Optimizing energy efficiency in brackish water reverse osmosis (BWRO)

A comprehensive study on prioritizing critical operating parameters for specific energy consumption minimization

Abkar, Leili; Aghili Mehrizi, Amirreza; Jafari, Morez; Beck, Sara E.; Ghassemi, Abbas; Van Loosdrecht, Mark C.M.

DOI
10.1016/j.scitotenv.2024.172772

Publication date
2024

Document Version
Final published version

Published in
Science of the Total Environment

Science of the Total Environment 932 (2024) 172772

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Optimizing energy efficiency in brackish water reverse osmosis (BWRO): A comprehensive study on prioritizing critical operating parameters for specific energy consumption minimization

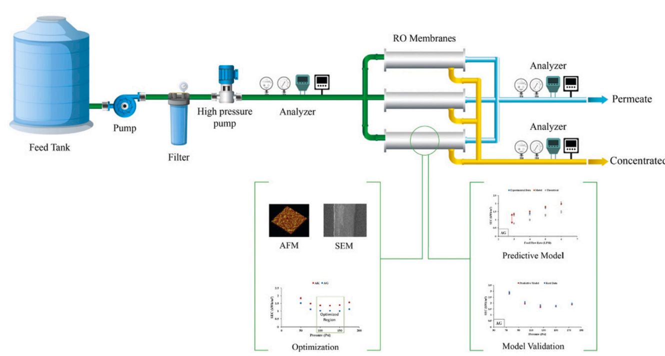
Leili Abkar [a,*], Amirreza Aghili Mehrizi [e], Morez Jafari [b], Sara E. Beck [a], Abbas Ghassemi [c], Mark C.M. Van Loosdrecht [d]

[a] Department of Civil Engineering, University of British Columbia, Vancouver, Canada
[b] OASEN Drink Water, Gouda, Netherlands
[c] Department of Civil and Environmental Engineering, University of California Merced, Merced, United States of America
[d] Department of Environmental Biotechnology, Delft University of Technology, Delft, Netherlands
[e] Department of Chemical and Materials Engineering, Concordia University, Montreal, Canada

HIGHLIGHTS

- The mechanistic interaction of input and output variables was studied in a BWRO.
- Order of importance of significant parameters in reducing SEC:P, Q_f, C_f, $Q_f \times P$, $C_f \times P$, T.
- SEC models were developed, and validated with empirical data ($R^2 = 0.93$, 0.95).
- Adjusting the operating variables could minimize the SEC by up to 36 %.
- Recovery increased >4 times when operated in the optimum operating region.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Paola Verlicchi

Keywords:
Sustainability
Modeling
Validation
Operational factor
Drinking water
Cost minimization
SDG6
Membrane desalination

ABSTRACT

Reverse osmosis (RO) systems offer a viable solution for treating brackish water (BW), a common but underutilized water resource. However, the energy-intensive nature of brackish water reverse osmosis (BWRO) systems poses affordability challenges to water supply, necessitating a focus on minimizing their energy consumption to support SDG6's goal of providing safe and affordable drinking water for all. This study addresses the critical need to minimize the specific energy consumption (SEC) of a typical BWRO system, defined as the energy consumed per unit of water recovered, mathematically and experimentally. Empirical models were developed proving there is a global minimum SEC while adjusting the operating conditions. Furthermore, we identified the key operating factors influencing SEC and their priority levels, along with their interactive effects. Notably, no prior study has discussed the significance and interaction of these operating factors (e.g., feed water salinity, temperature, pressure, flowrate and membrane permeability) on SEC of a BWRO system. Employing a full factorial

* Corresponding author.
E-mail addresses: l.abkar@ubc.ca (L. Abkar), morez.jafari@oasen.nl (M. Jafari), sara.beck@ubc.ca (S.E. Beck), aghassemi2@ucmerced.edu (A. Ghassemi), M.C.M.vanLoosdrecht@tudelft.nl (M.C.M. Van Loosdrecht).

https://doi.org/10.1016/j.scitotenv.2024.172772
Received 1 December 2023; Received in revised form 11 April 2024; Accepted 23 April 2024
Available online 28 April 2024

experimental design with mixed levels of operating parameters, the study developed regression models that elucidate the mechanistic interaction between these parameters and system performance. Moreover, the models were validated experimentally, with a new dataset demonstrating their accuracy and reliability. ANOVA statistical analysis identified feed salinity, pressure, flow rate, feed flow rate×pressure, salinity×pressure, and temperature as influential operating parameters in reducing SEC, in descending order of importance. Operating within the determined optimum range resulted in a 36 % decrease in SEC and a more than fourfold increase in water recovery. The study's systematic approach and findings can be extrapolated to optimize the performance of other desalination technologies and diverse feed water types, contributing significantly to global water sustainability efforts.

1. Introduction

Water resources face significant challenges due to climate change, global warming, urbanization, population growth, and pollution, impacting their quality and quantity, which, in turn, affects ecosystems, ecology, and public health (WWDR4, 2012). This situation is anticipated to worsen, with the World Health Organization (WHO) estimating that 48 countries (half of the global population) will face water stress by 2025, increasing to 54 countries by 2050 (Boretti and Rosa, 2019). As freshwater resources dwindle, there is a growing global need for cost-effective and reliable water treatment technologies.

Aligned with this concern, the United Nations (UN) introduced 17 Sustainable Development Goals (SDGs) in 2015, with SDG 6 specifically targeting equitable access to clean water and sanitation for all by increasing water efficiency and desalination in SDG 6a. (United Nations, 2020). This goal is particularly challenging in inland regions with limited access to large freshwater bodies. Inland water resources, often brackish, with a salinity of <10,000 mg/L, can be effectively treated using membrane desalination technologies such as nanofiltration (NF), reverse osmosis (RO), electrodialysis, and electrodialysis reversal (ED/R) (Rosentreter et al., 2021; Karimi et al., 2015).

Presently, over 80 % of desalinated brackish water relies on brackish water reverse osmosis (BWRO) (Xu et al., 2022; Jones et al., 2019). However, the energy-intensive nature of desalination technologies, especially BWRO, poses challenges, primarily in the form of electrical energy required by the high-pressure pump driving water through the RO membrane (Eke et al., 2020; Al-Obaidi et al., 2023). The proliferation of desalination plants, increasing by 6–12 % annually since 1982, raises concerns about the associated elevated water costs, carbon footprint, and contributions to climate change and global warming (Eyl-Mazzega and Cassignol, 2022). The number of desalination plants rose from 18,000 in 2017 to 21,000 in 2022, generating 110 million m^3/day of water (Eke et al., 2020). This upward trend necessitates investigating various approaches for their energy and performance optimization. As high energy consumption leads to elevated water costs, and carbon footprint, directly contributing to climate change and global warming, exacerbating the very reason desalination is being used in the first place.

To address this, various approaches, including energy recovery devices (ERDs), renewable energy integration (Karimi et al., 2015; Fairuz et al., 2023), and different design structures (Almansoori and Saif, 2014), have been explored to optimize specific energy consumption (SEC) (Rosentreter et al., 2021; Pan et al., 2020). Moreover, salinity gradient energy (SGE) recovery processes such as pressure retarded osmosis (PRO), reverse electrodialysis (RED), and single-pore osmotic generators (OPGs) have been suggested to extract energy from the retentate of the reverse osmosis. These technologies operate based on the salt concentration differences between two fluids (Rani et al., 2022).

Operational factors (e.g., water temperature, pressure, feed quality and recovery), inadequate chemical cleaning and pre-treatment processes lead to scaling and fouling (Ruiz-García and Ruiz-Saavedra, 2015). The formation of additional layers of scaling and fouling on the membrane surface will cause excess resistance to the water diffusion, decreasing the permeate flowrate and consequently recovery. Moreover, it increases the required transmembrane pressure leading to increased energy consumption (Sweity et al., 2015; Arras et al., 2009).

The following literature showcases successful investigations into modeling, simulating, and optimizing water desalination plants, specifically targeting the reduction of specific energy consumption, predominantly using Reverse Osmosis (RO) technology.

Zhu et al. (2009) utilized a mathematical approach, employing fundamental equations governing reverse osmosis and thermodynamic restrictions to demonstrate the existence of a region for minimum SEC when water recovery is adjusted in a multiple-pass RO system (Zhu et al., 2009a; Zhu et al., 2009b).

Ruiz-García and Ruiz-Saavedra (2015) evaluated the performance of a BWRO plant with a design capacity of 360 m^3/day including the SEC, permeate water quality and quantity over ten years of operation located in the Canary Islands, Spain. They compared the SEC changes with the ideal SEC (when the high-pressure pump efficiency is 100 %) and the theoretical minimum SEC (calculated based on the thermodynamic restriction). They reported that due to regular chemical cleaning and adequate pre-treatment the ideal SEC was approximately 50 % higher than the real SEC over 10 years. Cost analysis showed that membrane replacement could happen after 10 years of operation, balancing out the chemical cleaning and electricity cost (Ruiz-García and Ruiz-Saavedra, 2015).

