Dewatering of sewage for nutrients and water recovery by Forward Osmosis (FO) using divalent draw solution

Singh, N.; Dhiman, S.; Basu, S.; Balakrishnan, M.; Petrinic, I.; Helix-Nielsen, Claus

Published in:
Journal of Water Processing Engineering

Link to article, DOI:
[10.1016/j.jwpe.2019.100853](https://doi.org/10.1016/j.jwpe.2019.100853)

Publication date:
2019

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Singh, N., Dhiman, S., Basu, S., Balakrishnan, M., Petrinic, I., & Helix-Nielsen, C. (2019). Dewatering of sewage for nutrients and water recovery by Forward Osmosis (FO) using divalent draw solution. *Journal of Water Processing Engineering*, 31, [100853]. <https://doi.org/10.1016/j.jwpe.2019.100853>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Dewatering of sewage for nutrients and water recovery by Forward Osmosis (FO) using divalent draw solution

N. Singh¹, S. Dhiman², S. Basu^{2,3*}, M. Balakrishnan^{1,2}, I. Petrinic⁴, C. Helix-Nielsen^{4,5}

¹Department of Energy and Environment, TERI School of Advanced Studies, Vasant Kunj, New Delhi 110070, India

²The Energy and Resources Institute (TERI), Darbari Seth Block, IHC Complex, Lodhi Road, New Delhi 110003, India

³National Institute of Foundry and Forge Technology (NIFFT), Ranchi, Jharkhand 834003, India

⁴University of Maribor, Faculty of Chemistry and Chemical Engineering, Smetanova ulica 17, SLO-2000 Maribor, Slovenia

⁵Technical University of Denmark, Department of Environmental Engineering, Miljøvej 113, 2800 Kgs. Lyngby, Denmark

Corresponding author

Email address: Subhankar Basu (basusubhankar4@gmail.com, Subhankar.niffit@gov.in)

Abstract

Forward osmosis (FO), based on the phenomenon of osmosis, is a breakthrough technology for concentrating different feeds including domestic sewage. Globally, sewage treatment facilities are increasingly focusing on recovery of resources such as water, nutrients (nitrogen and phosphorus) and energy from sludge. In this context, FO can be applied for sewage up-concentration followed by nutrients recovery from the concentrated stream. Using biomimetic aquaporin membranes (thin film composite FO membranes incorporating aquaporin proteins), this work investigated divalent magnesium chloride as draw solution for sewage concentration. The effect of cross flow velocity and draw concentration on water recovery, rejection of organics and nutrients and membrane fouling was studied. Higher draw solution concentration and cross flow velocity enhanced water recovery but concentration of organics (in terms of chemical oxygen demand (COD)) remained unaffected. Over 24 h, an average water flux of 5.3 L/m² h was obtained with recovery of water (57%), phosphate (75%), ammonia (66%) and organics (73%). Membrane fouling was confirmed by zeta potential and FT-IR analysis and cleaning was required after every 24 h cycle to restore the performance. The findings indicate that sewage concentration by FO with divalent magnesium chloride draw solution is promising for water and nutrients recovery.

Key words: Forward Osmosis; Aquaporin membranes; Domestic sewage; Water recovery; Nutrient recovery; Membrane reusability

1. Introduction

Sewage treatment through conventional biological processes e.g. activated sludge process (ASP), sequencing batch reactor (SBR) etc. focus on meeting the local norms specified for discharge of treated wastewater into water bodies or on land. Recognizing that sewage is a rich source of

water, nutrients and energy, the focus is now shifting towards treatment integrated with resources recovery. Water scarcity is motivating the reuse and recycle of treated sewage. With phosphate rock mineral (the natural source of phosphorus fertilizer) becoming increasingly scarce, there is interest in utilizing the nutrients content in sewage. Recovery of water and nutrients as saleable by-products are expected to provide revenue generation opportunities to municipal wastewater treatment plants (Huang et al., 2014) making their operation more viable.

