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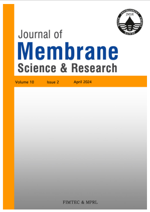

Research Paper

Application of Electrodialysis Reversal Method for Concentrate Management of Reverse Osmosis Process Following MBR Treatment of Wastewater

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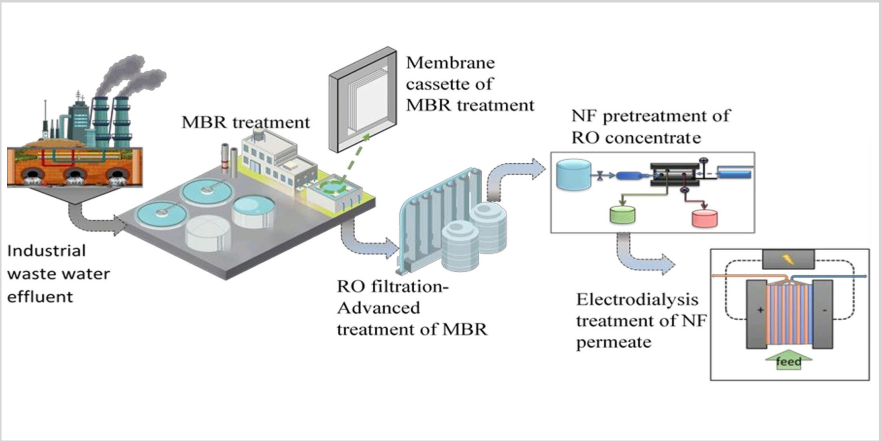
Highlights

- The RO concentrate of the MBR effluent of wastewater was further treated with EDR.
- Pretreatment of the RO concentrate was first performed by NF.
- A conductivity rejection of 98.0% within 42 min was possible with EDR at 5 V.
- NF integration with EDR was a feasible procedure for RO concentrate management.

Graphical abstract



Abstract

In recent years, potable water scarcity has been observed worldwide because of the growing population and industrialization. One of the solutions that might be employed to address this situation is the treatment of contaminated water. This study aimed to evaluate the application of nanofiltration (NF) followed by electrodialysis reversal (EDR) on the concentrate stream of reverse osmosis (RO) operation for the advanced treatment of the membrane bioreactor (MBR) effluent in industrial wastewater. To investigate the impact of applied voltage (3, 5, 10, and 15 V) and the rate of flow (30, 40, and 50 L/h) on the EDR operation, an NF process (10 bar and at constant concentrate stream flow rate as 96 L/h) was employed as a pre-treatment before the EDR process for RO concentrate (TDS: 5520 mg/L) management.

The flow rate showed almost no effect during the EDR process. Increasing the applied voltage led to a rapid rise in conductivity rejection, but it also caused a corresponding increase in specific power consumption (SPC). After considering the rejection performance, process time, and SPC, it became obvious that a 5 V of electrical potential is more appropriate than 3 V, 10 V, and 15 V. Application of EDR to NF permeate of the RO concentrate resulted in a conductivity rejection of 98.0% within 42 min when subjected to an electrical voltage of 5 V. The SPC was calculated to be 0.06 kWh/m^3.

To increase the amount of water recovered from the MBR effluent of wastewater and reduce the volume of brine discharged into surface water bodies, it has been demonstrated that NF integration with EDR was a feasible procedure for RO concentrate management.

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1. Introduction

The scarcity of freshwater has become one of the most serious global problems in recent days [1]. Increasing population growth creates an additional burden on the availability and purity of potable water, particularly in nations that are already experiencing water scarcity. In addition, as a result of urbanization and industrialization, certain water bodies and aquifers are rapidly becoming insufficient and contaminated. As a result, the scarcity of pure water on a global scale is emerging as the most significant challenge to advancement in both society and the economy. The development of sophisticated solutions that are sustainable and capable of meeting the growing water demands of future generations is a subject of notable concern [2].

Membrane-based separation methods have gained significant importance in several industrial sectors, including water and wastewater treatment, biotechnology, nanotechnology, and membrane-based energy devices. The economic feasibility of these processes is attributed to their low energy demands and the ease with which membrane modules may be scaled up. The progress in membrane technology, particularly in innovative materials, has the potential to enhance the competitiveness of this technology in comparison to conventional, energy-intensive, ecologically unfavorable, and expensive procedures [3,4].