Notably, Karimi et al. (2015) studied the significant factors on a pilot scale BWRO of SEC considering three main operating factors: salinity, temperature and product flow rate. However, their study lacks a comprehensive consideration of all factors and their interactions, particularly in determining their importance level on SEC (Karimi et al., 2015).

Atab et al. (2016) utilized a solution-diffusion mathematical-based model to analyze the impact of feed water temperature, pressure, salinity and recovery on SEC. They further used an energy recovery device (hydraulic turbine) and applied that to a real-case scenario. They found that the feed water temperature improved the SEC and using ERD reduced it from 2.8 to 0.8 kWh/m^3 (Sarai Atab et al., 2016).

Karabelas et al. (2018) studied the impact of membrane permeability, friction losses through the membrane module and channels, and efficiency of the pump and ERD on the specific energy consumption of a BWRO and SWRO, treating water with salinity levels of 2000 mg/L and 40,000 mg/L. Their results showed that membrane resistance (i.e., membrane permeability) and pump and ERD deficiencies composed the big portion of SEC while losses through the membrane module, spacers and permeate channels are less significant (Karabelas et al., 2018).

Ezzeghni (2018) reported that by selecting the proper membranes (employing ROSA software) followed by energy recovery devices, a reduction in the specific energy consumption of the Alwaha BWRO plant from 0.87 to 0.64 kWh/m^3 was achieved, resulting in an energy-saving of 30 %. The Alwaha plant is located in Libyan deserts with a capacity of 1000 m^3/day with the main purpose of providing drinking water with a salinity of <150 mg/L for a nearby oil field (Ezzeghni and Nuclear, 2018).

Alsarayreh et al. (2019) studied the impact of adding an ERD to a medium-scale brackish water plant and reported a potential decrease in energy consumption by 47 %–53.8 % (Alsarayreh et al., 2020). Later, they examined the effect of water permeability using a commercial membrane with data reported in the literature to be impactful on SEC minimization by 10 % (Alsarayreh et al., 2021).

Despite these valuable contributions, research on BWRO systems has often been case-specific, with a focus on additional devices or system design modifications. This study breaks new ground by applying a full factorial experimental analysis with mixed levels, aiming to empirically model and simulate the global minimum SEC of BWRO without additional capital costs or add-on technologies like ERDs. The single-stage, single-pass design eliminates confounding factors, providing a foundation to determine optimum SEC and water recovery. Overall, this research aimed to 1) determine the optimum (i.e., minimum) region for SEC and water recovery for different feed water salinities, 2) find the significant parameters and the interaction between them, 3) investigate their importance level, 4) develop and validate a predictive mathematical model using multiple regression to predict and optimize the SEC. The findings not only offer insights into BWRO desalination but also lay a framework for broader applications across different desalination technologies and feed water types, contributing significantly to global water sustainability efforts.

2. Specific energy consumption (SEC) modeling

To illustrate the mathematical modeling of SEC, a simplified RO system, single-stage and single pass, is considered (Eq. (1)). SEC is a performance indicator and comparison criterion for various RO systems (Rosentreter et al., 2021; Pan et al., 2020).

$$SEC = \frac{\eta W_{pump}}{Q_p} \tag{1}$$

where Q_p is the permeate flow rate, W_{pump} is the work done by the high-pressure pump, and η is the pump efficiency (Pan et al., 2020). W_{pump} is calculated by multiplying the differential pressure before and after the pump and feed flow rate. The pump efficiency is considered 100 % for simplicity, and the energy loss through pump heating and frictions before and after the pumps are neglected. Hence, SEC can be reformulated as follows (Bartman et al., 2010).

$$SEC = \frac{\Delta P\, Q_f}{Q_p} = \frac{\Delta P}{R} \tag{2}$$

where Q_f is the feed flow rate, Q_p is the permeate flow rate, ΔP is the differential pressure between the pressure at the membrane module entrance (P_f), and pressure of feed water (P_0). R is the recovery rate defined as the amount of water produced per unit of feed water (Q_p/Q_f). Maximizing water production through the membrane, which is a function of membrane permeability, is desirable, specifically when the water source is limited.

The solution-diffusion (SD) theory, which combines Fick's and Henry's laws, models water diffusion, membrane permeability, and flux in an RO membrane (Alsarayreh et al., 2020; Baker, 2012; Al-Obaidi et al., 2018). The SD model hypothesizes that the solutes (i.e., water) dissolve in the membrane material and then diffuse. Therefore, water flow through the membrane can be calculated from changes in osmotic pressure ($\Delta\pi$), transmembrane pressure (ΔP), active membrane area (A), and L_p which is the water permeability through the membrane (Baker, 2012; Williams, 2003). This equation represents the relationship between water flux and operating parameters, pressure and feed water salinity (Baker, 2012). Osmotic pressure is a function of feed water salinity (i.e., concentration) as represented in equation (Rosentreter et al., 2021; Al-Obaidi et al., 2023).

$$Q_p = A \times L_p(\Delta P - \Delta \pi) \tag{3}$$

$$\pi = 0.7994\, C[1 + 0.003\, (T - 25)] \tag{4}$$

where C represents the concentration (e.g., feed, permeate, and retentate) and T is temperature.

3. Material and methods

3.1. Pilot-scale BWRO setup

The process flow diagram of the pilot-scale BWRO, which was designed and built for this study, is shown in Fig. 1. This system with four pressure vessels was designed to be a single-stage and a single-pass, representing a simple design so that we can investigate the mechanistic interaction between input and output variables without the confounding factor of optimum design. Two of the four pressure vessels were used in the present study, with each one including one membrane. The initial centrifugal pump drew the saline water from the feed tank, providing 15 to 20 psi and then passed through the media filter, removing coarse particles. Water pressure was automatically monitored to protect the high-pressure pump. It was then directed to the high-pressure pump, which had a pressure level that could be adjusted manually. Pressurized water was passed through the RO membranes and divided into concentrated and permeated streams. Both streams were returned to the feed water tank and reused to keep the system running continuously. In-line sensors were used on each stream to monitor the operating parameters, such as temperature, pressure, flow rate, and salinity. The operational parameters were monitored during each set of experiments using in-line sensors. Signals measured by sensors for the salinity, pressure, temperature and flow rate were transmitted to a Programmable Logic Controller (PLC) (Productiviy1000, Automation Direct, USA) using Productivity Suit Programming Software, Version 1.9.2. The experiments were conducted in three separate runs, each of which was conducted in triplicate. The represented results are the average of all the replicated runs.

3.2. Operational variables

Five operating parameters were considered to evaluate their impact on the recovery and SEC) of a BWRO system. Table 1 summarizes the operating variables, their levels and values applied in this study. Details of each variable are explained in the following sections. It is noteworthy that while there are two pumps involved in the experimental setup, the energy consumption for the raw water pump was not counted in the results, and the focus was just on the high-pressure pump, which directly derived the water through the RO membranes.

3.2.1. Membranes

Two brand-new spiral wound RO membranes, AK2540TM and AG2540TM, manufactured by General Electric (GE), were used. The AK2540TM (AK) and AG2540TM (AG) membranes were selected among low-energy and high-flux BWRO elements that offer high rejection and low operating pressures. Two membranes were used to understand the membrane characteristics, mainly the impact of membrane permeability on the performance, SEC and recovery. These membranes are part of GE's A-Series, which features thin-film RO membrane elements with high flux (2.7 m^3/day) and high sodium chloride rejection (>99 % average NaCl rejection). The detailed membrane characteristics reported by the manufacturer are tabulated in Table S1.

3.2.2. Membrane characterization

Scanning Electron Microscopy (SEM) (Model TM-1000 - Hitachi High-Technologies, Japan) and Atomic Force Microscopy (AFM) (Dimension Icon- Bruker, US) were utilized to detect the morphology, roughness, and thickness of both membranes. Membrane samples were cut into 1 cm^2 pieces and then placed on the platform.

