Evaluation of draw solution for enhanced microalgae harvesting via forward osmosis

Aida Isma[1], *Mohamad* Idris[2], *Munira* Mohammad[1*] *Mesud* Mohamad[1], *Yang* Weimin[1], and *Poppy* Puspitasari[2]

[1]Centre for Water Research, Faculty of Engineering, Built Environment and Information Technology, SEGi University, 47810 Kota Damansara, Selangor Darul Ehsan, Malaysia
[2]Faculty of Engineering, Universitas Negeri Malang (UM), Jalan Semarang No. 5, Malang 65145, East Java, Indonesia

Abstract. Microalgae have attracted increasing attention as a renewable resource with potential applications in biofuels, wastewater treatment, and environmental remediation. However, large-scale harvesting remains a critical challenge due to the high energy requirements and cost inefficiencies of conventional techniques such as centrifugation and chemical flocculation. This study investigates forward osmosis (FO) as a sustainable alternative for microalgae harvesting, with sodium chloride (NaCl) evaluated as the draw solution (DS). A cellulose triacetate (CTA) FO membrane was employed to concentrate *Chlorella vulgaris* cultures using draw solution concentrations ranging from 2M to 7M. System performance was assessed based on water flux, electrical conductivity (EC), and total solids (TS) recovery under varying operating conditions. Results showed that water flux depended strongly on DS concentration, with higher NaCl molarity enhancing osmotic pressure and initial flux. The 6M NaCl DS produced the highest water flux (12.7 L/m²·h), although performance declined over time due to dilution effects and membrane fouling. The 4M NaCl solution provided the best balance between efficiency and cost, yielding the highest TS recovery (18.4%). FO effectively concentrated biomass, with the final concentration dependent on initial culture density and operational settings. FESEM analysis confirmed the presence of fouling layers on the membrane surface, which were manageable with periodic cleaning. Overall, the results highlight the importance of draw-solution optimisation to balance concentration efficiency, operational stability, and salt diffusion in FO-based microalgae harvesting systems.

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[1] Corresponding author: muniramohammad@segi.edu.my

1 Introduction

Chlorella vulgaris is one of the microalgae species recognized as a promising resource for biofuels, pharmaceuticals, and other valuable bioproducts due to its high growth rate and ability to sequester carbon dioxide [3]. The harvesting of microalgal biomass from dilute cultures is difficult because of the low biomass concentration (0.6 g L^{-1}) [6] small cell size (< 20 µm) [1], nearly neutral buoyancy ($\rho = 1.08 - 1.13$ g mL^{-1}) [7], and strongly negative surface charge [5]. Conventional dewatering methods such as centrifugation, filtration and flocculation are energy-intensive, costly and may result in biomass loss or contamination.
Forward osmosis (FO) is emerging as a promising technology for the concentration and dewatering of microalgae, driven by its lower energy requirements [11] and higher efficiency compared to traditional methods [12]. A critical aspect of FO is the choice of draw solution, which significantly influences the efficiency and effectiveness of the dewatering process. The characteristics of the draw solution, including osmotic pressure, solute diffusivity, and potential for recovery and reuse, directly influence the key parameters such as water flux, reverse-solute flux, and overall energy efficiency. FO utilises a semi-permeable membrane and a draw solution to induce water movement from the microalgae suspension into the draw solution, thereby concentrating the biomass. Despite its promise, the application of FO for microalgae dewatering faces several challenges such as membrane fouling, draw-solution regeneration, process optimization, and scalability. Notably, existing FO-based microalgae studies using NaCl draw solutions have largely focused on process feasibility, with limited emphasis on draw solution selection that balances concentration efficiency and fouling behaviour. In this context, this study aims to systematically evaluate the influence of NaCl draw-solution concentration on flux sustainability, reverse salt diffusion, biomass concentration efficiency, and membrane fouling during FO harvesting of *Chlorella vulgaris.*

2 Materials and Methods

2.1 Materials

Experiments were conducted using a laboratory-scale forward osmosis (FO) system equipped with a flat-sheet cellulose triacetate (CTA) membrane (Sterlitech, USA). The membrane consists of two distinct layers: a dense, smooth active layer responsible for selective water transport, and a porous support layer that provides mechanical strength. Sodium chloride (NaCl) was selected as the draw solution (DS) because of its high osmotic potential, low cost, and ease of regeneration.

