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Performance evaluation of reverse osmosis (RO) pre-treatment technologies for in-land brackish water treatment

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Abstract

Integration of renewable energy with desalination technologies has emerged as an attractive solution to augment fresh water supply sustainably. Fouling and scaling are still considered as limiting factors in membrane desalination processes. For brackish water treatment, pre-treatment of reverse osmosis (RO) feed water is a key step in designing RO plants avoiding membrane fouling. This study aims to compare at pilot scale the rejection efficiency of RO membranes with multiple pre-treatment options at different water recoveries (30, 35, 40, 45 and 50%) and TDS concentrations (3500, 4000, and 4500 mg/L). Synthetic brackish water was prepared and performance evaluation were carried out using brackish water reverse osmosis (BWRO) membranes (**Filmtec** LC-LE-4040 and Hydranautics CPA5-LD-4040) preceded by 5 and 1 μm cartridge filters, 0.02 μm ultra-filtration (UF) membrane, and forward osmosis (FO) membrane using 0.25 M NaCl and MgCl_2 as draw solutions (DS). It was revealed that FO membrane with 0.25 M MgCl_2 used as a draw solution (DS) and Ultra-filtration (UF) membrane followed by **Filmtec** membrane gave overall 98% rejection but UF facing high fouling potential due to high applied pressure. Use of 5 and 1 μm cartridge filter prior to **Filmtec** membrane also showed effective results with 95% salt rejection.

Keywords: Brackish water; Reverse Osmosis (RO); Forward Osmosis (FO); Ultrafiltration (UF); Rejection efficiency; Permeate TDS

1. Introduction

Energy and drinking water supply remain unsolved issues for many countries around the world [1]. Therefore, integration of desalination technologies with renewable energy have become an attractive solution to overcome water scarcity problem [2]. Major part of the world's water is seawater, brackish water and groundwater. Approximately, 97.4% of the entire water available on earth is salty and 1.984% is located in the ice caps and glaciers, while 0.592% is located as groundwater and only 0.014% of the earth's water is available as fresh water [3]. Many water-stressed countries are supplementing their fresh water supply with desalinated water to meet their increased water demand caused by population growth, rapid urban sprawl, agriculture development, industrialization, and tourism [4].

Inland salinity of ground water having total dissolved solids (TDS) of varying concentration, usually below 10,000 ppm, has been found in four provinces of Pakistan. For example, in the Punjab most ground water has TDS<1500 while in Balochistan it typically exceeds 3000 mg/L (see Fig.1) [5].

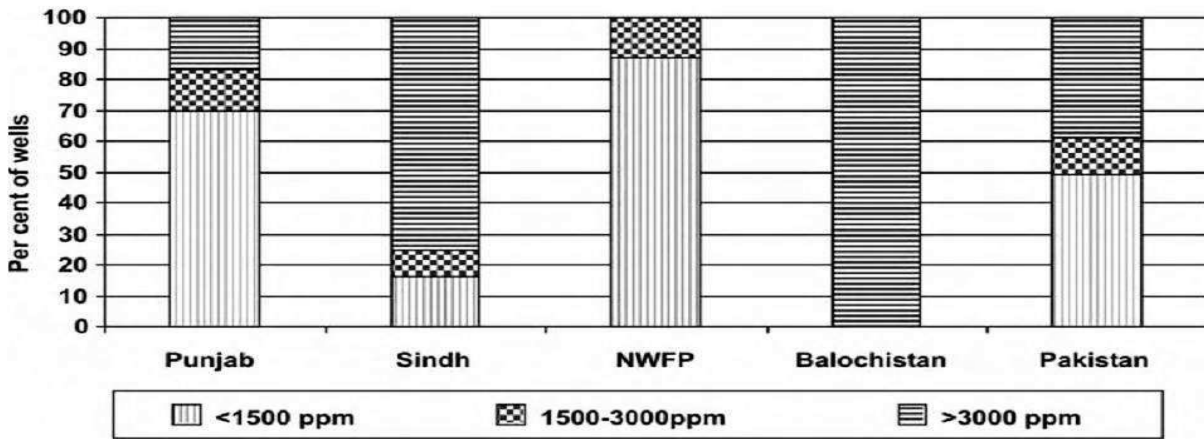


Fig. 1. Ground water quality in various provinces of Pakistan [5]