Roughness data were analyzed using the AFM embed software NanoScope 2. Roughness was calculated based on the average least squares (Rqs) of three different parts of the membranes. Thickness data were analyzed using the ImageJ online version (https://ij.imjoy.io/) as

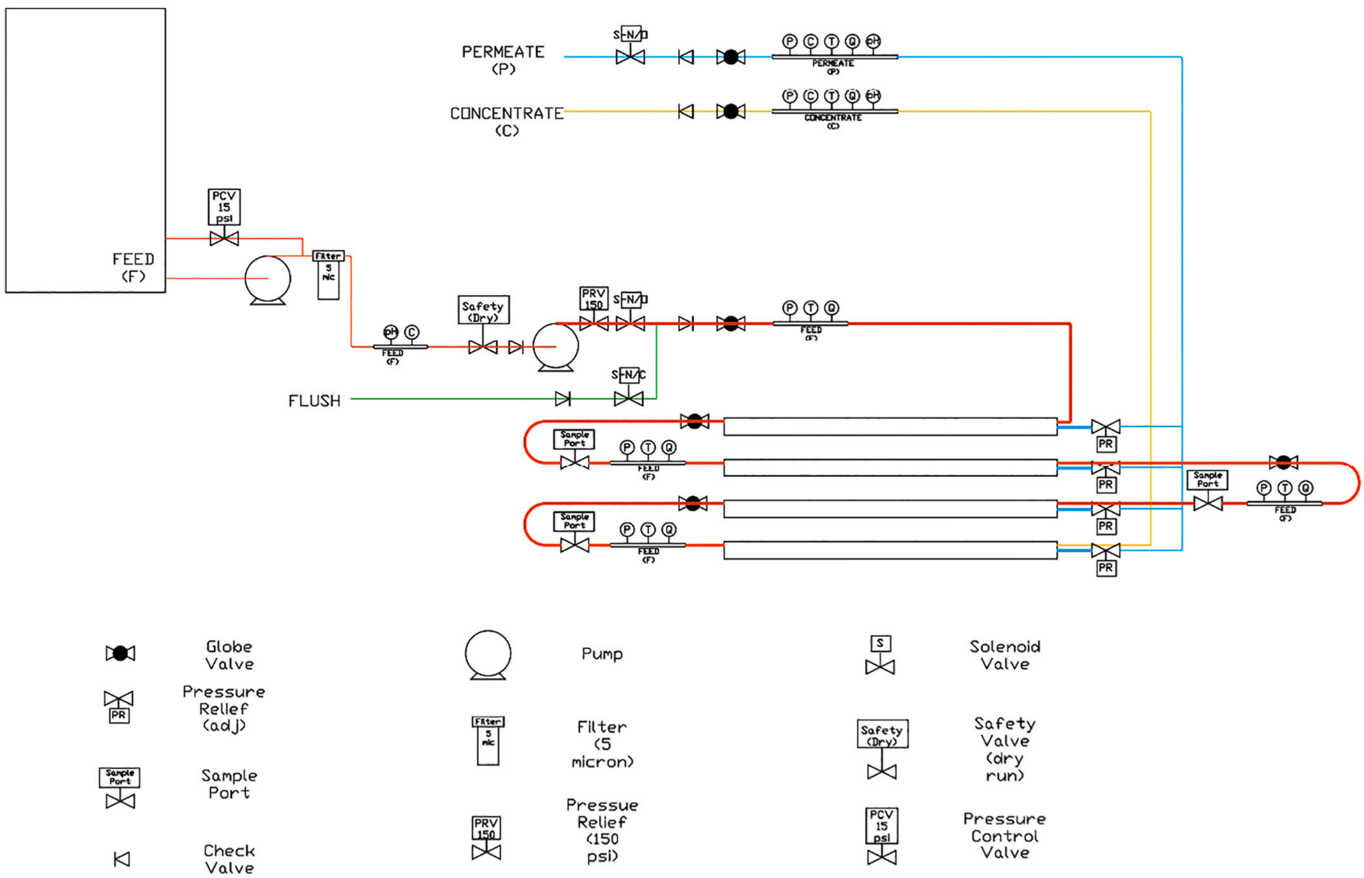


Fig. 1. Process flow diagram (PFD) of the pilot-scale BWRO system.

Table 1
Operating variables, levels, and their experimental values.

Variable	Levels	Values					
Pressure (psi)	6	50	75	100	125	150	175
Feed Flow Rate (L/min)	4	3	4	5	6		
Salinity (mg/L)	3	2000	2500	3000			
Temperature (°C)	2	30	40				
Membrane Type	2	BWRO-AG2540	BWRO-AK2540				

the average of six points in three different membrane sections. Membrane permeability was measured and reported as one of the membrane characteristics.

3.2.3. Salinity

The feedwater salinity was adjusted by adding the desired amounts of NaCl (>99 % purity, Sigma Aldrich, Germany). The high purity was chosen to ensure that other unwanted particles would not interfere with the experiments. Three different salinity levels, 2000, 2500, and 3000 mg/L, were used to simulate brackish groundwater sources. As the system design uses one membrane element per pressure vessel, a higher salinity level would be beyond the standard operating conditions suggested by the manufacturer for the AG and AK membranes. The salinity was measured by a conductivity meter, which detects the electroconductivity of a solution based on the ion charge, where higher conductivities indicate higher salinities. Conductivity was measured either manually (SensIon5, HACH, USA) or by an in-line sensor (400–13 ENDURANCE, Rosemount Analytical Inc., USA) in units of micro-Siemens per centimeter (μS/cm) with a cell constant of 1.0100.

3.2.4. Temperature

The feedwater temperature was adjusted using two different heat exchangers, one for heating and one for cooling. An in-line sensor (OMEGA, part number TC-T-NPT-U-72) was used to monitor and measure the feed water, concentrated and permeate stream temperature. The temperature sensor signal was translated with an OMEGA model TXDIN70 and transmitted to the PLC.

3.2.5. Pressure

The operational design of the system allowed us to run the experiments at pressure levels between 50 and 175 psi, with 25 psi increments. This range was selected based on the typical pressures suggested by the manufacturer for the AK and AG membrane series, 100 and 200 psi, respectively. This research investigated different pressure levels in increments of 25 psi to gauge the effect of even minor changes in pressure. To measure pressure, three pressure gauges (Ashcroft Model 1332, 0–300 psi) were installed on every stream. Three in-line piezoelectric pressure sensors (Automation Direct Prosense, model number PTD25–20-0500H) were also used.

3.2.6. Feed flow rate

Four feed flow rates, 3, 4, 5 and 6 L/min, were applied. The flow rates were measured using in-line sensors (McMillan Co., model number Flow-SEN SOR-107-9 N) and a rotameter (Blue-White, model number F-440 Polysulfone) in two different ranges of the feed water stream (0–18.9 LPM) and on the concentrated and permeate streams (0–7.5 LPM). The flowmeters were calibrated by manual measurements for every set of data collection.

3.3. Experimental design and statistical analysis

A full-factorial design with mixed levels was used to find the relationship between the input variables (salinity, pressure, temperature, and feed flow rate) and the response variables (SEC) and recovery. The full-factorial design was designed in Minitab v.18. The experimental results were analyzed statistically using analysis of variance (ANOVA) in SAS 9.4; results and codes are available in Sections 1 and 2 of the Supplemental Information. The significance of each parameter, the effect of priority (importance level) of each input variable and their interaction on SEC were studied. Tukey's method was utilized to identify sample means that considerably differ. Like-lettered groups in Figs. 2–5 indicate no significant differences. All experiments were performed in triplicate, showing an average standard deviation of 4.8 %.

3.4. Regression predictive models

Multiple regression models were developed for SEC as a response variable using the experimental data. The regression models were developed for each one of the membranes separately for simplicity. The operating parameters and the interaction between them were considered as input variables. A comprehensive blend of variables was analyzed between the various models, and ultimately, models with the highest R2, lowest Variance Inflation Factor (VIF) and standardized residuals between −3 and 3 were selected and reported. This part of the analysis was performed in the Statistical Analysis Software (SAS) 9.4, and the codes are provided in Supplemental Information Section 3–1.

3.5. Model validation

The multiple regression model was then validated using a different set of data to evaluate the model's predictability and reliability. Therefore, a new set of experiments was conducted with feed water salinity at 4000 mg/L, and the results were compared with the model prediction.

4. Result and discussion

4.1. Operating variables impact

4.1.1. Impact of salinity

The effect of salinity on specific energy consumption (SEC) and recovery was investigated for 2000, 2500, and 3000 mg/L at a fixed flow rate, temperature, and pressure of 3 L/min, 30 °C, and 50 psi for the AG and AK membranes (Fig. 2). It was observed that, for both membranes, the SEC increased with increasing feed salinity while the flux recovery decreased. However, the AG membrane showed a relatively linear trend for recovery and SEC, while the AK membrane reached a plateau. The AG membrane had 60 % less SEC at a feed salinity of 2000 mg/L and up to 55 % more water recovery than 3000 mg/L. This trend was observed for the AK membrane, with 45 % more water recovery for 2000 mg/L compared to 3000 mg/L and 40 % less SEC. The results proved that the membrane characteristics and permeability could respond differently when treating various water salinity, emphasizing the importance of selecting the proper membrane to obtain the desired outcomes discussed in section 4.1.5.

Raising the salinity at the same pressure means less driving force to push the water through the membrane. Hence, the recovery declines. Simultaneously, increasing the feed salinity requires greater energy consumption to remove the salt (Pan et al., 2020; Ruiz-García et al., 2020; Qureshi and Zubair, 2015). Feed concentration and salinity correlate with the osmotic pressure; the more saline the solution, the more osmotic pressure it has (Karimi et al., 2015; Bartman et al., 2010). Consequently, both membranes can achieve a minimum SEC and a maximum recovery with the lowest salinity. This aligns with the findings of other researchers (Bartman et al., 2010; Al-Obaidi et al., 2018; Zhu et al., 2009c). Al-Obaidi et al. (2018) also reported that the concentration polarization of the membrane's surface and osmotic pressure would rise as the feed salinity increased, restricting the permeate flow rate across the membrane (Al-Obaidi et al., 2018). Therefore, higher hydraulic pressure and energy are needed to overcome higher osmotic pressures (see Eqs. (1) and (2)). Thus, keeping the hydraulic pressure at the same level while increasing the salinity decreases the permeate flux and, consequently, the recovery (Bartman et al., 2010; Zhu et al., 2009c). This result is reasonable as raising the feed salinity increases the bulk concentration and the osmotic pressure, which will decrease the flux.

