g/L   | Concentration (Indices: 0: Start, f: final, x: biomass) |
| C. vulgaris |       | Chlorella vulgaris |
| CF     |       | Critical flux |
| DW     |       | Dry weight |
| E      | kJ/kWh | Energy (indices: v: per m³ permeate, w: per kg algae biomass) |
| EOM    |       | Extracellular organic matter |
| Fc     |       | Concentration factor |
| FS     |       | Flux-stepping |
| g      | kg m/s² | Gravity acceleration |
| H      | m     | Pumping height |
| HDPE   |       | High-density polyethylene |
| IFM    |       | Improved flux-step method |
| J      | L/m²/h | Permeate flux |
| $J_c$  | L/m²/h | Critical flux |
| MF     |       | Microfiltration |
| MWCO   |       | Molecular weight cut-off |
| OD     |       | Optical density |
| P      |       | Power (indices: th: theoretical, s: pump specific, a: aeration) |
| p      | bar   | Pressure (index hydro: hydrostatic) |
| PES-PVD|       | Polyethersulfone polyvinylpyrrolidone |
| PVDF   |       | Polyvinyliden efluorid |
| -R     |       | Relaxation |
| R_m    | m⁻¹   | Membrane resistance |
| S. cerevisiae |       | Saccharomyces cerevisiae |
| TMP    | mbar  | Transmembrane pressure |
| TSS    |       | Total suspended solids |
| UF     |       | Ultrafiltration |
| VRF    |       | Volumetric reduction factor |
| $\eta$ |       | Efficiency factor |
| $\rho$ | kg/m³ | Density |

**ACKNOWLEDGMENTS**

This research was funded by the EU program Horizon 2020 (project SABANA, grant no. 727874).

Open access funding enabled and organized by Projekt DEAL.

**CONFLICT OF INTERESTS**

The authors have declared no conflicts of interest.

**DATA AVAILABILITY STATEMENT**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**ORCID**

Franziska Ortiz Tena  
https://orcid.org/0000-0002-8170-4485

Clemens Posten  
https://orcid.org/0000-0001-5956-3180

**REFERENCES**

1. Richmond, A., Hu, Q. (Eds.), *Handbook of Microalgal Culture: Applied Phycology and Biotechnology*, John Wiley & Sons Ltd, Chichester West Sussex UK 2013.
2. Singh, G., Patidar, S. K., Microalgae harvesting techniques: a review. J. Environ. Manage. 2018, 217, 499–508.
3. Barros, A. I., Gonçalves, A. L., Simões, M., Pires, J. C., Harvesting techniques applied to microalgae: a review. Renew. Sustain. Energy Rev. 2015, 41, 1489–1500.
4. Molina Grima, E., Acín Fernández, F. G., Robles Medina, A., Downstream processing of cell mass and products, in: Richmond, A., Hu, Q. (Eds.), *Handbook of Microalgal Culture: Applied Phycology and Biotechnology*, John Wiley & Sons Ltd, Chichester West Sussex UK 2013, pp. 267–309.
5. Muylaert, K., Bastiaens, L., Vandamme, D., Gouveia, L., Harvesting of microalgae: overview of process options and their strengths and drawbacks, in: Gonzalez-Fernandez, C., Muñoz, R. (Eds.), *Microalgae-Based Biofuels and Bioproducts: From Feedstock Cultivation to End-Products*. Woodhead Publishing Series in Energy, Woodhead Publishing an imprint of Elsevier, Duxford, Cambridge, MA, Kidlington 2017, pp. 113–132.
6. Mata, T. M., Martins, A. A., Caetane, N. S., Microalgae processing for biodiesel production, in: Melero, J. A., Luque, R. (Eds.), *Advances in Biodiesel Production: Processes and Technologies*. Woodhead Publishing Series in Energy, no. 39, Woodhead Pub Ltd, Oxford 2012, pp. 204–231.
7. Alhattab, M., Microalgae harvesting methods for industrial production of biodiesel: critical review and comparative analysis. J. Fundam. Renew. Energy Appl. 2015, 05.
8. Uduman, N., Qi, Y., Danquah, M. K., Forde, G. M. et al., Dewatering of microalgal cultures: a major bottleneck to algae-based fuels. J. Renew. Sustain. Energy 2010, 2, 12701.
9. Alam, M. A., Wang, Z., *Microalgal Biotechnology for Development of Biofuel and Wastewater Treatment*, Springer Singapore, Singapore 2019.
10. Bux, F., Chisti, Y. (Eds.), *Algae Biotechnology: Products and Processes*. Green Energy and Technology, 1st Ed., Springer, Switzerland 2016.
11. Najjar, Y. S., Abu-Shamleh, A., Harvesting of microalgae by centrifugation for biodiesel production: a review. Algal Res. 2020, 51, 102046.
12. Bauer, L., Ranglová, K., Masojídek, J., Dros, B. et al., Digestate as sustainable nutrient source for microalgae—challenges and prospects. Appl. Sci. 2021, 11, 1056.
13. Bilad, M. R., Discart, V., Vandamme, D., Foubert, I. et al., Harvesting microalgal biomass using a magnetically induced membrane vibration (MMV) system: filtration performance and energy consumption. Bioresour. Technol. 2013, 138, 329–338.
14. Grivalský, T., Ranglová, K., da Câmaras Manoel, J. A., Lakatos, G. E. et al., Development of thin-layer cascades for microalgae cultivation: milestones (review). Folia Microbiol. (Praha) 2019, 64, 603–614.