Pressure-driven membrane technologies, such as NF and RO, have demonstrated their efficacy in the generation of potable water from saline water or brackish water [5,6] Currently, RO has the dominant position as the primary technique for the establishment of new desalination facilities, accounting for 75% of the global desalination production capacity [7].

The concentrate stream, an undesirable byproduct of the purification procedure, poses the primary challenge to the RO method [8]. The RO concentrate, also known as brine, is produced concurrently with the product water and contains significant amounts of diverse inorganic and/or organic chemicals. The outcome depends on the characteristics of the feed water and the recovery mechanism. In desalination applications, the RO concentrate is primarily released into the natural water body, either with or without dilution. The decision to dilution is determined by local discharge restrictions to prevent water body damage. The primary methods for disposing of concentrates include ejection into surface water, sea, and evaporation ponds, as well as deep well injection and land applications [7,9,10].

Despite the implementation of some environmental concerns, the standard procedure continues to be direct discharge. The release of this brine without prior treatment poses a significant threat to the aquatic environment of the surface waterways it encounters.

According to Zhang et al. [11], ED has been shown to be an effective technique for treating RO concentrate, increasing total RO water recovery beyond 90%, and achieving a "near zero liquid discharge approach." The benefits associated with the utilization of ED in the treatment of RO concentrate may be categorized into three distinct groups: minimizing waste disposal, enhancing chemical recovery, and improving water recovery. As demonstrated by Zhang et al. [11], ED assisted in minimizing the effects of RO concentrate disposal. The application of ED to the RO concentrate results in a beneficial environmental impact, as it enables its reuse in addition to its intended discharge into the environment. According to Praneeth et al. [12], the usage of ED is shown to be cost-effective, particularly for RO concentrate that has low levels of COD. The economic dimension of ED in the treatment of the RO concentrate is based on the expenses associated with energy and chemical decarbonization. The energy consumption of a system depends on several factors, including feed concentration, applied voltage, removal efficiency, flow rate, and operating time. Consequently, while operating with a high concentration of salt and a high flow rate, the power consumption rises due to the longer duration of the operation [12].

In the 1950s, the initial commercial apparatus employing ED technology was created with the aim of demineralizing brackish water. An improvement in ion exchange membrane properties, enhanced materials of construction, and different advances in technology have made ED advance rapidly. ED was utilized to reduce inorganic contaminants in potable water, including radium, perchlorate, bromide, fluoride, iron, manganese, and nitrate. Furthermore, recovering RO brine, desalting wells, surface waters, final effluent treatment for reuse in cooling towers, purification of whey and soy, table salt production, and numerous other industrial applications are all possible with this technology [13].

From the environmental point of view, recovering concentrates that come from pressure-driven processes is an important usage area for ED systems. Desalination processes generate saline solutions that have to be released into the environment. The dramatic rise in desalination capacity has made brine management an increasingly complex operation. Desalination capacity reached 87 Mm^3/day on a global scale in 2015, of which seawater desalination accounted for 51 Mm^3/day [14].

However, ED is efficient in the removal of ionic species only. Moreover, the ED membrane may be scaled or fouled by hardness ions contained in RO brine. A pre-treatment process should be considered to be applied prior to the ED process for the prevention of membrane scaling and removal of uncharged pollutants from the RO brine. The literature recommends adding an HCl solution to the ED feed to maintain pH at approximately 5.5 to prevent scaling on ED membranes [12]. For uncharged organic pollutants removal, the decarbonization of RO concentrates effluent before the ED process was studied [11].

The current study focused on the management of the RO concentrate obtained by advanced treatment of MBR effluent of wastewater by RO using an EDR system. In ED operation, some species such as suspended solids with positive or negative electrical charges can increase the resistance of the membrane dramatically due to their deposition on the membrane surface. The problem can be eliminated to a large extent by reversing in certain time intervals the polarity of the applied electrical potential which results in the removal of charged particles that have been precipitated on the membranes. This technique is known as EDR. In this study, before the EDR process, the NF operation was applied to the RO concentrate to remove hardness ions and uncharged pollutants. The investigation focused on examining the impact of applied voltage and flow rate on the performance of the system.