4.1.2. Impact of feed flow rate

The feed flow rate impact on SEC and recovery is represented in Fig. 3 at salinity, temperature, and pressure of 2000 mg/L, 30 °C, and 50 psi, respectively. A similar trend was observed for both membranes; by increasing the feed flow rate, the recovery decreased, and the SEC increased. The feed flow rate increase has no significant effect on rejection (Table S2). However, the feed flow rate directly impacts energy consumption, which agrees with the literature (Alsarayreh et al., 2021).

Increasing the feed flow rate by 33 %, from 3 to 4 L/min, with a feed water concentration of 2000 mg/L, 50 psi pressure, and 30 °C temperature, did not noticeably impact the recovery (which decreased by 3 %) and SEC (average 3 %) for both membranes. However, the SEC rose >45 % when the feed flow rate increased from 4 to 5 L/min. Alsarayeh et al. (2020) reported a 14.7 % decrease in recovery and an 8 % increase in SEC, with a 20 % increase in feed flow from 74 to 88.8 m^3/h in a medium-scale BWRO desalination plant at a fixed feed water concentration, pressure, and temperature at 1098.62 mg/L, 135.5 psi, and 25 °C (Alsarayreh et al., 2020). They reported that a higher feed velocity

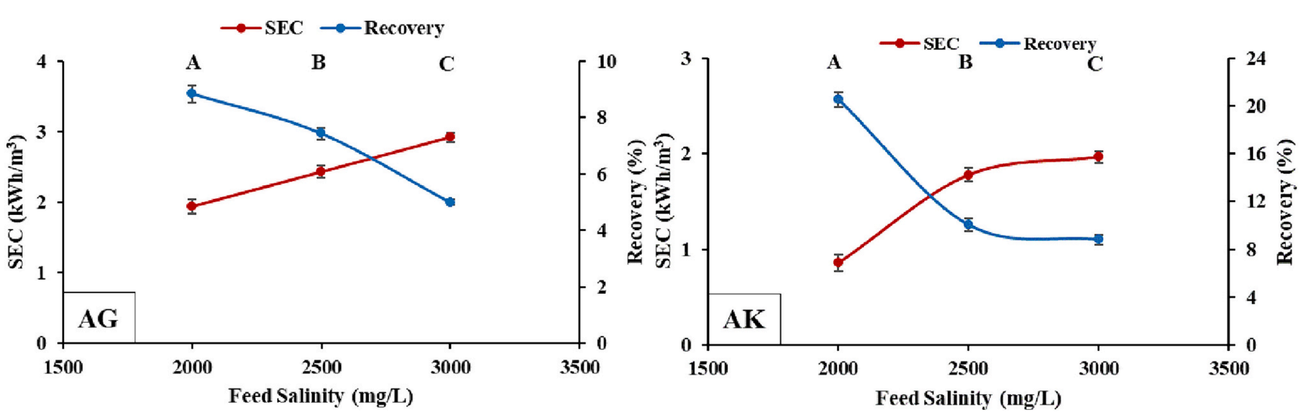


Fig. 2. Effect of salinity on SEC and recovery at 3 L/min, 30 °C, and 50 psi, for AG and AK membranes. Different letters, A, B and C which represent different salinity levels show significant difference regarding SEC. In other words, significantly impacts the SEC.

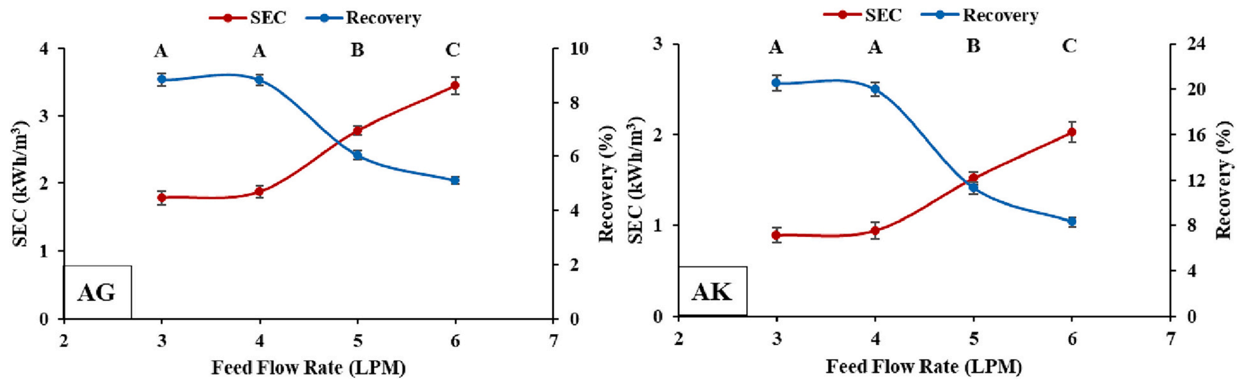


Fig. 3. Effect of feed flow rate on SEC and recovery for AG and AK membranes at 2000 mg/L, 30 °C, and 50 psi. Different letters show significant difference regarding SEC. In other words, feed flow rate significantly impacts SEC.

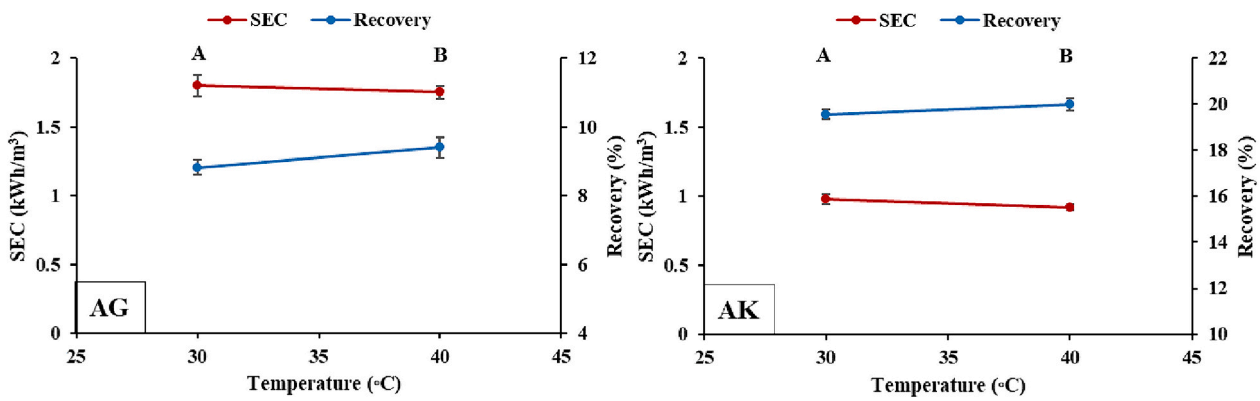


Fig. 4. Effect of temperature on SEC and Recovery for AG membrane and AK membrane at 2000 mg/L, 4 L/min, and 50 psi. Different groups of letters show significant differences regarding SEC.

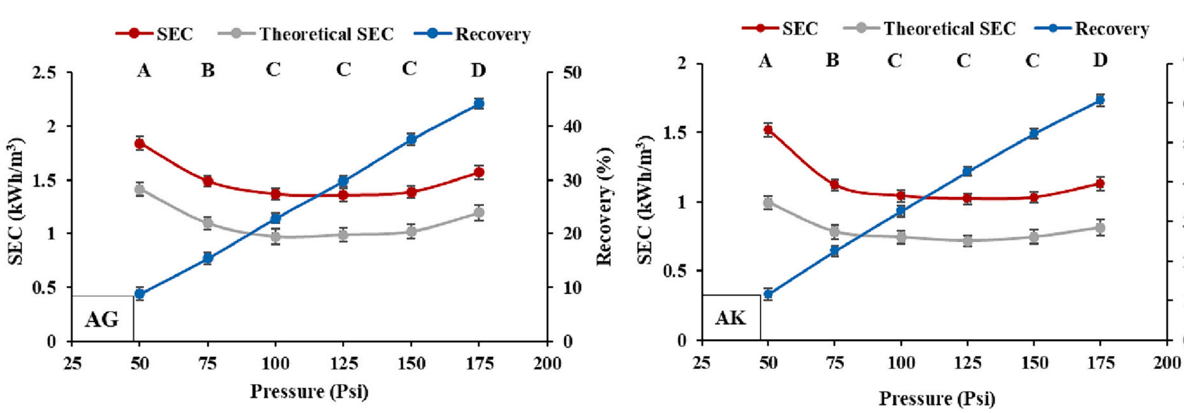


Fig. 5. Effect of pressure on SEC and recovery for AG and AK membranes at 2000 mg/L, 4 L/min, and 30 °C. Different letters show significant differences regarding SEC. In other words, pressure significantly impacts recovery.

resulted in a lower residence time in the RO vessels and lower water flux passing over the membrane. Despite the anticipated benefit of reduced concentration polarization, increasing the bulk velocity also leads to a rise in pressure losses throughout the feed channel, which passively influences the effective driving pressure (Alsarayreh et al., 2020; Kotb et al., 2015). Moreover, water production is a function of pressure, so at the same pressure level, if the feed flow rate increases, the recovery decreases based on the definition of water recovery in a reverse osmosis system (Alsarayreh et al., 2020).