Membrane filtration is an efficient and compact technology that has been used in sewage treatment to produce treated water suited for various reuse applications. Pressure driven membrane processes such as reverse osmosis (RO) and nanofiltration (NF) have been used for tertiary treatment while microfiltration (MF) and ultrafiltration (UF) in aerobic and anaerobic membrane bioreactors (MBRs) have been employed for sludge separation. More recently, forward osmosis (FO), based on the osmotic pressure gradient across the membrane, has gained attention for desalination (Altaee et al., 2016; Mazlan et al., 2016) as it is less energy intensive than RO. FO has also been investigated for the concentration of municipal wastewater (Xiao et al., 2018; Ortega-Bravo et al., 2016; Huang et al., 2015; Xue et al., 2016; Zhang et al., 2014) and various industrial wastewaters (Korenak et al., 2018; Xu et al., 2018; Lee et al., 2019; Dutta & Nath, 2018; Singh et al., 2018; Ansari et al., 2016; Lutchmiah et al., 2014; Gebreyohannes et al., 2015).

There are several studies on sewage concentration by FO. Water flux is influenced by the membrane type, with thin film composite (TFC) membranes displaying higher flux than cellulose triacetate (CTA) membranes (Ortega-Bravo et al., 2016). Concentration of organics (in terms of COD), ammonia nitrogen and total phosphorous is well-established (e.g. Gao et al., 2018; Xue et al., 2015; Wang et al., 2016b). FO has been successfully integrated in MBRs, either alone or with MF (Luo et al., 2015; Luo et al., 2016; Qiu et al., 2016). Both in direct FO and FO-MBRs, membrane fouling (Gao et al., 2018; Wang et al., 2016a; Zhang et al., 2016; Huang et al., 2015) and enhanced salinity of the feed has been reported (Chen et al., 2014; Gu et al., 2015). Sun et al., 2016 compared membrane fouling in direct FO and FO-MBR for municipal wastewater treatment. Though severe flux decline with thicker cake layer formation was observed for direct FO, water permeability could be more effectively restored by physical and chemical cleaning. Most works on sewage/municipal wastewater concentration have employed CTA and TFC membranes with limited studies using aquaporin based biomimetic membranes (TFC-FO membranes incorporating aquaporin proteins) (Hey et al., 2017; Hey et al., 2016a; Hey et al., 2016b; Li et al., 2017). NaCl or sea water have been used as draw solution in these studies. Overall, sewage concentration is influenced by choice of FO membrane, draw solution and the operation conditions.

Sewage concentration by FO offers an option for recovering water and nutrients for potential applications in agriculture. This work investigates FO of sewage with biomimetic aquaporin membrane using a divalent solute $MgCl_2$ as the draw solution. Effect of draw solution concentration and cross flow velocity on the FO performance was studied and membrane fouling and cleaning investigated. At the same concentration, $MgCl_2$ has higher osmotic pressure than NaCl. Compared to most other salts used to prepare draw solutions, $MgCl_2$ is cheaper (28 \$/kg) (Li et al., 2017); in the Indian market, industrial grade $MgCl_2$ is available at a low cost of 0.15 \$/kg. As reverse salt flux leading to increased salinity of the feed cannot be completely avoided,

using MgCl_2 as the draw could be beneficial as it would combine with the nutrients in the concentrated sewage to form the fertilizer magnesium ammonium phosphate (struvite). As per the International Fertilizers Association (IFA), India is a major importer of nitrogen and ammonia for the manufacture of urea and diammonium phosphate that are two widely used fertilizers (Yara Fertilizer Industry handbook, 2018). Part of the diluted MgCl_2 draw solution could be used to precipitate struvite from the concentrated sewage (Kataki et al., 2016). The balance could be subjected to NF to obtain water and concentrated draw for reuse in the FO process. Instead of higher pressure RO (required for concentrating diluted NaCl draw solution), NF is adequate for MgCl_2 rejection (Hilal et al., 2005).