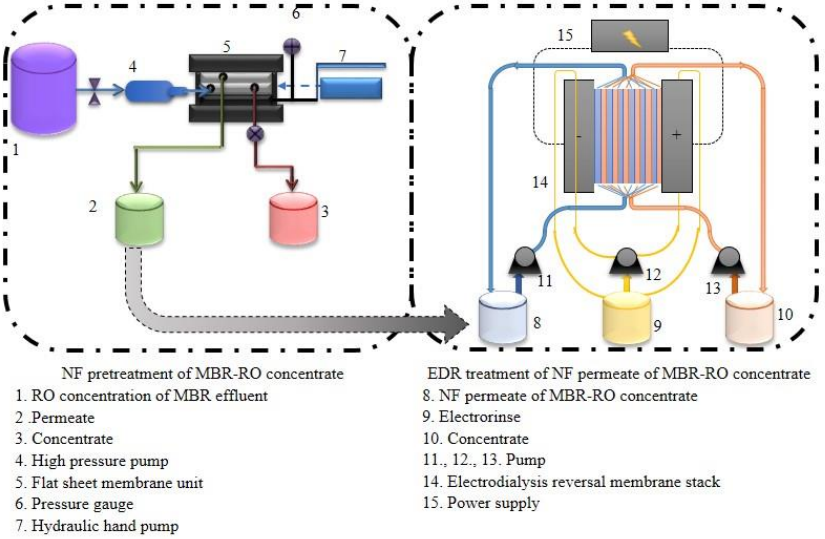
2. Material and Methods

A lab-scale EDR system (Mega EDR-Z Type CA) was used for the treatment of NF-90 permeate of the RO concentrate (ROC). The ROC was collected from the ITOB Organized Industrial Zone where the RO membrane process was used for the treatment of MBR effluent of wastewater. The NF-90 membrane as NF membrane was used to prevent scaling and fouling problems on EDR membranes. The overall flow of waste management from start to finish is given in Fig. 1. Images and flow diagrams of NF and EDR systems are given in Figs. 2 and 3, respectively.

Fig. 1. Overall flow diagram of the integrated membrane process for concentrate management of RO process following MBR operation for wastewater treatment.

The NF filtration process was conducted using laboratory-scale cross-flow flat sheet membrane test equipment (SEPA CF II GE Osmonics). Filtration was carried out under 10 bar of operation pressure using an NF-90 membrane. The flow rate of the concentrate stream was kept constant at 96 L/h. The characteristics of the NF-90 membrane are given in Table 1.

Fig. 2. SEPA CF II GE-Osmonics lab-scale cross-flow flat sheet membrane test system (left) and Mega EDR-Z Type CA lab-scale EDR test system (right).



NF pretreatment of MBR-RO concentrate
1. RO concentration of MBR effluent
2 .Permeate
3. Concentrate
4. High pressure pump
5. Flat sheet membrane unit
6. Pressure gauge
7. Hydraulic hand pump

EDR treatment of NF permeate of MBR-RO concentrate
8. NF permeate of MBR-RO concentrate
9. Electrorinse
10. Concentrate
11., 12., 13. Pump
14. Electrodialysis reversal membrane stack
15. Power supply

Fig. 3. Fow diagrams of integrated NF and EDR test systems.

Following pretreatment with the NF90 membrane, the produced permeate was subsequently transferred to the MEGA EDR system, which utilized RALEX heterogeneous ion exchange membranes. The EDR Module (EDR-Z Type CA) consists of 10 RALEX Anex AMH-PES membranes and 11 RALEX Catex CMH-PES membranes. The characteristics of ion exchange membranes are given in Table 2.

A 1 L of NF-90 permeate was fed to the EDR system. Sodium sulfate solution with a conductivity of around 500 µS/cm was used for both concentrate (1 L) and electrode compartments (250 mL). Applied voltages were 3, 5, 10, and 15 V. In the experiments, different flow rates (30, 40, and 50 L/h) were tested. The characteristics of RO concentrate of MBR effluent and NF-90 permeate (as EDR feed) are given in Table 3. In the diluate compartment, conductivity, salinity, TDS, and pH were measured by Hach Lange HQ40d multimeter while in the concentrate compartment, these parameters were measured by using WTW Cond 3110 and WTW pH 3110. After that, conductivity rejection and conductivity change were calculated as given in Equations 1 and 2. With the help of Equation 3, specific power consumption (SPC) was also calculated.

$$\text{Conductivity Rejection}\left(\%\right)=\frac{C_o-C_i}{C_o}\times 100 \tag{1}$$

$$\text{Conductivity Change}=\frac{C_i}{C_o} \tag{2}$$

$$\text{SPC}\left(\text{kWh}/\text{m}^3\right)=\frac{E\int_0^t I\left(t\right)dt}{V} \tag{3}$$

Where C_o (µS/cm) and C_i (µS/cm) are the initial and at any time t (h) conductivities of the solution, E (V) is voltage, I (A) is current and V (m^3) is the volume of the sample solution used.