Eq. (2) states that SEC theoretically rises with increasing feed flux while other operating variables remain constant due to a reduced gain of freshwater penetrating the membranes and a significant drop in water recovery and permeation. As a result, to achieve maximum water recovery and the lowest energy consumption, running the RO process at lower feed flow rates is recommended if it is economically feasible.

4.1.3. *Impact of temperature*

The temperature effect on recovery and SEC is shown in Fig. 4 for the AG and AK membranes at 4 L/min, 50 psi and salinity of 2000 mg/L, respectively. The data was presented at the feed flow rate of 4 L/min as there were no significant differences between recovery and SEC of 3 and 4 L/min. Increasing the temperature from 30 to 40 °C decreased the SEC from 1.8 to 1.75 kWh/m^3 for AG membranes and from 0.98 to 0.92 kWh/m^3 in AK membranes. The recovery rate improved as the temperature increased from 30 to 40 °C for both membranes. As demonstrated, the highest recovery rate was achieved at 40 °C, with a 5.6 % water recovery increase for the AG membrane and 3.2 % for the AK membrane. Changing the membrane pore size and distribution along with increasing membrane diffusivity due to raising the temperature can explain the increase in water recovery (Kotb et al., 2015; Zaidi et al., 2015).

Raising the temperature from 30 to 40 °C increased the recovery and permeate flow rate while decreasing the required feed pressure and SEC. However, the temperature increase had negative impacts, such as the deterioration of the membrane performance in terms of salt rejection (given the larger pore size) and the permeate water quality, which is one of the most critical design parameters of RO systems and should not be ignored. Karimi et al. (2015) varied the temperature from 15 to 35 °C in a pilot-scale BWRO membrane with feed water salinity of up to 3000 mg/L and observed the same decreasing trend of SEC when raising the temperature (Karimi et al., 2015). Koutsou et al. 2020 (Koutsou et al., 2020) investigated the impact of temperatures ranging from 15 to 40 °C on the SEC and found that temperature significantly impacts SEC in BWRO. They divided the temperature effect on SEC into various items, including membrane resistance against water permeation through the membrane, extra needed energy due to concentration polarization at the membrane surface, friction losses due to crossflow at the retaining channels, and permeation channelling (Karabelas et al., 2018; Koutsou et al., 2020). Therefore, the optimal temperature in this study to minimize SEC with high recovery was achieved at 30 °C. This trend is also has been observed by other researchers (Alsarayreh et al., 2020; Koutsou et al., 2020; Sassi and Mujtaba, 2012).

4.1.4. Impact of pressure

Fig. 5 shows the effect of operating pressure on SEC and water recovery at 2000 mg/L, 4 L/min, and 30 °C for AG and AK membranes. When the pressure increased from 50 to 175 psi, the recovery rate increased from 8.8 % to 45 % for the AG membrane and 19.9 % to >67 % for the AK membrane. The recovery rate linearly increased due to pressure increment, which aligns with the literature (Avlonitis et al., 2012; Ramon and Hoek, 2013; Wei et al., 2017). The detailed data is presented in Table S3.

As presented in Fig. 5, the pressure variation relation and impact on SEC seem non-linear. This could be because increasing the permeate flow at higher pressures consumes less specific pumping energy. This trend was observed in other studies (Bartman et al., 2010; Ruiz-García et al., 2020; Qureshi and Zubair, 2015). The lowest SEC of 1.36 kWh/m^3 with 29.8 % recovery for the AG membrane was obtained at 125 psi; for the AK membrane, 1.01 kWh/m^3 with 51.4 % recovery, was recorded at 150 psi. Similar letters from the ANOVA analysis showed no significant difference between the SEC at 100, 125, and 150 psi (letter C in Fig. 5) for both membranes. In comparison, the recovery at 150 psi appeared to be more than at 125 psi. This demonstrated that the optimum pressure is at 150 psi, with the highest water recovery of 37.51 % for the AG membrane and 51.4 % for the AK membrane.

4.1.5. Membrane permeability impact

As explained previously, two different BWRO membranes, AG and AK, were used to assess the membrane characteristics, mainly permeability, impact on SEC and recovery. As shown in Fig. 6 and confirmed by ANOVA analysis, there was a significant difference in SEC and recovery for the two membranes.

This can be related to the membrane characteristics, such as roughness, thickness, surface area, and permeability. The membranes' thickness and roughness were analyzed using imaging techniques, AFM (Fig. 7) and SEM (Fig. 8). Membrane permeability was calculated from Eq. (4) using the experimental data with the parameters reported in Table 2. While the thickness of the two membranes was similar, the roughness and permeability were different, explaining the difference in SEC and recovery. As the SEM images in Fig. 8 also show, the surface of the AG membrane is much denser than the AK membrane, which indicates that the AG membrane was less permeable than the AK, resulting in less recovery. With a higher permeability, the AK membrane had a higher recovery, hence lower SEC in various operating pressures. The literature has no general correlation and consensuses between roughness and RO membrane flux (Al-Jeshi and Neville, 2006). However, some studies suggested a correlation between higher roughness and enhanced flux by attributing the increased interfacial surface between the feedwater (Ramon and Hoek, 2013).

4.1.6. Significant parameters and their importance level

This study examined not only the operational parameters' effects but also their interaction with SEC as a critical performance indicator (Fig. 9) in a typical BWRO setup. Using the ANOVA analysis, the significant factors and their importance levels on the SEC were determined as pressure > feed flow rate > salinity > feed flow rate×pressure > salinity×pressure > temperature. The results showed that the feed flow rate and pressure combination are more important than the feed water temperature. This means for a BWRO system, decreasing feed flow simultaneously with pressure has a more significant impact on minimizing SEC than increasing temperature. This is the same for salinity and pressure. The details of ANOVA analysis, significant factors and their importance levels for the two membranes are tabulated in Tables S4 and S5. Like other studies, pressure was determined as the most important parameter on both recovery and energy consumption in BWRO systems (Pan et al., 2020; Al-Jeshi and Neville, 2006). To our surprise, the feed water temperature had the lowest effect on SEC among all other parameters. This could be due to the fact that only two levels of temperature were studied. Moreover, the differences between 30 and 40 °C on SEC are negligible compared to greater temperature variances, such as in lower temperature levels (e.g., <20 °C). Considering the challenges of increasing water temperature, this proves the efforts should be directed to adjust other parameters, such as feed water flow rate and pressure in a given situation, to achieve minimum SEC.

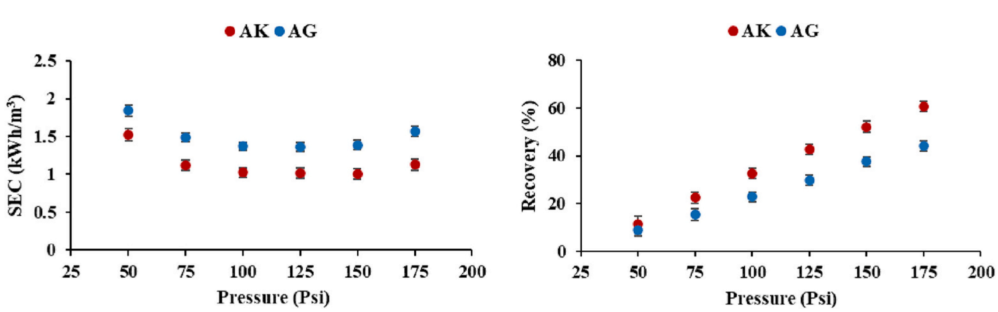


Fig. 6. As shown AK has a lower SEC and higher recovery compared to the AK membrane.

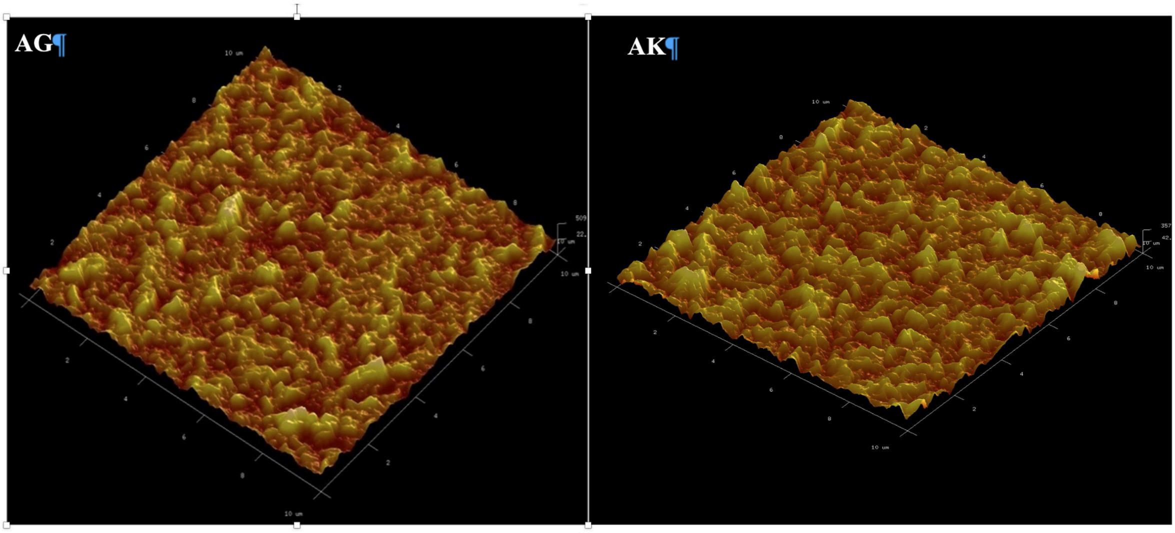


Fig. 7. AFM images of AG and AK membrane surfaces. As shown, the AK membrane surface has a significantly higher roughness, contributing to its higher permeability, further higher recovery and lower SEC.