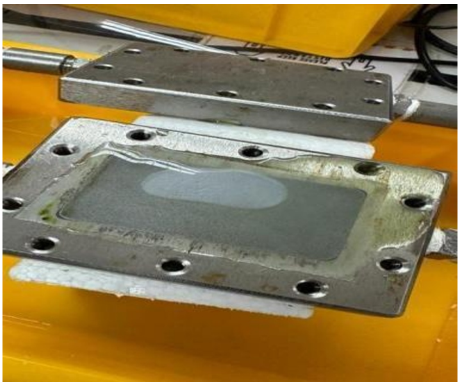


Fig. 1. Membrane module forward osmosis experiment

2.2 Membrane intrinsic transport parameter

The intrinsic membrane transport parameters were evaluated using a laboratory-scale forward osmosis (FO) filtration system with an active membrane area of 28 cm², as shown in Fig. 1. Prior to each experiment, the membrane samples were pre-compacted with deionized (DI) water for 30 minutes at a flow rate of 1 L min⁻¹ to stabilize the water flux. The active layer of the cellulose triacetate (CTA) membrane, characterized by its smooth surface, was oriented toward the feed solution, while the porous support layer, known for its rough texture, faced the draw solution. The feed solution was placed on a magnetic stirrer to ensure uniform mixing throughout the experiment. The pure-water flux (Jw) was determined using Equation (1):

$$J = \frac{\Delta V}{A_m \Delta t} \quad (1)$$

where ΔV is the permeate volume (L), A_m is the active membrane area (m²), and Δt is the filtration time (h). Following flux stabilization, the DI water feed was replaced with NaCl draw solutions of varying molarities (2 M to 7 M) to optimize biomass harvesting during the FO dewatering process. The draw solution was placed on a precision balance to continuously monitor volume changes. Two peristaltic pumps were employed to circulate the draw and feed solutions, maintaining a flow rate of 1.5 L min⁻¹. Fig. 2 shows the schematic diagram of the configuration of the FO filtration system used in this study. All experiments were conducted in duplicate to ensure reproducibility.

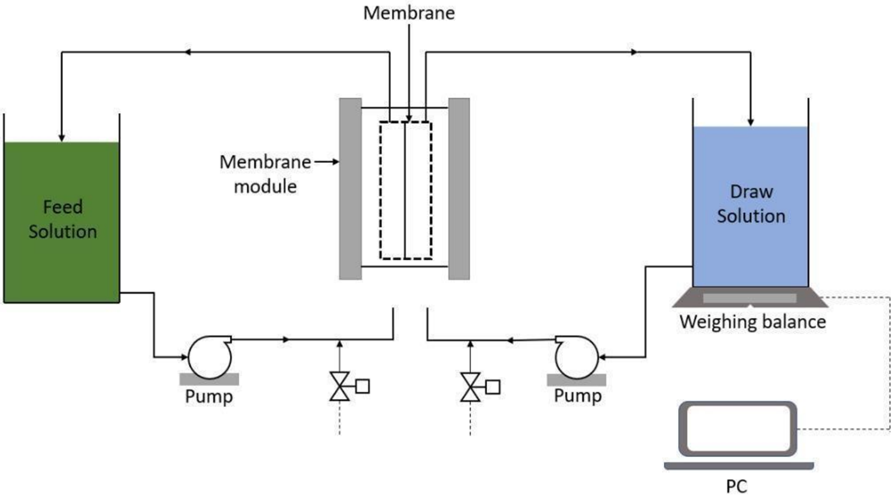


Fig. 2. Schematic diagram of the configuration of the forward osmosis system

A locally isolated freshwater microalgae strain, *Chlorella sp* obtained from International Institute of Aquaculture and Aquatic Sciences (I-AQUAS), UPM was used in this study supplied as an actively growing suspension. The culture was maintained under standard laboratory cultivation conditions prior to the experiment. In general. Microalgae growth was supported under continuous illumination at moderate light intensity, nutrient-sufficient growth medium, and an adequate cultivation period to achieve active griwth prior to harvesting. The species possesses a cell size of 2 – 4 um and a cell density ranging from 1.2 – 1.4 g/L. The harvesting efficiency was evaluated using concentration factor (CF), volumetric reduction factor (VRF) and recovery rate (Re), as expressed in Equation (2) – (4):

$$CF = \frac{C_f}{C_o} \tag{2}$$

$$VRF = \frac{V_o}{V_f} \tag{3}$$

$$Re = \frac{(C_f \times V_f)}{(C_o \times V_o)} \times 100\% \tag{4}$$

where C_o, C_p and C_f represent the initial, permeate and final microalgae concentrations (g/L), respectively, while V_o and V_f denote the initial and final suspension volumes (L).