However, these areas also receive 5.1-6.2 kWh/m²/day of annual average mean daily solar radiation, making photovoltaic electricity an attractive solution to conventional energy to fulfill their water requirements via desalination [6]. Treatment of brackish water using desalination technologies is an effective option to overcome fresh water scarcity problem [7]. Brackish water desalination represents over 21 % of the total worldwide desalination capacity due to its low operating cost and energy requirement [8]. Reverse Osmosis (RO) is a water treatment technology that has gained world-wide acceptance. Over the years, remarkable advancement has been made in RO technology [9-11]. Recent study revealed that reverse osmosis (RO) is the most optimized technology for water desalination related activities [12].

Membrane scaling and fouling are among the most serious concerns in membrane-based treatment processes. In brackish/sea water desalination process, pre-treatment of the saline feed is a crucial step in designing of the process to avoid membrane fouling and scaling and to reduce its cleaning frequency [13]. Proper pre-treatment is an essential aspect in desalination process via reverse osmosis technology for successful plant operation to ensured treatment performance [14-16].

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4 1 Compared to conventional pre-treatment technologies, membrane technologies were found to be
5 2 more cost effective and give better results by removing the particles having size greater than the
6 3 pore size of the membrane. This results in low silt density index (SDI) value, which make them
7 4 more attractive pre-treatment technologies for the water having high total dissolved solids (TDS)
8 5 [17-20]. Among membrane processes, micro-filtration (MF) and ultra-filtration (UF) are the
9 6 technologies that have gained global acceptance as suitable pre-treatment technologies for saline
10 7 water [21].
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14 8 Ultra-filtration (UF) was found to be cost effective and efficient technique for the removal of
15 9 suspended solids and bacteria [13]. The selection of the pre-treatment option is site specific and is
16 10 mainly based on feed water quality, but in some cases the feed water quality is influenced by
17 11 seasonal variation (i.e. flood, drought, and climatic impact) which make pre-treatment design more
18 12 complicated. Forward Osmosis (FO) was found to be a feasible pre-treatment option for variable
19 13 quality feed water and for the feed having high fouling potential. It is capable of providing uniform
20 14 treated water quality with less fouling potential instead of variable feed quality.
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23 15 Forward Osmosis is an emerging technology used in water reuse and desalination [22-25]. It is
24 16 regarded as a natural process that utilizes osmotic pressure gradient to draw the water from the
25 17 dissolved solutes in feed solution across a semi-permeable membrane [26-28]. Among the other
26 18 RO pre-treatments, FO has much lower fouling tendency and can operate over a longer period of
27 19 time without cleaning [29]. Increasing interest in FO is fueled by the global demand for less
28 20 fouling, high recovery and low energy consuming process increasing lifespan of the membrane
29 21 compared to the pressure-driven membrane process [30.31].
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33 22 Though UF and MF has been widely used in RO pre-treatment, the use and availability of FO is
34 23 relatively recent. Side-by-side comparison of pre-treatment options is lacking. This study sets out
35 24 to provide pre-treatment comparison for a stand-alone **photovoltaic (PV)** powered RO plant
36 25 designed to meet the growing water needs of inland areas of Pakistan.
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39 27 **2. Materials and methods**

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41 29 **2.1. System Configuration**