15. Doucha, J., Livanský, K., Novel outdoor thin-layer high density microgal culture system: productivity and operational parameters. Algal. Stud. 1995, 76, 129–147.

16. Masojídek, J., Kopecký, J., Giannelli, L., Torzillo, G., Productivity correlated to photobiological performance of Chlorella mass cultures grown outdoors in thin-layer cascades. J. Ind. Microbiol. Biotechnol. 2011, 38, 307–317.

17. Babaei, A., Ranglová, K., Malapascua, J. R., Masojídek, J., The synergistic effect of selenium (selenite, -SeO₃²⁻) dose and irradiance intensity in Chlorella cultures. AMB Express 2017, 7, 56.

18. Ranglová, K., Lakatos, G. E., Câmaras Manoel, J. A., Grivalský, T. et al., Growth, biostimulant and biopesticide activity of the MACC-1 Chlorella strain cultivated outdoors in inorganic medium and wastewater. Algal Res. 2021, 53, 102136.

19. Ranglová, K., Lakatos, G. E., Câmaras Manoel, J. A., Grivalský, T. et al., Rapid screening test to estimate temperature optima for microalgae growth using photosynthesis activity measurements. Folia Microbiol. (Praha) 2019, 64, 615–625.

20. Kanchanatip, E., Su, B.-R., Tulaphol, S., Den, W. et al., Fouling characterization and control for harvesting microalgae Arthospira (Spirulina) maxima using a submerged, disc-type ultrafiltration membrane. Bioreour. Technol. 2016, 209, 23–30.

21. Field, R. W., Wu, D., Howell, J. A., Gupta, B. B., Critical flux concept for microfiltration fouling. J. Membr. Sci. 1995, 100, 259–272.

22. Le Clech, P., Jefferson, B., Chang, I. S., Judd, S. J., Critical flux determination by the flux-step method in a submerged membrane bioreactor. J. Membr. Sci. 2003, 227, 81–93.

23. Bacchin P., Aimir P., Field R. W., Critical and sustainable fluxes: theory, experiments and applications. J. Membr. Sci. 2006, 281, 42–69.

24. Diez, V., Ezquerra, D., Ceza, J. I., Garcia, A. et al., A modified method for evaluation of critical flux, fouling rate and in situ determination of resistance and compressibility in MBR under different fouling conditions. J. Membr. Sci. 2014, 453, 1–11.

25. van der Marel, P., Zwijnenburg, A., Kemperman, A., Wessling, M. et al., An improved flux-step method to determine the critical flux and the critical flux for irreversibility in a membrane bioreactor. J. Membr. Sci. 2009, 332, 24–29.

26. Zhang, X., Hu, Q., Sommerfeld, M., Puruhiito, E. et al., Harvesting algal biomass for biofuels using ultrafiltration membranes. Bioreour. Technol. 2010, 101, 5297–5304.

27. Møkkus, S., Howell, J., Nyström, M., Critical flux in ultrafiltration of myoglobin and baker’s yeast. J. Membr. Sci. 2002, 196, 13–25.

28. Wu, Z., Wang, Z., Huang, S., Mai, S. et al., Effects of various factors on critical flux in submerged membrane bioreactors for municipal wastewater treatment. Sep. Purif. Technol. 2008, 62, 56–63.

29. Cheng, T., Wei, C.-H., Leiknes, T., Polishing of anaerobic secondary effluent by Chlorella vulgaris under low light intensity. Bioreour. Technol. 2017, 241, 360–368.

30. Baerdemaeker, T. D., Lemmens, B., Dotremont, C., Fret, J. et al., Benchmark study on algae harvesting with backwashable submerged flat panel membranes. Bioreour. Technol. 2013, 129, 582–591.

31. Wicaksana, F., Fane, A. G., Pongpairoj, P., Field, R., Microfiltration of algae (Chlorella sorokiniana): critical flux, fouling and transmission. J. Membr. Sci. 2012, 387–388, 83–92.

32. Mo, W., Soh, L., Werber, J. R., Elimelech, M. et al., Application of membrane dewatering for algal biofuel. Algal Res. 2015, 11, 1–12.

33. Akhondi, E., Zaman, F., Tng, K., Leslie, G. et al., The performance and fouling control of submerged hollow fiber (HF) systems: a review. Appl. Sci. 2017, 7, 765.