2.3 Analysis method

The surface morphologies of the membranes were observed using a field mission scanning electron microscope (FESEM, USA).

3 Results and Discussion

3.1 Membrane flux profile

The flux profiles presented in Fig. 3 demonstrated a pronounced dependence on NaCl draw-solution concentration, with higher molarity producing greater osmotic driving force, particularly during the early stages of operation. At 20 minutes, the 5 M NaCl solution produced the highest initial flux (50 ±2.3 LMH), indicating rapid transmembrane water transport driven by the strong osmotic gradient. In contrast, lower concentrations (2–3 M) resulted in comparatively lower flux values (18-28 ± 1.5 – 2.0 LMH), while higher concentrations (6 M and 7 M) exhibited reduced flux performance relative to 5 M, likely due to increased reverse salt diffusion and more pronounced early-stage fouling effects.

As filtration progressed, a decline in flux was observed under all operarting conditions, attributable to draw solution dilution and membrane fouling resulting from algal biomass accumulation and extracellular organic matter deposition. By 120 minutes, the 5 M NaCl draw solution maintained the highest flux (22 ± 1.6 LMH), demonstrating superior flux stability compared with other concentrations. Meanwhile, the 4 M NaCl solution exhibited stable and moderate flux values throughout the filtration cycle (18 ± 1.2 LMH), suggesting a favourable balance between flux performance and osmotic energy demand. Overall, these findings confirm that 5 M NaCl provided the most favorable flux characteristics for FO-based microalgae concentration, while 4 M NaCl represents a practical and cost-effective alternative for extended harvesting operations.

Reverse salt diffusion is an intrinsic phenomenon in forward osmosis processes and may influence microalgae viability and biomass quality during concentration. The diffusion of NaCl from the draw solution into the feed increases the salinity of the microalgae suspension and may induce osmotic stress in salt-sensitive species such as *Chlorella vulgaris*. However, under moderate salt diffusion levels and short operating durations, microalgae cells have been reported to tolerate transient salinity increases without severe physiological disruption, particularly under controlled laboratory conditions [15]. Similar dependencies between operating conditions, solution chemistry, and membrane fouling behaviour have also been reported in other membrane-based separation systems, underscoring the critical role of process parameters in governing membrane performance and fouling propensity [24].

This observation is consistent with recent findings by Nguyen et al. [4], who reported that higher draw-solution concentrations improved water flux during forward-osmosis microalgae dewatering due to greater osmotic-pressure differences. However, elevated molarity also promoted internal concentration polarization (ICP) and reverse-salt diffusion.