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43 31 In this study, pilot-scale reverse osmosis plant was designed to investigate rejection of RO
44 32 membranes at different water recoveries and TDS concentrations. To make process performance
45 33 more effective and sustainable, multiple pre-treatment options were coupled prior to both (RO)
46 34 membranes operated in parallel. The general layout of the pilot scale plant showing all components
47 35 is shown in **Fig. 2**, while the actual picture of the system is depicted in **Fig. 3**.
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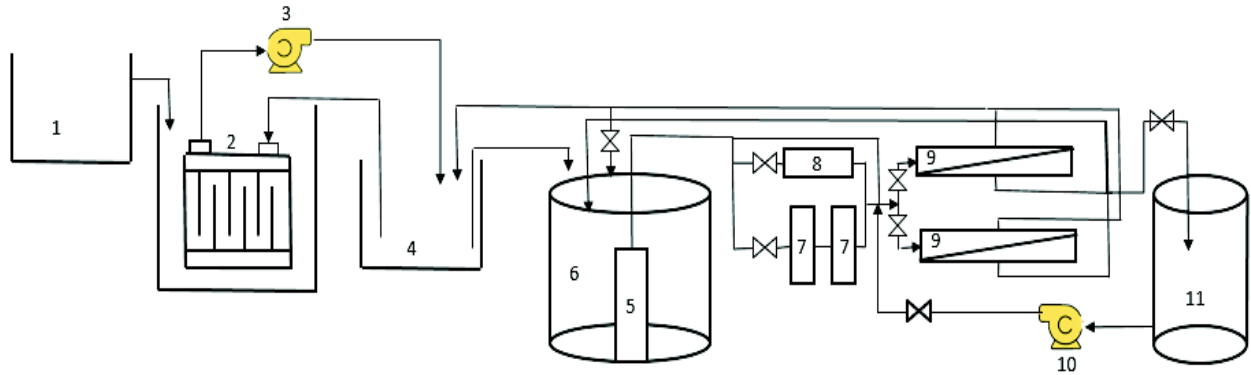


Fig. 2. Layout of the process (1) Brackish water feed tank. (2) Forward osmosis membrane module. (3) Circulation pump. (4) Draw solution tank. (5) Submersible feed pump. (6) RO feed tank. (7) Cartridge filters. (8) UF membrane. (9) RO membranes. (10) CIP pump. (11) CIP tank.



Fig. 3. Pilot scale Reverse Osmosis (RO) Plant at National University of Sciences and Technology (NUST), Islamabad, Pakistan

A 2 kWh **photovoltaic (PV)** system consisting eight monocrystalline silicon solar panels (model: CS6P-265M, Canadian Solar) connected with a grid inverter was installed to provide solar energy input. The specification of the **photovoltaic (PV)** system and modules is illustrated in Table 1.

The pilot-scale reverse osmosis (RO) unit consists of a feed tank, high pressure submersible feed pump (model: SQF 0.6-3, Grundfos, UK), clean-in-place (CIP) tank, and clean-in-place pump (model: MSP 230, Marchmay, UK) along with membrane modules consisting of two spiral wound RO membrane (**Filmtec** LC-LE-4040 and Hydranautics CPA5-LD-4040) in combination with different pre-treatment technologies comprising of 5 and 1 μm cartridge filter (CF), 0.02 μm pore size ultra-filtration (UF) membrane and a cellulose tri-acetate (CTA) flat sheet forward osmosis (FO) membrane. Permeate and feed flow rate were measured by rotameters and recycled to the feed tank to make operation continuous. Membrane inlet and outlet pressure was measured using bourdon gauge (model: 233.55 LBM, WIKA Instrument Corporation, USA) which was under the permissible limit recommended by the membrane manufacturers (Table 2). Feed and permeate TDS and pH were also measured with in-line meters.

Table 1
 Technical data of photovoltaic (PV) system

Component	Value
Number of modules	8
Module specification	
Max. power (Watts)	265
Voltage at power at max. power point (Pmpp), Vmp (Volts)	30.9
Current at Pmpp, Imp (Amps)	8.61
Open circuit voltage, Voc (Volts)	37.9
Short circuit current, Isc, Amps	9.11
Maximum system voltage, Volts	1000
Maximum series fuse rating, Amp	15

Table 2. RO membrane specifications

Membrane	Model	Permeate flow rate (m ³ /d)	Max. operating pressure (MPa)	Membrane filtration area (m ²)	Max. operating temperature	pH range
Hydranautics	CPA5-LD-4040	7.95	4.13	7.43	45°C	2 – 11
Filmtec	LC-LE-4040	9.5	4.13	8.7	45°C	2 – 11

2.2. Synthetic brackish water feed conditions

Filtration tests were performed using synthetic brackish water [2]. Three brackish water feed conditions of 3500, 4000, and 4500 mg/L TDS concentration were prepared in accordance to target feed water quality found in the substantial areas of Pakistan (Table 3) [5]. Sodium metabisulphite (Na₂S₂O₅) at a concentration of 2 mg/L was also added to neutralize residual chlorine in the tap water and inhibit bacterial growth [32].