34. Zhang, Y., Fu, Q., Algal fouling of microfiltration and ultrafiltration membranes and control strategies: a review. Sep. Purif. Technol. 2018, 203, 193–208.

35. Le-Clech, P., Chen, V., Fane, T. A., Fouling in membrane bioreactors used in wastewater treatment. J. Membr. Sci. 2006, 284, 17–53.

36. Zhang, Y., Tang, C. Y., Li, G., The role of hydrodynamic conditions and pH on algal-rich water fouling of ultrafiltration. Water Res. 2012, 46, 4783–4789.

37. Alipourzadeh, A., Mehrnia, M. R., Hallaj Sani, A., Babaei, A., Application of response surface methodology for investigation of membrane fouling behaviours in microalgal membrane bioreactor: the effect of aeration rate and biomass concentration. RSC Adv. 2016, 6, 111182–111189.

38. Luo, Y., Le-Clech, P., Henderson, R. K., Simultaneous microalgae cultivation and wastewater treatment in submerged membrane photobioreactors: a review. Algal Res. 2017, 24, 425–437.

39. Liao, Y., Bokhary, A., Maleki, E., Liao, B., A review of membrane fouling and its control in algal-related membrane processes. Bioreour. Technol. 2018, 264, 343–358.

40. Qu, F., Liang, H., Tian, J., Yu, H. et al., Ultrafiltration (UF) membrane fouling caused by cyanobacteria: Fouling effects of cells and extracellular organics matter (EOM). Desalination 2012, 293, 30–37.

41. Castaing, J. B., Massé, A., Séchet, V., Sabiri, N.-E. et al., Immersed hollow fibres microfiltration (MF) for removing undesirable micro-algae and protecting semi-closed aquaculture basins. Desalination 2011, 276, 386–396.

42. Safi, C., Zebib, B., Merah, O., Pontalier, P.-Y. et al., Morphology, composition, production, processing and applications of Chlorella vulgaris: a review. Renew. Sustain. Energy Rev. 2014, 35, 265–278.

43. Drexlcr, I. L. C., Yeh, D. H., Membrane applications for microalgae cultivation and harvesting: a review. Rev. Environ. Sci. Biotechnol. 2014, 13, 487–504.

44. Kinnarinen, T., Tuunila, R., Häkkinnen, A., Reduction of the width of particle size distribution to improve pressure filtration properties of slurries. Miner. Eng. 2017, 102, 68–74.

45. Wiącek, J., Stasiak, M., Effect of the particle size ratio on the structural properties of granular mixtures with discrete particle size distribution. Granul. Matter 2018, 20, 1–9.

46. Chu, H., Zhao, F., Tan, X., Yang, L. et al., The impact of temperature on membrane fouling in algae harvesting. Algal Res. 2016, 16, 458–464.

47. Zhao, F., Chu, H., Yu, Z., Jiang, S. et al., The filtration and fouling performance of membranes with different pore sizes in algae harvesting. Sci. Total Environ. 2017, 587–588, 87–93.

48. Boonchai, R., Seo, G., Microalgae membrane photobioreactor for further removal of nitrogen and phosphorus from secondary sewage effluent. Korean J. Chem. Eng. 2015, 32, 2047–2052.
49. Bilad, M. R., Vandamme, D., Foubert, I., Muylaert, K. et al., Harvesting microalgal biomass using submerged microfiltration membranes. Bioresour. Technol. 2012, 111, 343–352.
50. Chiou, Y.-T., Hsieh, M.-L., Yeh, H.-H., Effect of algal extracellular polymer substances on UF membrane fouling. Desalination 2010, 250, 648–652.
51. Zhang, M., Yao, L., Maleki, E., Liao, B.-Q. et al., Membrane technologies for microalgal cultivation and dewatering: recent progress and challenges. Algal Res. 2019, 44, 101686.
52. Bilad, M. R., Arafat, H. A., Vankelecom, I. F. J., Membrane technology in microalgae cultivation and harvesting: a review. Biotechnol. Adv. 2014, 32, 1283–1300.
53. Gerardo, M. L., Oatley-Radcliffe, D. L., Lovitt, R. W., Minimizing the energy requirement of dewatering Scenedesmus sp. by microfiltration: performance, costs, and feasibility. Environ. Sci. Technol. 2014, 48, 845–853.

**SUPPORTING INFORMATION**
Additional supporting information may be found in the online version of the article at the publisher’s website.

**How to cite this article:** Ortiz Tena F, Ranglová K, Kubač D, Steinweg C, et al. Characterization of an aerated submerged hollow fiber ultrafiltration device for efficient microalgae harvesting. *Eng Life Sci.* 2021;21:607–622.

[https://doi.org/10.1002/elsc.202100052](https://doi.org/10.1002/elsc.202100052)