ABSTRACT

In the past few decades, rapid industrial and urban development with exponential growth in human population has significantly impacted freshwater reserves, leading to an acute scarcity of usable freshwater. Membrane-based desalination of seawater and industrial saline wastewater has emerged as a promising solution to fulfil freshwater needs. However, conventional membrane technologies, such as reverse osmosis (RO)/nanofiltration (NF) suffer critical performance limitations, including high energy consumption (3 to 6 kWh/m^3), water recovery (30-40%) and fouling, which undermine their suitability for viable and large-scale desalination. Therefore, this study proposes osmotically enhanced hybrid systems like Forward Osmosis-Nanofiltration (FO-NF) and Pressure Assisted Forward Osmosis-Nanofiltration (PAFO-NF) as a potential alternative for treating salinity in wastewater effluents. Subsequently, several critical aspects of the module-scale hybrid process are evaluated using experimental and transport modeling studies and investigate the impact of continuous draw solute regeneration in these hybrid systems over standalone NF performance. Furthermore, a unique data-driven modelling for the FO-NF hybrid system is developed to predict the permeate fluxes and concentrations for different draw solutes.

Initially, in transport modelling, Speigler-Kedem model, along with the concentration polarization model, is used to describe the local mass transport in the FO and NF membranes. Following this, the combined mathematical models for FO and NF are integrated into the hybrid FO-NF system. Furthermore, FO-NF process optimization reveals that NF hydraulic pressure and inlet draw concentration control the NF retentate concentration and then simulate the desired operating conditions for the hybrid system when the NF retentate stream is directly used as a draw solution for the FO unit. Further experimental observations shows that standalone NF water recovery degrades with time from 40 to 15.6% due to fouling, while increasing the SEC from 0.89 to 2.38kWh/m^3. At the same time, the FO-NF hybrid system shows consistent water recovery 32.6% and 28.6%, with process SECs 3.26 kWh/m^3 for Na_2SO_4 and 4.70 kWh/m^3 for $MgSO_4$ as draw solutes, respectively.

It is also observed that compared to the standalone NF system, the FO-NF exhibits relatively lower water recovery but higher SEC. Consequently, this observation motivates to investigate the potential of PAFO-NF systems through experimental and modeling approaches for enhancing the water recovery by simultaneously reducing SEC. The same FO-NF transport

model with minor modification in FO modeling for the PAFO process is utilized for the PAFO-NF modeling. Membrane performance is then simulated for fouling prone feed stream containing 3.5 g/L of $CaCl_2$ using Na_2SO_4 and $MgSO_4$ as the draw solutes at a concentration of 40 g/L each. Simulated results under optimized operating conditions show that, FO feed side assisted pressure (ΔP_{PAFO}), FO membrane area (A_{mFO}) and the FO water permeability (A_{FO}) are the key factors for reducing the PAFO-NF process SEC and improving the water recovery, while using Na_2SO_4 as draw solute. Simulations reveal that at 1.0 m^2 A_{mFO}, increasing ΔP_{PAFO} (from 0 to 7.5 bar) may reduce the SEC from 2.95 to 1.47 kWh/m^3 while simultaneously increasing water recovery from 60.5 to 95.54%. In fact, merely increasing the A_{mFO} from 0.25 to 1.0 m^2 may reduce the process SEC compared to the FO-NF process by up to 63% and increase water recovery to as much as 90 %. Similarly, increasing A_{FO} (1.22×10^{-12} to 3.0×10^{-12} m/Pa.s) may also reduce the process SEC by nearly 42 % while also increasing the water recovery by 45.73%. Alternatively, inlet feed and draw concentrations and inlet feed flowrates have negligible impact on the process SEC. In conclusion, PAFO-NF hybrid process demonstrates significant potential for treating both fouling-prone and non-fouling saline waters and surpasses the FO-NF and standalone NF (under non-fouled conditions) processes by achieving lower SEC under the same operating conditions.

The above transport modeling for the FO-NF hybrid process is complex and each draw solute needs validation to predict permeate fluxes and concentrations, which is time consuming and rigorous process. However, nowadays, enormous experimental datasets are available for FO and NF membrane processes. Therefore, artificial neural network (ANN) based data-driven model is developed and compared to the FO-NF transport modeling. to predict the permeate flux and concentration. The optimized ANN-based model showed high R^2 values: 95.03% and 96.08% for FO and NF datasets, respectively. However, model accuracy is compromised because of limited variation in training datasets, resulting in higher errors (5-12%) when compared to the transport-based model errors (2%). Despite larger errors, ANN model is competent in predicting the suitable draw solute and responses for the feed side solute.