Table 3
Concentrations used for synthetic feed preparation [2]

Compounds	Amount (TDS-mg/L)		
	Feed I	Feed II	Feed III
NaCl	889	1016	1169
CaCl ₂	941	1076	1241
MgCl ₂ . 6H ₂ O	983	1124	1293
NaNO ₃	45	52.4	60.3
Na ₂ SO ₄	617	705	811
NaHCO ₃	18	21	24.6

2.3. Operational conditions

The synthetic water was fed to RO membranes preceded by different pre-treatment technologies including 5 and 1 μm melt blown cartridge filter, 0.02 μm ultrafiltration (UF) membrane and forward osmosis (FO) membrane. For FO system, 0.25 M NaCl and MgCl₂ were used as draw solutions (DS). Experiments were performed in batch recirculation mode and the flux across the FO membrane, active layer facing feed side was measured by digital data logging weight balance (UX 6200H, Shimadzu, Japan). The diluted DS was then fed to the RO membrane for the separation of clean water and regeneration of DS for reuse. System was operated for two hours for each set of recoveries 30, 35, 40, 45, and 50 % along with each pre-treatment option. For each TDS condition, the duration was sufficient enough to achieve steady-state condition [33].

Percent rejection of solute was calculated using Eq. (1)

$$\% \text{ Rejection} = \left(1 - \frac{C_p}{C_f}\right) \times 100\% \quad (1)$$

where C_p and C_f are permeate and feed concentration respectively (mg/L). Rejection value was calculated under each condition (after 2 hours operation)

Water recovery from each membrane arrangement were measured using Eq. (2)

$$\text{Water recovery} = \frac{Q_p}{Q_f} \times 100\% \quad (2)$$

where Q_p and Q_f are the permeate and feed water flow rates respectively (L/h).

Flux across the RO membranes were calculated using Eq. (3)

$$J_v = L_p (\Delta P - \sigma \Delta \Pi) \quad (3)$$

1 where J_v is the hydraulic permeate flux ($L \cdot h^{-1} \cdot m^{-2}$), L_p is the membrane permeability ($L \cdot h^{-1} \cdot m^{-2} \cdot bar^{-1}$), ΔP and $\Delta \Pi$ are the transmembrane pressure and osmotic pressure (bar) respectively and σ is the local reflection coefficient.

2 The solute flux across the RO membrane is the sum of diffusive and convective flux. Therefore, mass transfer across the RO membrane can be expressed as Eq. (4) [33-34].

$$J_s = J_v \cdot C_p = J_{diff} + J_v \cdot C_{conv} \quad (4)$$

3 where J_s is the solute flux ($mg \cdot m^{-2} \cdot s^{-1}$), C_p is the solute permeate concentration ($mg \cdot L^{-1}$), J_{diff} is the diffusive flux ($mg \cdot m^{-2} \cdot s^{-1}$) and C_{conv} is the solute permeate concentration due to convective transport. The above equation can also be re-written as.

$$C_p = J_{diff}/J_v + C_{conv} = P_s \Delta C_s / J_v + C_{conv} \quad (5)$$

4 where P_s is the membrane solute permeability ($m \cdot h^{-1}$), and ΔC_s is the concentration difference ($C_b - C_p$) across the membrane ($mg \cdot L^{-1}$), and C_b is the solute brine concentration.

5 After each run, forward washing of RO membrane was performed with treated water using clean in place (CIP) pump to avoid membrane surface deposition. Each pre-treatment option was evaluated using parameters including membrane inlet pressure, feed TDS, feed pH, membrane outlet pressure, permeate pH, and permeate TDS.

3. Results and discussion

6 Figs. 4 and 5 shows the percent rejection performance of both RO membranes coupled with multiple pre-treatment options at different recoveries obtained against different trans-membrane pressure for the feed TDS condition I i.e. 3500 mg/L. From the filtration tests with Filmtec membrane, minimum 95% salt rejection with cartridge filter as a pre-treatment (CF-RO) and 98% salt rejection with ultrafiltration as a pre-treatment (UF-RO) was observed with a maximum permeate TDS of 175 mg/L and 68 mg/L, respectively. While for the similar set of arrangement with forward osmosis as a pre-treatment (FO-RO), 93 and 96% salt rejection with NaCl and MgCl₂, respectively as DS was observed with a maximum permeate TDS of 234 and 120 mg/L, respectively (Fig. 4). In parallel, from the Hydranautics membrane, minimum 85% salt rejection with cartridge filter (CF-RO) and 97% salt rejection with ultrafiltration (UF-RO) as a pre-treatment was observed with maximum permeate TDS 500 and 98 mg/L, respectively. While with forward osmosis as a pre-treatment, minimum 77% rejection with NaCl and 96% salt rejection with MgCl₂ as DS was observed with a maximum permeate TDS of 775 and 130 mg/L, respectively (Fig. 5).