2. Materials and methods

2.1 FO system

The FO experimental set-up (Fig. 1) consisted of a membrane module connected to containers for draw solution (2000 mL) and feed solution (250 mL) through suitable piping and pumps. The feed solution (sewage) was collected from the inlet of the SBR unit of a local sewage treatment plant housed in India Habitat Centre (IHC), New Delhi, India. The treatment plant receives wastewater from the kitchen and toilets of IHC. The sewage characteristics are shown in Table 1. Industrial grade magnesium chloride hexahydrate ($\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$) (purchased from Advance Chemical Sales Corporation, New Delhi) was used to prepare the draw solution. 1M $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ solution possesses an osmotic pressure of 150 bar and viscosity of 1.29 cP. A locally fabricated acrylic FO cell (20 cm x 15 cm x 5 cm), with an area of 0.00437 m^2 , was fitted with a flat sheet Aquaporin Inside™ prototype membrane (gifted by Aquaporin A/s, Denmark). This TFC-FO membrane incorporates aquaporin proteins into its polyamide-based selective layer. The $110 \mu\text{m}$ thick membrane is stable in the pH range of 2 to 11 and has a contact angle of $41.22 \pm 2.24^\circ$ with zeta potential of -68 mV at pH 6 (as provided by the supplier). The membrane was placed in the FO module, supported by stainless steel mesh and polypropylene spacers. Two pumps (Kemflo, India) with maximum flow rate of 1.5 L/min were used for circulation of the feed and draw solutions in the module. Flow meters (Adwyn Chemicals Pvt. Ltd., Delhi) were used to maintain the flow of feed and draw solutions. Change in the volume of feed solution was measured using a weighing balance (A&D, Japan) connected to a laptop. The draw solution was continuously stirred using a magnetic stirrer and its conductivity was measured using a conductivity meter (Acmaas Technologies Pvt. Ltd., India).

Fresh sewage (osmotic pressure of 0.02-0.05 bar) was collected and passed through a tea strainer to remove suspended particles. Draw solution of different concentrations of $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ (1M, 1.5M, 2M) were studied. The cross flow velocity of both feed and draw solution was initially fixed at 0.38 cm/sec and FO experiment was performed over five hours. The water flux was monitored and was calculated every 5 minutes using Eqn. 1. Similar experiments were done varying the feed and draw solution cross flow velocity (0.29 cm/sec, 0.38 cm/sec and 0.48 cm/sec) at a fixed draw solution concentration of 1M.

$$J_w = (W_2 - W_1) / A \times \Delta t \quad (1)$$

where, J_w is water flux ($L/m^2 h$), (W_2-W_1) is the weight change observed (g), A is the effective membrane filtration area (m^2) and Δt is the time interval (h).

Based on the results, optimal cross flow velocity and draw solution concentration were identified and longer duration testing (24 h) was done to evaluate the membrane performance.

Reverse solute flux was calculated using deionized (DI) water as feed. The conductivity of the feed solution was measured during FO after known time interval and was converted into concentration using total dissolved solids (TDS) standard curve for the draw solute ($MgCl_2 \cdot 6H_2O$). Reverse solute flux was calculated by Eqn. 2.

$$J_s (g/ m^2 h) = (C_t V_t - C_o V_o) / A \times \Delta t \quad (2)$$

where, C_o (g/L) and V_o (L) are the initial concentration and initial volume of the feed solution, respectively, and C_t (g/L) and V_t (L) are the solute concentration and the volume of the feed solution measured at time $t = 5$ h, respectively.

Fig.1. Schematic representation of the FO set-up

Table 1. Physiochemical properties of feed solution (sewage)

Parameter	Value
pH (-)	7.4±0.06
Conductivity (mS/cm)	2.3± 0.04
Total suspended solids (TSS mg/L)	300± 0.02
Total dissolved solids (TDS mg/L)	1600± 0.37
Chemical oxygen demand (COD mg/L)	661±99
Density (g/cm ³)	1.00
Total nitrogen (mg/L)	38±3
NH ₄ -N (mg/L)	31±3.2

2.2 Analytical methods

pH and conductivity were measured using pH meter (Bionics Scientific Technology Pvt Ltd., India) and conductivity meter (Acma Technologies Pvt. Ltd, India). Chemical oxygen demand (COD), total nitrogen, ammonia nitrogen ($\text{NH}_4\text{-N}$), total phosphorous and total solids were analyzed as per the Standard Methods for the Examination of Water and Wastewater (APHA, 2005). Samples for COD analysis were digested with potassium chromate in a Spectralab digester (India) (open reflux method) before titration with ferrous ammonium sulfate. Ammonical nitrogen was determined using a distillation process and total phosphorus by using stannous chloride method followed by a spectrophotometer analysis at 690nm.