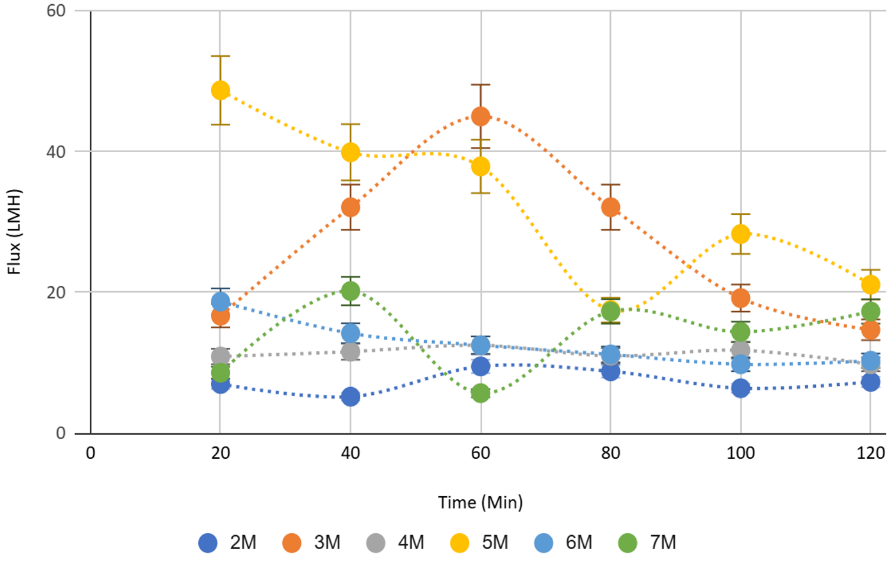


Fig. 3. Trend of membrane flux at different NaCl molarity

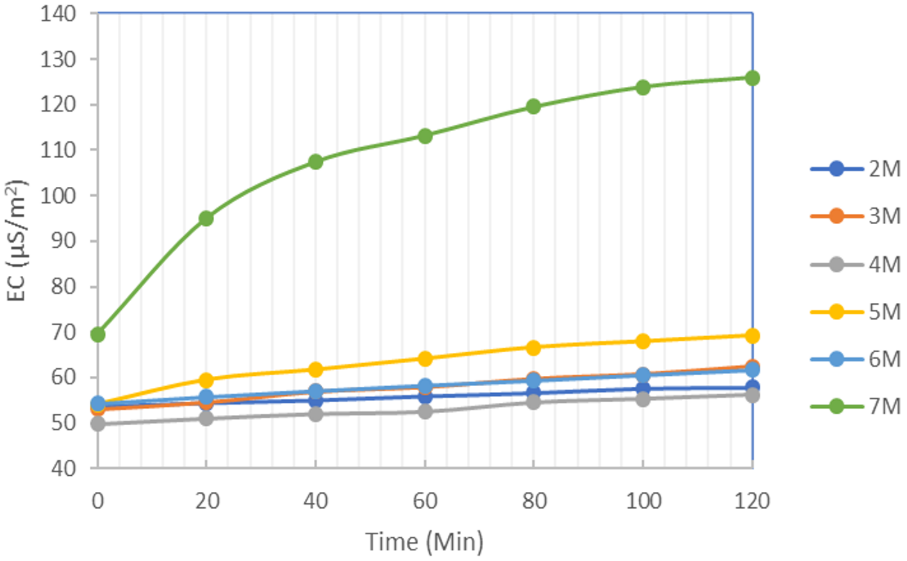


Fig. 4. Electro conductivity values over time at different NaCl molarity

Electrical conductivity was usedas a qualitative indicator of salt leakage, as quantitative reverse salt flux was not measured. Fig. 4 presents the variation in electrical conductivity (EC) during the concentration of *Chlorella vulgaris* using the forward osmosis (FO) process. As the draw-solution concentration increased from 2 M to 7 M NaCl, progressively higher EC values were recorded in the feed. The electrical conductivity (EC) trend over time reflects progressive solute leakage from the draw solution into the feed side, indicating reverse salt diffusion across the FO membrane. EC values increased for all NaCl concentrations throughout the 120-minute operation, with higher draw solute concentrations producing more pronounced EC increases. The 7 M NaCl solution exhibited the highest EC rise, reaching ~125 µS/m², followed by 5 M and 6 M, whereas lower concentrations (2 – 4 M) demonstrated smaller and more gradual increases, with final EC values below ~60 µS/m². This pattern aligns closely with the flux behavior: systems with higher initial flux (e.g., 5 M and 7 M) also experienced greater reverse salt diffusion, as enhanced osmotic driving force facilitated both water transport and solute back-diffusion. Conversely, lower-molarity draw solutions (2 – 4 M) maintained relatively stable EC profiles, corresponding to their lower but more consistent flux rates.