Table 1
The characteristics of NF-90 membrane.

Membrane	**NF-90**
Manufacturer	Dow FilmTech
Membrane Type	Polyamide thin film composite
Operating Conditions	Maximum Pressure: 41 bar Maximum Temperature: 45 (°C) Operating pH Range:3-10
Minimum NaCl rejection (%)	> 85
MWCO (Dalton)	200

Table 2
The characteristics of RALEX ion exchange membranes.

Membrane	**AMH-PES**	**CMH-PES**
Fitting fabrics	polyester	polyester
Ion-exchange group	R – $(CH_3)_3N^+$ quaternary ammonium	R – SO_3^- sulphonate
Ionic form – counter ion	Cl^-	Na^+
Swelled membrane thickness (mm)	< 0.75	< 0.77
Electrical resistance (Ω-cm^2)	7.5	8.0
Permselectivity (%)	>90	>90

Table 3
Properties of NF-90 feed (RO Concentrate of MBR effluent) and feed of EDR (NF-90 permeate).

	Feed of NF-90 (RO Concentrate of MBR effluent)	Feed of EDR (NF-90 Permeate)
EC (μS/cm)	11000	335.9
TDS (mg/L)	5520	165
pH	7.32	6.15
Salinity (‰)	5.69	0.16

3. Results and Discussion

3.1. Effect of applied voltage on ED performance

After pretreatment of the RO concentrate of MBR effluent with NF-90 membrane, the permeate of NF-90 membrane was used as feed for EDR tests at different electrical potentials. Pretreatment of the RO concentrate with NF-90 membrane reduced Ca, Mg concentrations and COD to 7.71, 0.36, and 7.20 mg/L, respectively. Therefore, the EDR feed was free of membrane scaling and fouling agents. For the EDR process, the applied electrical potentials were 3, 5, 10, and 15 V at 50 L/h of diluate flow rate. Similar conductivity rejections were achieved with EDR at all applied voltages with an average rejection of 97.9±0.5% (Fig. 4). The conductivity changes in both samples (diluate and concentrate streams) at different voltages were depicted in Fig. 5. An increase in applied electrical potential means an increase in driving force which is the current density in EDR case. Higher current density results in a rapid ion transfer through ion exchange membranes. The kinetics of ion transfer exhibit a rising pattern as the electrical potential increases. In other words, as the electrical potential increased, the time needed to get the equivalent outcome decreased (Table 4). On the other hand, the SPC increased with an increase in electrical potential applied as summarized in Table 4.

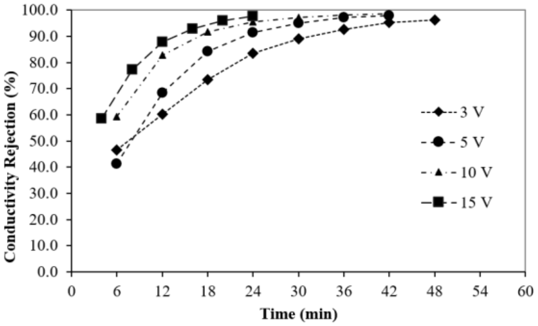


Fig. 4. Conductivity rejection vs. time plots as a function of electrical potential.

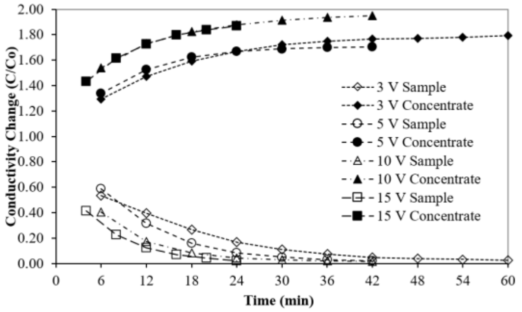


Fig. 5. Conductivity changes vs. time plots as a function of applied electrical potential.

Table 4
Results obtained at different electrical potentials by EDR process.