COD concentration in the feed solution was calculated as

$$r_{\text{COD}} (\%) = (C_t \times V_t) \times 100 / (C_0 \times V_0). \quad (3)$$

where, r_{COD} is the accumulation ratio of COD (%), C_0 and V_0 are the COD concentration (g/L) and volume (L) of feed solution at time $t = 0$ h and C_t and V_t are the COD concentration (g/L) and volume (L) of feed solution at time $t = 5$ h respectively.

Water recovery rate (R) was determined as

$$R_{\text{H}_2\text{O}} = (V_p / V_f) \times 100\%. \quad (4)$$

where, V_p (L) is the volume of the permeate water, and V_f (L) is the volume of feed.

All the FO experiments were performed in duplicate with fresh membranes and average of three consecutive readings has been presented.

2.3 Membrane reusability

Membrane reusability was studied under optimized condition (1.5M draw solution and 0.38 cm/sec cross flow velocity of feed and draw solutions) for five days covering 5 continuous cycles (C1-C5, each cycle lasting 24 h). Fresh draw solution (1.5M $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$, 3L) and feed (sewage, 1L) was used in each cycle. Physical cleaning (after C1, C3 and C4) and chemical cleaning (after C2) was performed for a duration of 30 min at a feed and draw cross flow velocity of 0.57 cm/sec (equivalent to 1.5 L/min flow rate of pump). Chemical cleaning on both sides of the membrane was done using 500 mL 0.5N NaOH (Fisher Scientific, India). Reusability was checked in terms of average water flux and corresponding water recovery for each cycle. COD, ammonia and phosphate (as nutrients) concentration in the feed was also measured after each FO cycle.

2.4 Membrane characterization

Surface groups on virgin and fouled membranes were studied using Attenuated Total Reflection Fourier Transform Infrared (ATR-FTIR) spectroscopy (IR Affinity 1, Shimadzu). Zeta potential was measured using 1mM KCl solution with polypropylene membrane as reference (SurPASS electrokinetic analyser, Anton-Paar, Graz, Austria).

3. Results and discussions

3.1 Effect of draw solution concentration and cross flow velocity

Fig 2. Effect of draw solution concentration on (a) water flux (standard deviation: ± 0.43 (1M); ± 0.88 (1.5M) and ± 1.35 (2M)), and (b) COD retention. Feed and draw solution cross flow velocity was fixed at 0.38 cm/sec.

The filtration properties of the biomimetic aquaporin membrane with DI water as feed and 1M NaCl as draw solution were as follows: pure water permeability (A) 0.52 $L/m^2 h$ bar; salt permeability (B) 0.09 $L/m^2 h$; structural parameter (S) 569 μm ; B/A 0.17 bar; water flux (J_w) 8.7 $L/m^2 h$ and reverse salt flux (J_s) 4 $g/m^2 h$. The average water flux and salt passage of the membrane using DI water as feed and $MgCl_2 \cdot 6H_2O$ (1M) as the draw solution was 5.7 $L/m^2 h$ and 0.49 $g/m^2 h$ respectively.

Figure 2 shows the effect of different draw solution concentrations on water flux and COD retention. The average J_w was 5.11 $L/m^2 h$ (1M), 6.66 $L/m^2 h$ (1.5M) and 6.92 $L/m^2 h$ (2M) (Fig 2a). The gradual increase in water flux with increased draw solution concentration is attributed to increasing driving force across the membrane. A narrow range of draw solution concentrations was tested as an increase of 0.5M corresponds to a large increase of 75 bar in osmotic pressure. The water flux for DI water and sewage feed with 1M $MgCl_2 \cdot 6H_2O$ was similar ($\sim 5 L/m^2 h$) because the low osmotic pressure of sewage (0.02-0.05 bar) resulted in a comparable osmotic pressure difference of around 150 bar. The water flux profiles for draw solution concentrations of 1M and 1.5M were relatively stable whereas more fluctuations in the flux were observed for 2M $MgCl_2 \cdot 6H_2O$. This instability in the water flux could be due to enhanced internal concentration polarization at higher driving force (Zou et al., 2011). For all the three draw concentrations, r_{COD} of the concentrated sewage remained in the range 76%-80% (Fig. 2b). This supports the findings by Ansari et al., 2017 that FO membranes are not completely impermeable to dissolved COD imparting solutes. The effect becomes more prominent with higher osmotic pressure difference across the membrane.