Overall, the EC results confirm the trade-off between achieving high flux and managing salt leakage. Although 5 M NaCl provided the most favourable flux performance, its elevated EC profile indicates a need for careful management of reverse solute diffusion to prevent feed contamination and maintain membrane integrity. Meanwhile, 4 M NaCl exhibited moderate flux with lower EC increase, reinforcing its suitability as a cost-effective and operationally stable option for extended FO-based microalgae harvesting applications.The biomass concentration results confirm the effectiveness of forward osmosis in concentrating *Chlorella vulgaris* across all draw solution strengths, with final biomass concentrations consistently higher than the initial culture (~2100 mg/L) as shown in Fig. 5. Biomass concentration increased progressively with increasing NaCl molarity, reaching a maximum at 7 M (~3200 mg/L), representing approximately a 30% increase relative to the initial concentration. Draw solutions at 5 M and 6 M also produced substantial concentration enhancement, while lower molarities (2–4 M) achieved moderate biomass enrichment. These results correlate strongly with the observed flux profiles, where higher osmotic driving force at elevated NaCl concentrations enabled greater water removal from the feed, resulting in enhanced biomass thickening. Likewise, the increasing electrical conductivity trends for higher molarities reflected greater reverse salt diffusion, which, while contributing to higher osmotic efficiency, also introduced potential ionic stress that must be balanced for prolonged microalgal harvesting operations.

Taken together, the flux, conductivity, and biomass concentration findings demonstrate that a 5 M NaCl draw solution offers the most favourable performance, providing high water flux, significant biomass concentration, and manageable salt leakage. While 7 M NaCl achieved the highest biomass concentration due to its strong osmotic pull, its elevated EC values and accelerated flux decline indicate diminishing returns and greater operational challenges. Conversely, 4 M NaCl provided stable performance with lower salinity intrusion, supporting its suitability for cost-efficient and energy-conscious operation.

The strong correlation between EC and biomass concentration confirms that higher ionic strength in the draw solution effectively promotes water flux and dewatering efficiency. This conditions may be associated with osmotic stress-related effects on the system performance,although direct evidence of metabolic impairment was not assessed~~.~~ Similar observations have been reported by Hao et al., [13], who demonstrated that higher draw-solution osmotic strength enhances the concentration of solids and biomass. Despite this limitation, the improved performance at 7 M NaCl highlights the importance of optimizing osmotic gradients to balance efficient biomass recovery with minimal physiological stress.

Overall, the results validate forward osmosis as a viable low-energy strategy for microalgae concentration, with optimal performance achieved through careful selection of draw solute strength to balance flux efficiency, salt diffusion, and biomass recovery.

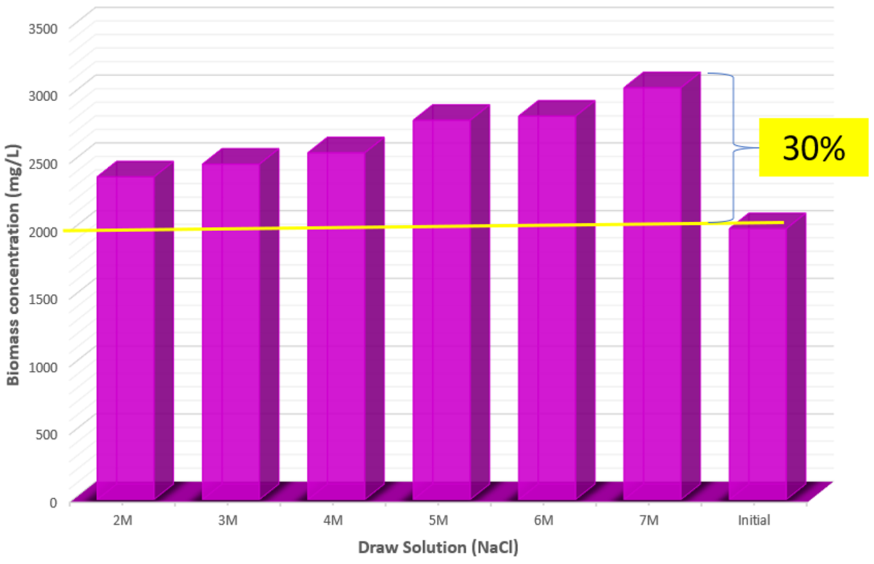


Fig. 5. Microalgae biomass concentration harvested using different concentration of NaCl