Voltage (V)	3		5		10		15	
	Feed	Diluate	Feed	Diluate	Feed	Diluate	Feed	Diluate
Conductivity (μS/cm)	341	8.7	325	6.51	320	4.75	352	8.03
Magnesium (mg/L)	0.36	< 0.10	0.36	< 0.10	0.36	< 0.10	0.36	< 0.10
Sodium (mg/L)	77.02	0.94	77.02	1.07	77.02	< 0.10	77.02	0.21
Potassium (mg/L)	55.37	0.29	55.37	0.26	55.37	< 0.10	55.37	0.21
Calcium (mg/L)	7.71	1.71	7.71	2.12	7.71	1.72	7.71	1.95
COD (mg/L)	58.0	6.80	58.0	6.50	58.0	7.0	58.0	6.60
Total process time (min)	60		42		42		24	
Conductivity rejection (%)	97.4		98.0		98.5		97.7	
SPC (kWh/m^3)	0.03		0.06		0.15		0.17	

3.2. Effect of diluate flow rate on EDR performance

The effect of flow rate on EDR performance was investigated at 5 V of electrical potential. Three different flow rates such as 30, 40, and 50 L/h were set for diluate and concentrate compartments of the EDR unit. As shown in Fig. 6, an increase in the flow rate did not influence the performance of the EDR process. A similar conductivity rejection of 97.3±1.0% (Table 5) was achieved at different flow rates in 42 min. Since the SPC was found to be similar with an average value of 0.061±0.004 kWh/m^3 (Table 5) to achieve a conductivity rejection of 97.3±1.0%, the lower flow rate should be chosen as an optimum for the system to minimize the pumping energy. The findings from this work were similar to that found in the literature [15]. On the other hand, lower flow rate is expected to enhance the separation efficiency. Sadrzadeh et al. [16] reported such impact of lower flow rates on the ED process. Therefore, two different ranges of flow rates can be distinguished in the ED process: a range where the flow rate can influence the separation efficiency and a range where the flow rate has no impact on the separation efficiency. Since the lower flow rates are in favor of both separation efficiency and economic aspects in ED, the ED system designers should specify the minimum effective flow rate for the system.

Table 5
The feed and diluate characteristics at different flow rates during EDR tests.

Flow-rate (L/h)	30		40		50	
	Feed	Diluate	Feed	Diluate	Feed	Diluate
Conductivity (μS/cm)	328	7.15	360	14	325	6.51
Magnesium (mg/L)	0.36	< 0.10	0.36	< 0.10	0.36	< 0.10
Sodium (mg/L)	77.02	0.53	77.02	1.72	77.02	0.85
Potassium (mg/L)	55.37	0.25	55.37	0.37	55.37	0.28
Calcium (mg/L)	7.71	2.52	7.71	2.57	7.71	2.53
COD (mg/L)	58.0	6.20	58.0	7.00	58.0	6.50
Total process time (min)	42		42		42	
Conductivity rejection (%)	98.0		96.1		97.8	
SPC (kWh/m^3)	0.060		0.065		0.058	

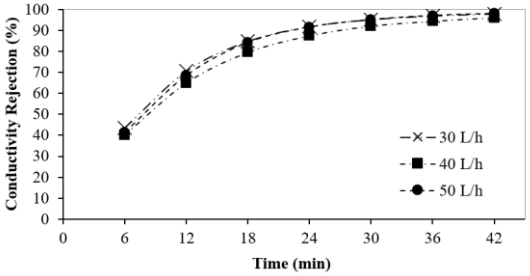


Fig. 6. Conductivity rejection vs. time plots as a function of diluate flow rate.

4. Conclusions

From this study, the integration of NF and ED processes was found to be an effective strategy to increase water recovery from wastewater treatment systems based on the RO process following MBR operation and to reduce the brine discharge from the RO treatment plants to the environment. Based on the experimental results, the following conclusions were formulated:

- Pre-treatment of the RO concentrate with NF membranes prevented the EDR membranes from scaling and fouling by removing Ca, Mg ions and COD from the RO concentrate.
- An increase in electrical potential applied during the EDR process resulted in a higher rejection in a short period of time. However, a higher applied electrical potential resulted in an elevated SPC. The sample flow rate did influence the rejection efficiency. However, lower flow rates should be preferred to reduce the pumping cost of the system.
- Applying the ED process for the NF permeate of the RO concentrate stream at an optimum electrical potential with a minimum flow rate could give a good water quality from the RO concentrate of MBR effluent at a lower cost.

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Data availability

They can be available when requested.

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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.

Credit authorship contribution statement

S. C. Özkök: Investigation, Writing original draft
E. Altıok: Writing-review & editing
S. Bunani: Conceptualization, Investigation, Methodology
D. İpekçi: Conceptualization, Investigation, Methodology
N. Kabay: Supervision; Writing-review editing; Project administration; Funding acquisition
M. Arda: Project administration; Formal analysis
M. Yüksel: Supervision

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