Fig 3. The effect of cross flow velocity on FO membrane (a) water flux, and (b) COD concentration of feed solution. Initial draw solution concentration was fixed at 1M.

Figure 3 shows the effect of cross flow velocity on water flux and COD concentration in the sewage feed. Water flux increased with increasing cross flow velocity of the feed and draw solutions (Fig. 3a) with average flux of 5.5 $L/m^2 h$ (0.29 cm/sec), 6 $L/m^2 h$ (0.38 cm/sec) and 8 $L/m^2 h$ (0.48 cm/sec). Membrane surface scouring due to increased cross flow velocity hinders surface deposits and thus reduces the internal concentration polarization across the membrane (Boo et al., 2013). The corresponding COD concentration of feed solution did not increase linearly with increasing cross flow velocity. The maximum concentration of COD (76%) was obtained at 0.38 cm/sec.

Fig 4. Water flux and water recovery over 24 h in FO of sewage as feed solution and $MgCl_2 \cdot 6H_2O$ (1.5M) as draw solution. Cross flow velocity of feed and draw was 0.38 cm/sec. Standard deviation for flux was ± 0.61 and for water recovery was ± 0.43 .

Longer duration FO study shows that water recovery increased with time. Correspondingly the water flux decreased from 8 $L/m^2 h$ at the start of the experiment to 7 $L/m^2 h$ (6 h), further reducing to 5.5 $L/m^2 h$ (8-12 h) before reaching 3.5 $L/m^2 h$ at the completion of the 24 h cycle (Fig 4). Water recovery was around 57% and the feed components were concentrated as follows:

73% (COD), 75% (phosphate) and 66% (ammonia). The final concentrations were 3417 mg/L COD, 135 mg/L phosphate and 161 mg/L ammonia. Factors for water flux decline could be fouling from cake layer formation on membrane surface and decrease in osmotic driving force (Zhang et al., 2016). Deposits on the membrane surface were visually observed indicating fouling. The conductivity of the draw solution changed marginally from the initial value of 94.3 mS/cm to 91.6 mS/cm after 24 h FO indicating that dilution of the draw (resulting in drop in osmotic pressure) was negligible. The flux decline therefore appears to be primarily due to membrane fouling.

Fouling was also confirmed with the change in zeta potential of the membrane surface (Fig. 5a), and appearance of the new functional group (-C-H group) at 2328 cm^{-1} in the ATR-FTIR spectra (Fig. 5b). The virgin membrane has an isoelectric point at pH 2.8. At pH 7, the virgin membrane has a zeta potential of -80mV, whereas the fouled membrane has a higher negative potential between -90mV to -100mV. Deposition of cationic species such as NH_4^+ contributes to surface fouling (Li et al., 2017). In this application, fouling renders the hydrophilic membrane surface more negative that is expected to repel anionic species (PO_4^{3-}). Preliminary studies show that around 75% phosphate and 66% ammonia in the concentrated sewage can be recovered as struvite at pH 9 by precipitation using the diluted draw.

Fig. 5 (a) Zeta potential, and **(b)** ATR-FTIR spectra of the virgin and fouled membranes.

3.2 Effect of membrane cleaning and subsequent nutrients recovery

Fig.6 (a) Water flux and water recovery of the membrane in consecutive 24 h FO cycles, and (b) recovery of nutrients and organics in each cycle. Cross flow velocity of feed and draw was 0.38 cm/sec and 1.5M $MgCl_2 \cdot 6H_2O$ was used as draw solution.