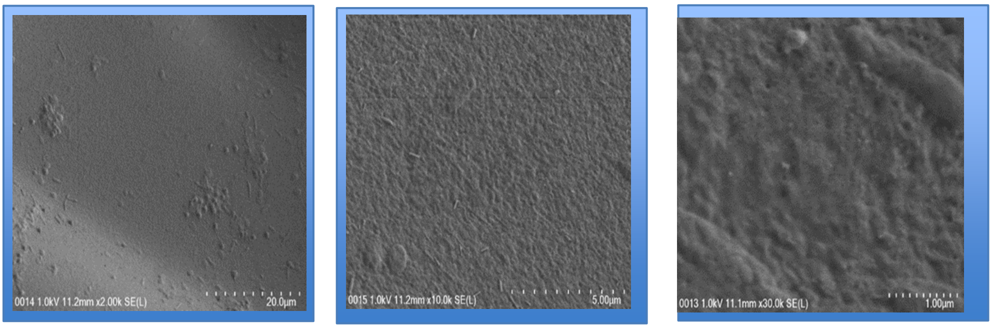
3.2 Morphology of cellulose triacetate membrane

Fouling characterization in this section is qualitative and morphology-based, with no quantitative fouling metrics reported. Fig. 6 presents the FESEM images of the cellulose triacetate (CTA) membrane captured at magnifications of 20 µm, 5 µm, and 1 µm after 120 minutes of forward osmosis operation. At the low magnification of 20 µm (Fig.6 (i)), the overall surface morphology shows localized fouling patterns attributed to microalgae attachment, likely resulting from variations in cell density and uneven distribution within the microalgae suspension. The viscosity of the draw solution exerts a noticeable influence on these patterns, as it governs the hydrodynamic behavior and mass transfer near the membrane surface, thereby affecting the apparent surface morphology observed.

At the medium magnification of 5 µm (Fig. 6(ii)), the membrane surface exhibits only a few scattered deposits, consistent with the small size of the microalgae used in this study, which reduces the likelihood of forming large agglomerates. However, concentrated draw solution may suppress flow turbulence near the membrane surface, promoting localized solute accumulation and osmotic imbalance.

At the high magnification of 1 µm (Fig. 6(iii)), detailed surface imaging reveals small regions of pore clogging, indicating localized interactions between microalgae cells and the membrane surface. Nevertheless, the hydrophilic and smooth surface morphology of the membrane effectively minimizes particle adhesion and organic deposition. The combination of osmotic-driven operation, controlled draw solution viscosity, and the membrane's intrinsic antifouling properties leads to minimal structural deformation and a clean surface profile after operation.

These findings are consistent with previous reports by Li et al. [8] and Niksefat et al. [9], which demonstrated that CTA membranes possess high biofouling resistance due to their compact structure and low surface roughness. Additionally, Xu et al. [10] noted that shorter filtration durations and moderate cross-flow velocities can further minimise fouling formation in FO-microalgae systems. Therefore, controlling the viscosity of the draw solution is crucial not only for influencing hydrodynamics and solute diffusion but also sustaining consistent flux, maintaining membrane integrity, and ensuring suitability for longterm or repeated FO operation cycles with minimal maintenance requirements.



(ii) (iii) (i)

Fig. 6. FESEM images of the membranes captured at magnifications of 1 µm, 5 µm, and 20 µm after 120 minutes

4 Conclusion

In conclusion, the results demonstrated that the concentration and properties of the draw solution played a critical role in determining the efficiency of microalgae harvesting using the forward osmosis (FO) process. Among the concentrations tested, a 5 M NaCl draw solution exhibited the most effective performance, achieving a biomass recovery of 3,040 mg L^{-1} within 2 hours, equivalent to approximately 27% of the total biomass. The increase in draw solution concentration enhanced the osmotic pressure gradient, resulting in higher water flux and increased biomass concentration harvested, thereby confirmed effective dewatering and biomass concentration. However, the elevated osmotic gradient at 7 M NaCl was accompanied by a moderate decline in flux stability, suggesting the occurrence of internal concentration polarization (ICP) and reverse-salt diffusion. Additionally, the viscosity of the concentrated draw solution influenced hydrodynamic conditions near the membrane surface, potentially affecting solute diffusion and localized fouling patterns. FESEM analysis confirmed that membrane fouling remained minimal despite the high draw solution concentration, due to the short operating duration and the hydrophilic characteristics of the membrane. These findings emphasize the importance of optimizing draw solution concentration and viscosity to balance water flux, fouling control, and membrane stability in FO-based microalgae harvesting.

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