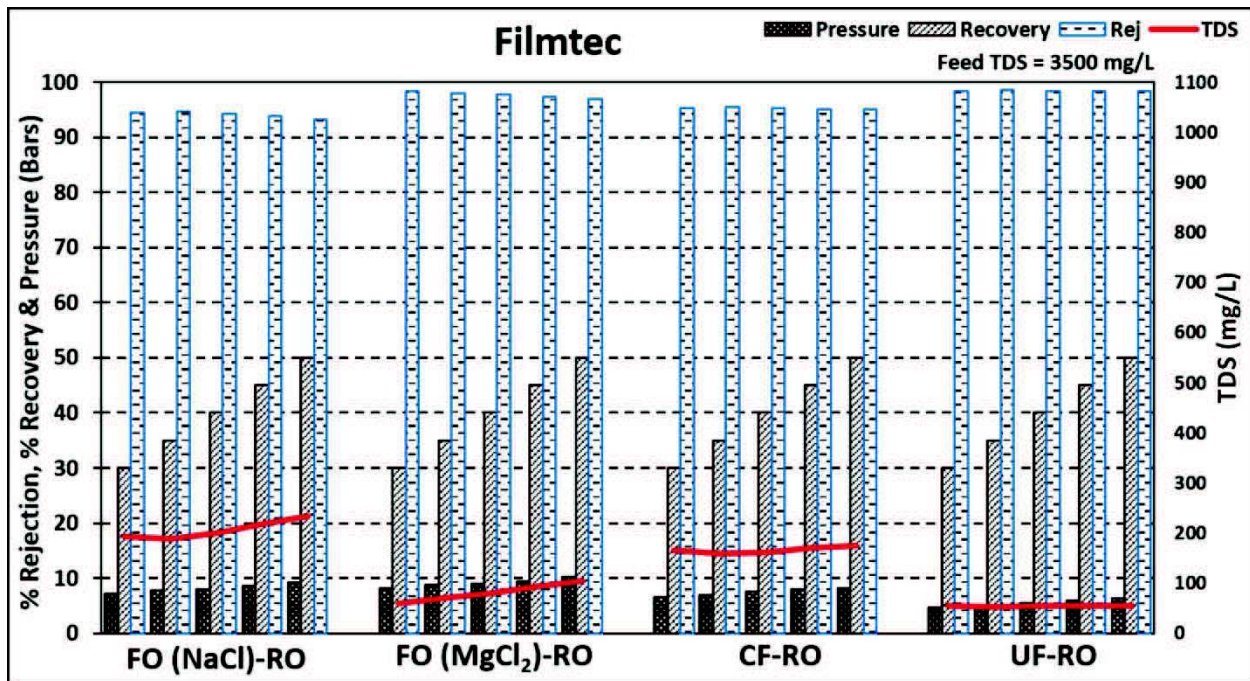


Fig. 4 Rejection and TDS at different recoveries and pressure for FO-RO, UF-RO & CF-RO system with Filmtec membrane.