To evaluate membrane reusability in terms of water flux and corresponding water recovery, FO was performed in 5 continuous cycles (C1-C5) of 24 h each (Fig. 6a). Physical cleaning was done after C1, C3 and C4 and chemical cleaning after C2. The water flux and water recovery respectively in C1, C2, C4 were similar ($3.9 \pm 1 L/m^2 h$ and $38 \pm 2\%$) and dropped marginally in C5 ($3.6 \pm 0.1 L/m^2 h$ and $35 \pm 1.3\%$). However, water flux and water recovery in C3 (after

chemical cleaning) was 4.5 ± 0.5 L/m² h and $45 \pm 2\%$ respectively, which was higher than that obtained with the virgin membrane. The results indicate that for sewage concentration with biomimetic aquaporin membranes, regular cleaning is required to improve the membrane reusability. It is reported that when aquaporin membranes are cleaned chemically, there is an increase in localized water permeability through the aquaporin vesicles because of increase in hydrophilicity of surrounding surface to vesicles (Li et al., 2017). This could be the reason for flux and water recovery enhancement after chemical cleaning. The water flux in C5 is around 86% of the value obtained with the pristine membrane in C1. This loss in water flux could be due to irreversible fouling on the membrane surface. Fig 6b shows that the COD concentrations in C1-C3 were similar (60%), but reduced subsequently (38% in C4 and 30% in C5). The ammonia concentration increased initially (32% in C1 to 53% in C2, C3) but reduced later (45% in C4 and 40% in C5). The phosphate concentration was high in C1-C4 (68-74%) but dropped to 44% in C5. Taken together, this shows that regular cleaning of the membrane active surface maintains the flux and its concentration ability.

4. Conclusions

In this study, biomimetic aquaporin FO membrane was used to concentrate domestic sewage with MgCl₂·6H₂O as draw solution. Increase in draw solution concentration and cross flow velocity enhances water flux but COD concentration remains unaffected. Membrane fouling occurs but regular cleaning enables restoration of membrane performance in terms of water flux, water recovery and concentration of organics and nutrients. Further investigations are required for effective management of the diluted MgCl₂·6H₂O draw solution covering struvite precipitation from concentrated sewage and re-concentration by NF for reuse in FO.

Acknowledgements

The authors gratefully acknowledge support from Department of Science and Technology (DST) and Slovenian Research Agency under the collaborative project grants INT/Slovenia/P-15/2014 and BI-IN/15-17-001 respectively. CHN also acknowledges support from the Innovation Fund Denmark via the IBISS and MEMENTO projects. N. Singh acknowledges scholarship support from DST under Women Scientists Scheme (WOS-A; grant no. SR/WOS-A/ET-56/2016).

References

- Altaee, A., Millar, G.J., Zaragoza, G., Sharif, A., Energy efficiency of RO and FO–RO system for high-salinity seawater treatment. Clean Techn. Environ. Policy, 2016 DOI 10.1007/s10098-016-1190-3.
- Ansari, A.J., Hai, F.I., Guo, W., Ngo, H.H., Price, W.E., Nghiem, L.D., Factors governing the pre-concentration of wastewater using forward osmosis for subsequent resource recovery, Sci.Total Environ., 2016, 566-567, 559-566.
- Ansari, A.J., Hai, F.I., Price, W.E., Drewes, J.E., Nghiem, L.D., Forward osmosis as a platform for resource recovery from municipal wastewater - A critical assessment of the literature. J. Membr. Sci., 2017, 529, 195-206.