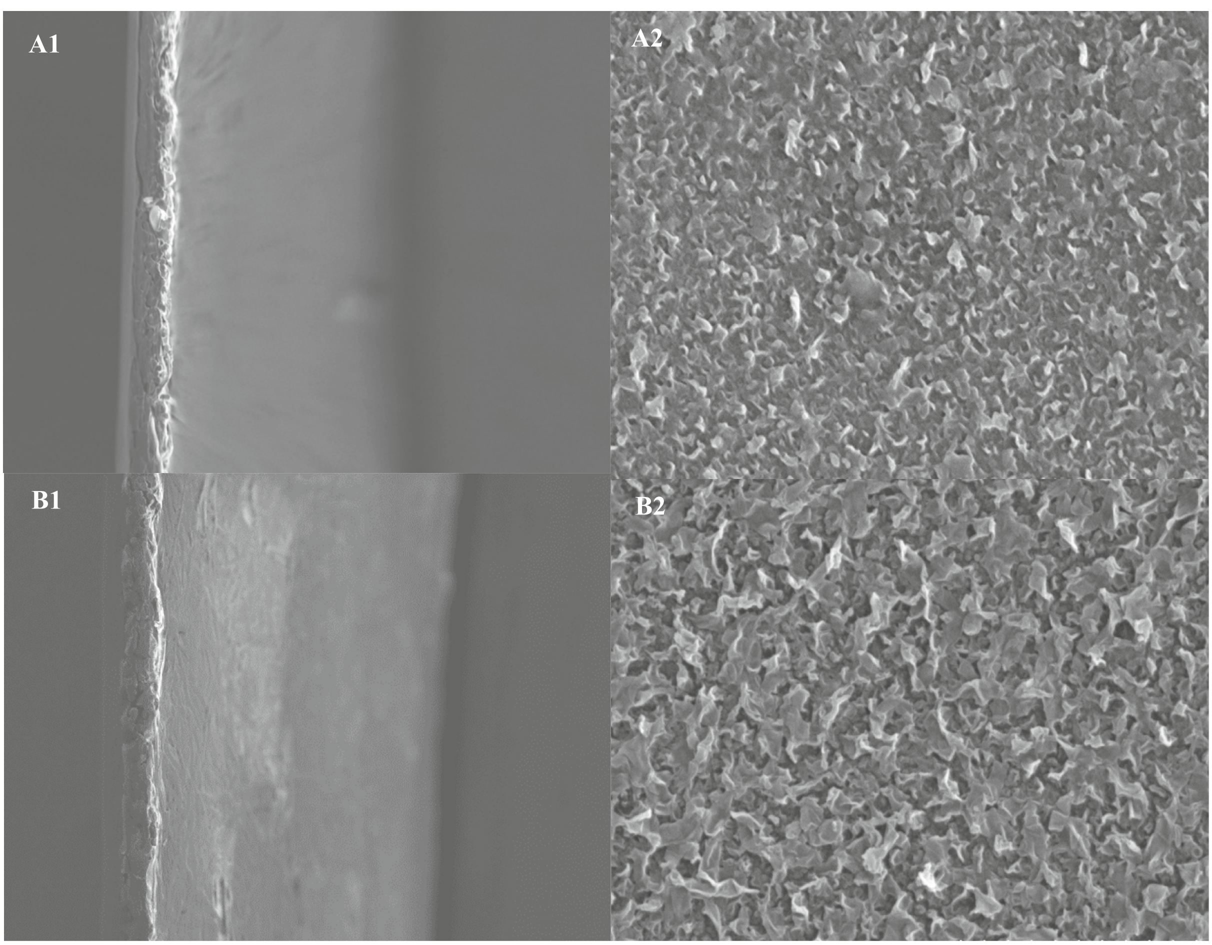


Fig. 8. SEM image of (A1) AG membrane cross-section, (A2) AG membrane surface at 500 × magnification, (B1) AK membrane cross-section, and (B2) AK membrane surface at 500 × magnification.

4.2. Optimized operating region for minimized SEC

The optimum operating range to achieve minimum SEC was determined for different feed water salinity levels. In real scenarios, water salinity is not adjustable and normally is pre-determined due to the site location. The other operating parameters when designing the desalination systems are flexible and can be manipulated to gain the best possible and desired outcome, which is in our minimum SEC. Collecting

Table 2
Characteristics of two BWRO membranes, AG and AK.

Parameter	AG	AK
Roughness (Rq nm) ± STDV	54.73 ± 1.3	88.88 ± 1.7
Thickness (nm) + STDV	49.4 ± 5.6	50.8 ± 4.23
Permeability (L m^{-2} h^{-1} bar^{-1})	3.9	4.6
Surface area (m^2)	2.6	2.5

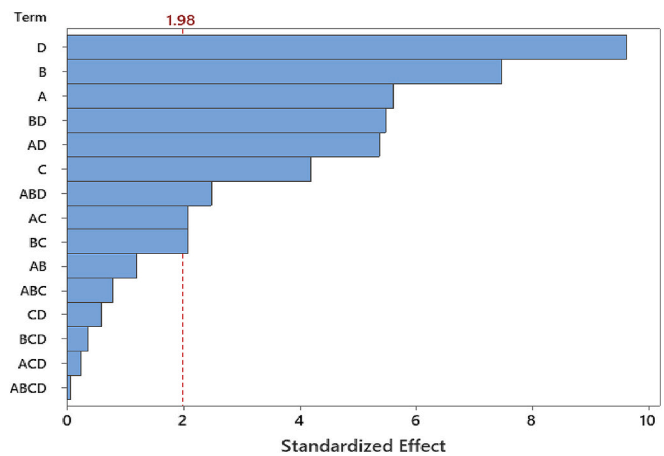


Fig. 9. Full factorial design and ANOVA analysis of operational parameters determined the level of significance and importance of the operating parameters. The letters represent A: Salinity, B: Feed flow rate, C: Temperature, and D: Pressure.

all the data and considering both membranes, SEC had the same trend when changing the operating variables at different salinities (2000, 2500 and 3000 mg/L) (Fig. S1, S2). The optimal operating region of the operating parameters (temperature, pressure, feed flow rate, and membrane permeability) to achieve minimum SEC was determined for each water salinity level (Table 3). As demonstrated, the optimum operating parameter levels to achieve minimum SEC are 1) a temperature of 40 °C, 2) a feed flow rate of 4 L/min, and 3) operating pressure between 100 and 150 psi for all the salinity levels. The water recovery can be increased to 73 % at feed water salinity and flow rate of 2000 mg/L and 3 L/min, which is much higher than the recommended 15 % by the manufacturer. The manufacturer reports that the standard condition of AK membrane recovery is 15 % to avoid scaling and fouling and guarantee the membrane's lifetime. Depending on the feed water quality and considering the scaling factor of present ions (such as silica, calcium, carbonate, etc.), the recovery can be adjusted, directly contributing to the final cost of water. This should be considered for long-term operation and membrane replacement costs in the overall operational cost of the system.

Avlonitis et al. (2012) studied the minimum SEC for a pilot scale BWRO SEC with feed water salinity of 2000 mg/L at 25 °C and 3 L/min feed flow rate, which is similar to the conditions determined in this study (Avlonitis et al., 2012). They reported an optimum SEC of 7 kWh/m^3 was achieved at 175 psi with 60 % water recovery. In this study, it was observed that by increasing the water temperature to 40 °C and at a lower pressure of 100 psi an SEC of 0.697 kWh/m^3 can be achieved, which leads to significant energy saving.

Table 3
The optimum range of operating variables to achieve minimum SEC at feed water salinity of 2000, 2500 and 3000 mg/L at feed flowrate of 3 L/min and temperature of 40 °C. Values in the parenthesis are standard deviations.