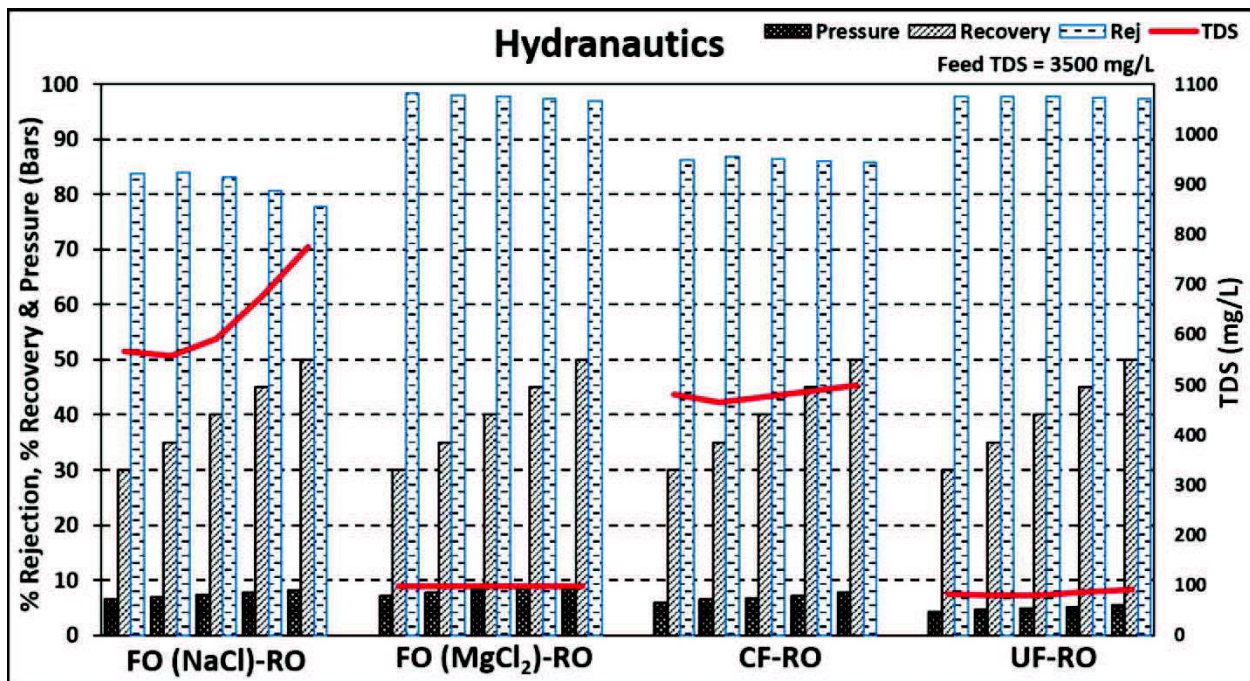


Fig. 5 Rejection and TDS at different recoveries and pressure for FO-RO, UF-RO & CF-RO system with Hydranautics membrane

Ultrafiltration (UF) membrane followed by RO membranes showed effective salt rejection at low operating pressure as compared with CF-RO and FO-RO. Both membranes showed consistent operational behavior with all the pre-treatment arrangements over a wide range of pressures applied in order to achieve high recovery except for FO-RO arrangement with NaCl as DS using

Hydranautics membrane resulting in decline in rejection performance at higher pressure condition accompanied with significant increase in permeate TDS (Fig. 5). Moreover, the performance of CF-RO in terms of permeate TDS was also poor among the pre-treatment options tested.

For FO as a pre-treatment with NaCl as DS using Hydranautics membrane, a 4% decline in rejection at per bar increase in pressure was observed. MgCl₂ as a draw solution was more effective as compared to NaCl because of its high osmotic potential and divalent ionic structure. It was observed that the flux across the FO membrane has a direct relation with the molar concentration of draw solution (DS) and inverse with the feed solution (FS) concentration [35]. Higher molar concentration of DS resulted in higher flux across the FO membrane and ultimately concentrated FS and diluted DS which required high operating pressure for the regeneration of DS and separation of pure water.

Figs. 6 and 7 shows the percent rejection performance of RO membranes for the feed condition II i.e. 4000 mg/L. Under feed condition II, the filtration test using Filmtec membrane showed minimum 95% salt rejection with the cartridge filter (CF-RO) and 97% salt rejection with ultrafiltration (UF-RO) as a pre-treatment was observed with a maximum permeate TDS of 186 and 110 mg/L, respectively (Fig. 6).