- APHA, Standard Methods for the Examination of Water and Wastewater, (19th ed.) (2005) ed., American Public Health Association, Washington, DC, USA, 2005.
- Boo, C., Elimelech, M., Hong, S., Fouling control in a forward osmosis process integrating seawater desalination and wastewater reclamation, *J. Membr. Sci.* 2013, 444, 148-156.
- Chen L., Gu Y., Cao C., Zhang J., Ng J.W., Tang C., Performance of a submerged anaerobic membrane bioreactor with forward osmosis membrane for low strength wastewater treatment, *Water Res.*, 2014, 50, 114–123.
- Dutta S., and Nath K., Feasibility of forward osmosis using ultra low pressure RO membrane and Glauber salt as draw solute for wastewater treatment, *J. Environ. Chem. Eng.*, 2018, 6 (4), 5635-5644.
- Gao, Y., Fang, Z., Liang, P., Huang X., Direct concentration of municipal sewage by forward osmosis and membrane fouling behaviour, *Bioresour. Technol.*, 2018, 247, 730-735.
- Gebreyohannes A. Y., Curcio E., Poerio T., Mazzei R., Profio Di G., Drioli E., G. Lidietta, Treatment of olive mill wastewater by forward osmosis, *Sep. Purif. Technol.*, 2015, 147, 292-302.
- Gu Y., Chen L., Ng J.W., Lee C., V. W.C. Chang, C. Y. Tang, Development of anaerobic osmotic membrane bioreactor for low strength wastewater treatment at mesophilic condition, *J. Membr. Sci.*, 2015, 490, 197-208.
- Hey, T., Bajraktari, N., Davidsson, Å., Vogel, J., Madsen, H. T., Hélix-Nielsen, C., la Cour Jansen, J., Jönsson, K., Evaluation of direct membrane filtration and direct forward osmosis as concepts for compact and energy-positive municipal wastewater treatment, *Environ. Technol.* 2017, 1-13.
- Hey, T., Bajraktari, N., Vogel, J., Hélix Nielsen, C., la Cour Jansen, J., Jönsson, K., The effects of physicochemical wastewater treatment operations on forward osmosis, *Environ. Technol.* 2016a, 1-10.
- Hey, T., Zarebska, A., Bajraktari, N., Vogel, J., Hélix-Nielsen, C., la Cour Jansen, J., Jönsson, K., Influences of mechanical pretreatment on the non-biological treatment of municipal wastewater by forward osmosis, *Environ. Technol.* 2016b, 1-10.
- Hilal N., Al-Zoubi H., Darwish N. A. , Mohammad A. W., Nanofiltration of Magnesium Chloride, Sodium Carbonate, and Calcium Sulphate in Salt Solutions, *Separation Science and Technology*, 2005, 40, 3299-3321
- Huang H., Yang J., Li D., Recovery and removal of ammonia–nitrogen and phosphate from swine wastewater by internal recycling of struvite chlorination product, *Bioresour. Technol.*, 2014, 172, 253-259.

Huang, L., Lee, D., Lai, J., Forward osmosis membrane bioreactor for wastewater treatment with phosphorous recovery, *Bioresour. Technol.*, 2015, 198, 418-423.

Kataki S., West H., Clarke M., Baruah D. C., Phosphorus recovery as struvite from farm, municipal and industrial waste: Feedstock suitability, methods and pre-treatments, *Waste Manage.*, 2016, 49, 437-454.

Korenak J., Hélix-Nielsen C., Bukšek H., Petrinić I., Efficiency and economic feasibility of forward osmosis in textile wastewater treatment, *J. Clean. Prod.*, 2019, 210, 1483-1495.

Lee W. J., Goh P. S., Lau W. J., Ong C. S., Ismail A. F. Antifouling zwitterion embedded forward osmosis thin film composite membrane for highly concentrated oily wastewater treatment, *Sep. Purif. Technol.*, 2019, 214, 40-50.

Li Z., Linares R.V., Bucs S., Fortunato L., Amy G., Aquaporin based biomimetic membrane in forward osmosis: Chemical cleaning resistance and practical operation, *Desalination*, 420, 2017, 208-215.

Luo W., Hai F. I., Kang J., Price W. E., Nghiem L. D., Elimelech M., The role of forward osmosis and microfiltration in an integrated osmotic-microfiltration membrane bioreactor system, *Chemosphere*, 2015, 136, 125-132.

Luo W., F. I., Price W. E., Guo W., Nghiem L. D., Phosphorus and water recovery by a novel Hai osmotic membrane bioreactor–reverse osmosis system, *Bioresour. Technol.*, 2016, 200, 297-304.

Lutchmiah K., Verliefde A. R. D., Roest K., Rietveld L. C., Cornelissen E. R., Forward osmosis for application in wastewater treatment: A review, *Water Res.*, 2014, 58, 179-197.