Salinity (mg/L)	Pressure (psi)	Recovery	SEC_Mean (kWh/m^3)
	100	0.53 ± (0.02)	0.69 ± (0.01)
2000	125	0.67 ± (0.01)	0.74 ± (0.01)
	150	0.73 ± (0.01)	0.82 ± (0.03)
	100	0.44 ± 0.02	0.94 ± 0.02
2500	125	0.55 ± 0.01	0.96 ± 0.01
	150	0.64 ± 0.01	1.03 ± 0.02
	100	0.41 ± 0.01	0.95 ± 0.01
3000	125	0.52 ± 0.02	0.97 ± 0.02
	150	0.61 ± 0.01	1.00 ± 0.03

Sassi and Mujtaba (2011) used a mathematical model to determine a minimum SEC of a three-stage BWRO with three RO membranes in series in each pressure vessel and brine recovery energy devices. They varied pressure levels from 75 to 350 psi to achieve the lowest SEC with a fixed feed flow rate and concentration of 20.4 cubic m^3/h and 2500 mg/L. A 57 % water recovery and the minimum SEC, 0.6 kWh/m^3, were obtained at 175 psi (Sassi and Mujtaba, 2011). Achieving the lower SEC despite the higher feed flowrate in this study is due to different system RO design and using the energy recovery devices.

4.3. SEC predictive model

A different combination of effective parameters was considered to develop the SEC model based on the experimental data, and various models were evaluated and examined. However, adding recovery as one of the input variables decreased the variance inflation factor (VIF) (i.e., a measurement of multicollinearity) to an acceptable level with a high R^2 of 0.93, Eq. (5). The multiple regression was selected as a predictive model for the AK membrane as follows:

$$SEC_{AK} = -1.014 + 0.35\left(\frac{1}{Re}\right) + 0.008(P) - 0.01\left(\frac{1}{Re^2}\right) + 0.00013(\text{Salinity}) \quad (5)$$

The same procedure and steps followed for the AG membrane and the predictive model is shown in Eq. (6) with R2 of 0.95. The effective parameters for the two membranes are the same, which explains the same trend in the two membranes and presents the possibility of having a model with good predictability regardless of the membrane type as long as the permeability is similar. However, the parameter estimates differ, describing the distinctive values observed in the same condition for both membranes.

$$SEC_{AG} = -1.64 + 0.39\left(\frac{1}{Re}\right) + 0.013\ (P) - 0.009\left(\frac{1}{Re^2}\right) + 0.0001\ (\text{Salinity}) \quad (6)$$

Fig. 10 shows the comparison between the experimental data, the result of the predictive model and the theoretical equations. The predictive model was calculated based on the above equations, whereas the theoretical prediction was calculated based on Eq. (2), considering a typical pump efficiency (i.e., 0.8). As shown in Fig. 10, the result of the predictive model is close to the experimental results, demonstrating the reliability and accuracy of the model. However, there is a considerable difference between theoretical values and experimental results, which is expected. The theoretical model has several assumptions to simplify the relationship between effective parameters, which can explain the difference between the theoretical model and the experimental data and the predictive model results.

4.3.1. Model validation

The models were validated using a new data set that was not applied for the model development. Therefore, additional experiments were conducted with feed water salinity of 4000 mg/L at various pressure levels at 30 °C and 3 L/min. Fig. 11 demonstrates the experimental data (labelled as real data) and model prediction values (marked as predictive model). The predictive model values and the experimental data have the same trend and fall within the standard deviation of each other. This confirms the model's accuracy, reliability and predictability even in higher feed concentrations, 4000 mg/L.

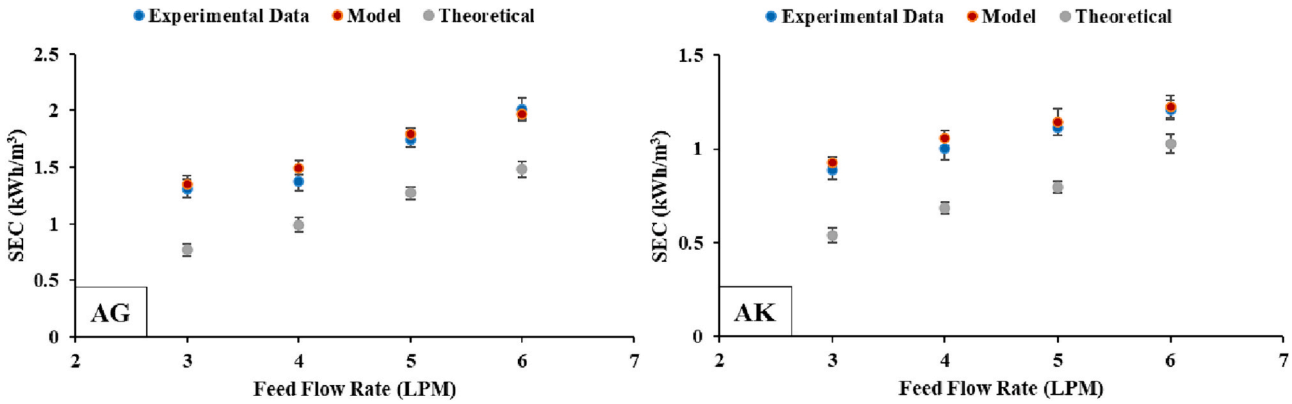


Fig. 10. Comparison of SEC experimental data, predictive models and theoretical values for AG and AK membrane in different feed flow rates at 150 psi, 30 °C, and 2000 mg/L. This demonstrates the accuracy of the models as the results are within the standard deviation and distinct difference for theoretical values which is expected.

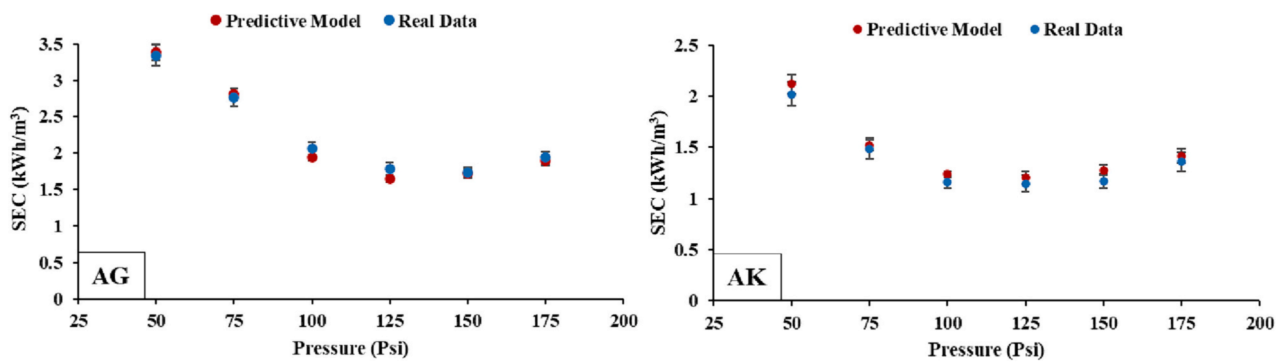


Fig. 11. Comparison of experimental and model prediction results for feed water salinity of 4000 mg/L using AG and AK membrane. The values generated by the models fall between the standard deviation of the experimental data, demonstrating the accuracy and reliability of the predictive models for both membranes even in higher feed salinities, 4000 mg/L.

5. Conclusions

In conclusion, this study addressed the critical challenges associated with brackish water reverse osmosis (BWRO) desalination, focusing on minimizing specific energy consumption (SEC) without resorting to additional capital costs or add-on technologies like energy recovery devices (ERDs). The research conducted a comprehensive full factorial experimental analysis, utilizing a single-stage, single-pass design to eliminate confounding factors and establishing a foundation for determining optimum SEC and water recovery.

The design of experiments allowed for determining the significant operating parameters and their importance level on SEC. Using statistical analysis, pressure was the most significant (aligning with literature), followed by feed flowrate, salinity, the combination of feed flow rate and pressure, the combination of salinity and pressure and the temperature. These results suggested that decreasing pressure and salinity has a more significant impact on SEC minimization than increasing temperature. These findings can answer the long-standing question of design engineers and operators regarding the usefulness of increasing the feed water temperature, as heating large volumes of water is challenging and costly. Based on our findings, it is possible to decrease the SEC by up to 36 % and water recovery by four times by adjusting the operating parameters effectively to avoid the costly procedure of heating the feedwater.

Notably, the study compared two different BWRO membranes, AG and AK, revealing substantial differences in SEC and recovery due to variations in membrane characteristics such as roughness and permeability. Membrane permeability was found to be a critical factor affecting SEC and recovery, emphasizing the importance of selecting membranes tailored to specific operational conditions.

The optimization of operating conditions revealed that, across different salinity levels, and regardless of the membrane type, the optimal parameters for minimizing SEC included a temperature of 40 °C, a feed flow rate of 4 L/min, and an operating pressure between 100 and 150 psi.

Furthermore, empirical models were developed for two membranes using multiple regression, applying exploratory and stepwise approaches considering various combinations of variables and their interactions. The selected models had the highest R^2 (i.e., 0.93 and 0.95). It should be noted that the concentration polarization effect was not considered, however, its exclusion did not compromise the accuracy of our predictions within the scope of our study objectives. Finally, the models were validated with the new data set at higher salinity (i.e., 4000 mg/L), confirming the accuracy, reliability and predictability of the developed models for even higher feedwater salinities.