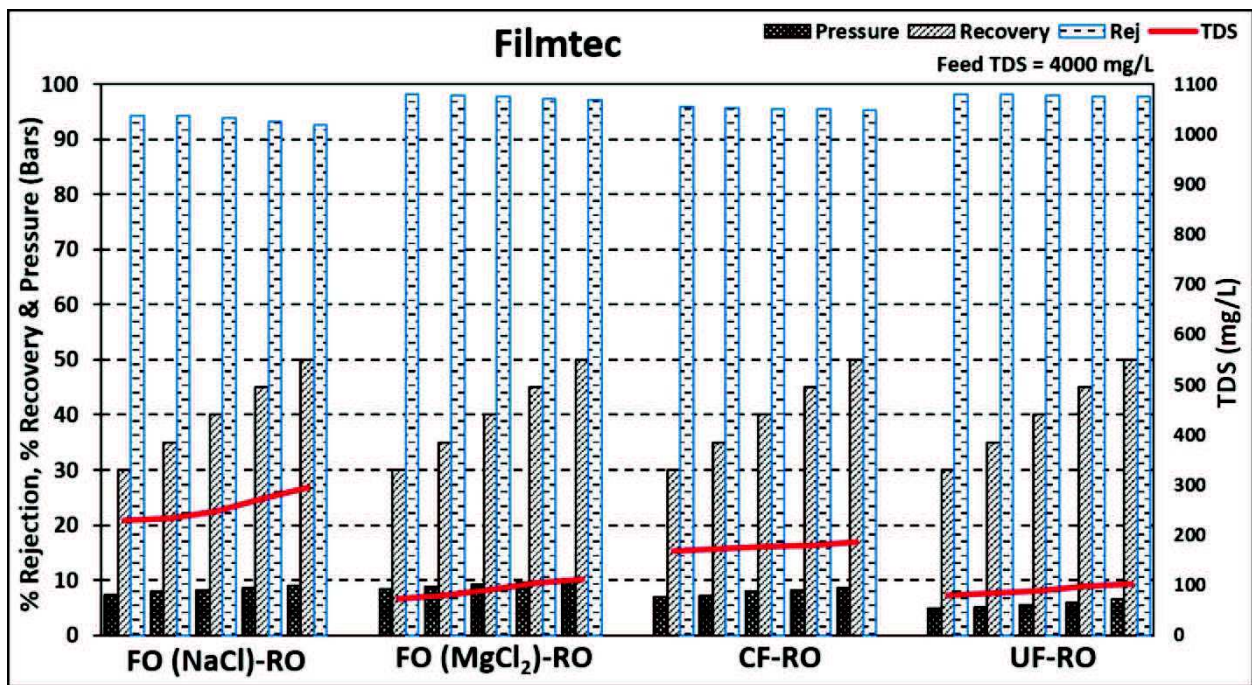


Fig. 6 Rejection and TDS at different recoveries and pressure for FO-RO, UF-RO & CF-RO system along with Filmtec membrane.

Increased feed water TDS inversely effects rejection performance of RO membranes with all the pre-treatment options. Major decline in rejections was observed in FO-RO with NaCl as DS followed by CF-RO combinations using Hydranautics membrane. The significant increase in permeate TDS in FO-RO with NaCl as DS was due to presence of mono-valent ionic structure of NaCl and consequently its poor rejection (Fig. 7).