Madsen H. T., Bajraktari N., Nielsen C. H., Bruggen B. Van der, Søgaard E. G., Use of biomimetic forward osmosis membrane for trace organics removal, *J. Membr. Sci.*, 2015, 476, 469-474.

Mazlan N.M., Peshev D., Livingston A.G., Energy consumption for desalination—a comparison of forward osmosis with reverse osmosis, and the potential for perfect membranes. *Desalination*, 2016, 377, 138–151

Ortega-Bravo J.C., Ruiz-Filippi G., Donoso-Bravo A., Reyes-Caniupán I.E., Jeison D., Forward osmosis: Evaluation thin-film-composite membrane for municipal sewage concentration, *Chem. Eng. J.*, 2016, 306, 531-537.

Qiu G., Zhang S., Raghavan D. S. S., Das S., Ting Y.P., The potential of hybrid forward osmosis membrane bioreactor (FOMBR) processes in achieving high throughput treatment of municipal wastewater with enhanced phosphorus recovery, *Water Res.*, 2016, 105, 370-382.

- Singh N., Petrinic I., Hélix-Nielsen C., Basu S., Balakrishnan M., Concentrating molasses distillery wastewater using biomimetic forward osmosis (FO) membranes, *Water Res.*, 2018, 130, 271-280.
- Sun Y., Tian J., Zhao Z., Shi W., Liu D., Cui F, Membrane fouling of forward osmosis (FO) membrane for municipal wastewater treatment: A comparison between direct FO and OMBR. *Water Res.*, 2016, 104, 330-339.
- Wang X., Chang V.W. C., Tang C.Y., Osmotic membrane bioreactor (OMBR) technology for wastewater treatment and reclamation: Advances, challenges, and prospects for the future, *J. Membr. Sci.*, 2016a, 504, 113-132.
- Wang, Z., Zheng, J., Tang, J., Wang, X., Wu, Z., A pilot-scale forward osmosis membrane system for concentrating low-strength municipal wastewater: performance and implications, *Sci. Reports*, 2016b, 6.
- Xiao T., Dou P., Wang J., Song J., Wang Y., Li X. M., He T. , Concentrating greywater using hollow fiber thin film composite forward osmosis membranes: Fouling and process optimization, *Chem. Eng. Sci.*, 2018, 190, 140-148.
- Xie, M., Luo, W., Guo, H., Nghiem, L.D., Tang, C.Y., Gray, S.R., Trace organic contaminant rejection by aquaporin forward osmosis membrane: Transport mechanisms and membrane stability. *Water Res.*, 2018, 132, 90-98.
- Xu J., Tran T.N., Lin H., Dai N., Removal of disinfection by products in forward osmosis for wastewater recycling, *J. Membr. Sci.*, 2018, 564, 352-360.
- Xue W., Yamamoto K., Tobino T. Membrane fouling and long-term performance of seawater-driven forward osmosis for enrichment of nutrients in treated municipal wastewater, *J. Membr. Sci.*, 2016, 499, 555-562.
- Xue W., Tobino T., Nakajima F., Yamamoto K., Seawater-driven forward osmosis for enriching nitrogen and phosphorous in treated municipal wastewater: Effect of membrane properties and feed solution chemistry, *Water Res.*, 69, 2015, 120-130.
- Yara Fertilizer Industry Handbook, 2018. Electronic source: <https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2018/fertilizer-industry-handbook-2018-with-notes.pdf/> (accessed on 23rd March 2019).
- Zhang M., Liu R., Wang Z., Zhao B., Song J., Park M.J., Shon H.K., Li X. M., He T., Dehydration of forward osmosis membranes in treating high salinity wastewaters: Performance and implications, *J. Membr. Sci.*, 2016, 498, 365-373.
- Zhang X., Nin, Z., Wang D.K., Costa J.C.D., Processing municipal wastewaters by using forward osmosis using CTA membrane, *J. Membr. Sci.*, 2014, 468, 269-275.

475 Zou S., Gu Y., Xiao D., Tang C.Y., The role of physical and chemical parameters on forward
476 osmosis membrane fouling during algae separation, J. Membr. Sci. 2011, 366, 356-362.
477
478