The findings contribute not only to the understanding of BWRO desalination but also provide a framework applicable to various desalination technologies and feed water types. The identified optimum operating conditions offer insights for achieving energy-efficient desalination processes, aligning with global sustainability efforts in addressing water scarcity and quality challenges. This research can help desalination plants stay one step ahead in achieving targets for UN Sustainable Development Goal 6a.

CRediT authorship contribution statement

Leili Abkar: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Amirreza Aghili Mehrizi:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Morez Jafari:** Data curation. **Sara E. Beck:** Writing – review & editing, Data curation. **Abbas Ghassemi:** Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Mark C.M. Van Loosdrecht:** Writing – review & editing, Supervision, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors would like to acknowledge that the funding for this study was granted by the United States - Bureau of Reclamation, R10AC80283. We are also grateful to Karl Dykeman for his help designing and building the BWRO setup and Mr. John Piechel from GE for generously providing membranes used in this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.172772.

References

Al-Jeshi, S., Neville, A., 2006. An investigation into the relationship between flux and roughness on RO membranes using scanning probe microscopy. Desalination 189 (1–3 SPEC. ISS).
Almansoori, A., Saif, Y., 2014. Structural optimization of osmosis processes for water and power production in desalination applications. Desalination 344.
Al-Obaidi, M.A., Alsarayreh, A.A., Al-Hroub, A.M., Alsadaie, S., Mujtaba, I.M., 2018. Performance analysis of a medium-sized industrial reverse osmosis brackish water desalination plant. Desalination 443.
Al-Obaidi, M.A., Alsarayreh, A.A., Bdour, A., Jassam, S.H., Rashid, F.L., Mujtaba, I.M., 2023. Simulation and optimisation of a medium scale reverse osmosis brackish water desalination system under variable feed quality: energy saving and maintenance opportunity. Desalination 565.
Alsarayreh, A.A., Al-Obaidi, M.A., Al-Hroub, A.M., Patel, R., Mujtaba, I.M., 2020. Evaluation and minimisation of energy consumption in a medium-scale reverse osmosis brackish water desalination plant. J. Clean. Prod. 248.
Alsarayreh, A.A., Al-Obaidi, M.A., Farag, S.K., Patel, R., Mujtaba, I.M., 2021. Performance evaluation of a medium-scale industrial reverse osmosis brackish water desalination plant with different brands of membranes. A simulation study. Desalination 503.
Arras, W., Ghaffour, N., Hamou, A., 2009. Performance evaluation of BWRO desalination plant - a case study. Desalination 235 (1–3).
Avlonitis, S.A., Avlonitis, D.A., Panagiotidis, T., 2012. Experimental study of the specific energy consumption for brackish water desalination by reverse osmosis. Int. J. Energy Res. 36 (1).
Baker, R.W., 2012. "Membrane Transport Theory". In: Membrane technology and applications. John Wiley & Sons, Ltd., Publication, pp. 15–96. Chapter 2.
Bartman, A.R., Zhu, A., Christofides, P.D., Cohen, Y., 2010. Minimizing energy consumption in reverse osmosis membrane desalination using optimization-based control. J. Process Control 20 (10), 1261–1269.
Boretti, A., Rosa, L., 2019. Reassessing the projections of the world water development report. npj Clean Water 2 (1).
Eke, J., Yusuf, A., Giwa, A., Sodiq, A., 2020. The global status of desalination: an assessment of current desalination technologies, plants and capacity. Desalination 495.
Eyl-Mazzega, M.-A., Cassignol, É., 2022. The geopolitics of seawater desalination. Études l'Ifri Ifri September.
Ezzeghni, U., Nuclear, L., 2018. Optimization Study of Alwaha Bwro Plant for Minimum Water Optimization Study of Alwaha Bwro Plant for Minimum, April, pp. 0–10.
Fairuz, A., Faeshol Umam, M., Hasanuzzaman, M., Rahim, N.A., Mujtaba, I.M., 2023. Modeling and analysis of hybrid solar water desalination system for different scenarios in Indonesia. Energ. Conver. Manage. 276.
Jones, E., Qadir, M., van Vliet, M.T.H., Smakhtin, V., Kang, S., mu., 2019. The State of Desalination and Brine Production: A Global Outlook. In: Science of the Total Environment, vol. 657. Elsevier B.V, pp. 1343–1356.
Karabelas, A.J., Koutsou, C.P., Kostoglou, M., Sioutopoulos, D.C., 2018. Analysis of specific energy consumption in reverse osmosis desalination processes. Desalination 431 (February), 15–21.
Karimi, L., Abkar, L., Aghajani, M., Ghassemi, A., 2015. Technical feasibility comparison of off-grid PV-EDR and PV-RO desalination systems via their energy consumption. Sep. Purif. Technol. 151.
Kotb, H., Amer, E.H., Ibrahim, K.A., 2015. Effect of operating conditions on salt concentration at the wall of RO membrane. Desalination 357.
Koutsou, C.P., Kritikos, E., Karabelas, A.J., Kostoglou, M., 2020. Analysis of temperature effects on the specific energy consumption in reverse osmosis desalination processes. Desalination 476.
Pan, S.Y., Haddad, A.Z., Kumar, A., Wang, S.W., 2020. Brackish water desalination using reverse osmosis and capacitive deionization at the water-energy nexus. Water Res. 183.
Qureshi, B.A., Zubair, S.M., 2015. Exergetic analysis of a brackish water reverse osmosis desalination unit with various energy recovery systems. Energy 93, 256–265.
Ramon, G.Z., Hoek, E.M.V., 2013. Transport through composite membranes, part 2: impacts of roughness on permeability and fouling. J Memb Sci. 425–426.
Rani, A., Snyder, S.W., Kim, H., Lei, Z., Pan, S.Y., 2022. Pathways to a net-zero-carbon water sector through energy-extracting wastewater technologies. npj Clean Water 5.
Rosentreter, H., Walther, M., Lerch, A., 2021 Feb 1. Partial desalination of saline groundwater: comparison of nanofiltration, reverse osmosis and membrane capacitive deionisation. Membranes (Basel) 11 (2), 1–22.
Ruiz-García, A., Ruiz-Saavedra, E., 2015. 80,000h operational experience and performance analysis of a brackish water reverse osmosis desalination plant. Assessment of membrane replacement cost. Desalination 375.
Ruiz-García, A., Nuez, I., Carrascosa-Chisvert, M.D., Santana, J.J., 2020. Simulations of BWRO systems under different feedwater characteristics. Analysis of operation windows and optimal operating points. Desalination 491.
Sarai Atab, M., Smallbone, A.J., Roskilly, A.P., 2016. An operational and economic study of a reverse osmosis desalination system for potable water and land irrigation. Desalination 397.
Sassi, K.M., Mujtaba, I.M., 2011. Optimal design and operation of reverse osmosis desalination process with membrane fouling. Chem. Eng. J. 171 (2).
Sassi, K.M., Mujtaba, I.M., 2012. Effective design of reverse osmosis based desalination process considering wide range of salinity and seawater temperature. Desalination 306.
Sweity, A., Zere, T.R., David, I., Bason, S., Oren, Y., Ronen, Z., et al., 2015. Side effects of antiscalants on biofouling of reverse osmosis membranes in brackish water desalination. J Memb Sci. 481.
United Nations, 2020. Peace, Justice, and Strong Institutions: Why they Matter.
Wei, Q.J., McGovern, R.K., Lienhard, J.H., 2017. Saving energy with an optimized two-stage reverse osmosis system. Environ. Sci.: Water Res. Technol. 3 (4).
Williams, M.E., 2003. A Review of Reverse Osmosis Theory. EET Corp Williams Eng Serv Company, Inc.
WWDR4, 2012. Managing Water Report under Uncertainty and Risk - UNESCO, vol. 54. Managing Water Report under Uncertainty and Risk-UNESCO.
Xu, X., Ness, J.E., Miara, A., Sitterley, K.A., Talmadge, M., O'Neill, B., et al., 2022. Analysis of brackish water desalination for municipal uses: Case studies on challenges and opportunities. In: ACS ES and T Engineering, vol. 2. American Chemical Society, pp. 306–322.
Zaidi, S.M.J., Fadhillah, F., Khan, Z., Ismail, A.F., 2015. Salt and water transport in reverse osmosis thin film composite seawater desalination membranes. Desalination 368.
Zhu, A., Christofides, P.D., Cohen, Y., 2009a. Minimization of energy consumption for a two-pass membrane desalination: effect of energy recovery, membrane rejection and retentate recycling. J Memb Sci. 339 (1–2).
Zhu, A., Christofides, P.D., Cohen, Y., 2009b. Effect of thermodynamic restriction on energy cost optimization of RO membrane water desalination. Ind. Eng. Chem. Res. 48 (13).
Zhu, A., Christofides, P.D., Cohen, Y., 2009c. Energy consumption optimization of reverse osmosis membrane water desalination subject to feed salinity fluctuation. Ind. Eng. Chem. Res. 48 (21).