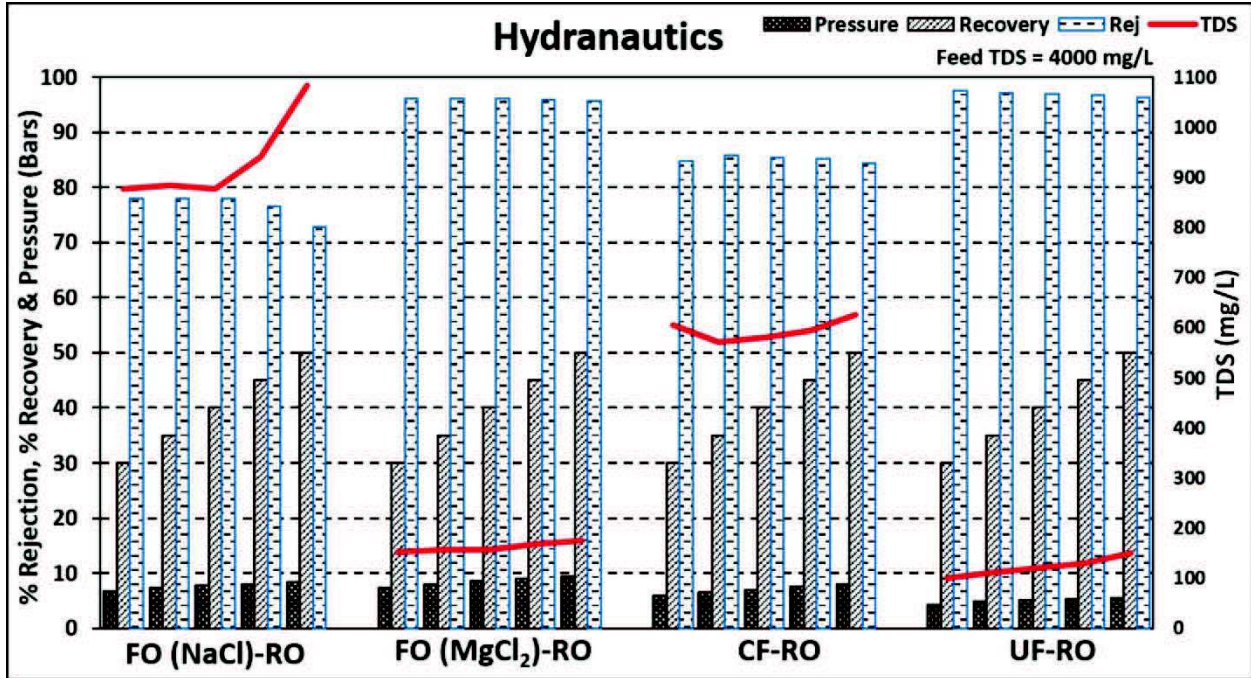


Fig. 7 Rejection and TDS at different recoveries and pressure for FO-RO, UF-RO & CF-RO system along with Hydranautics membrane

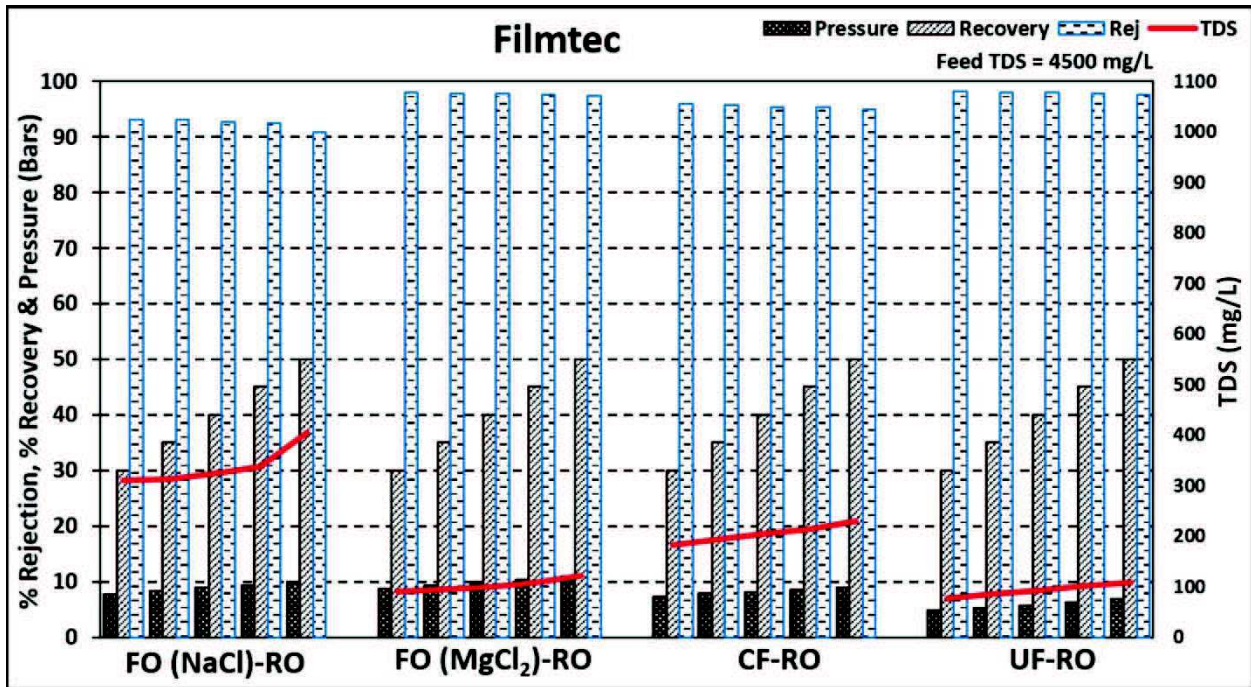
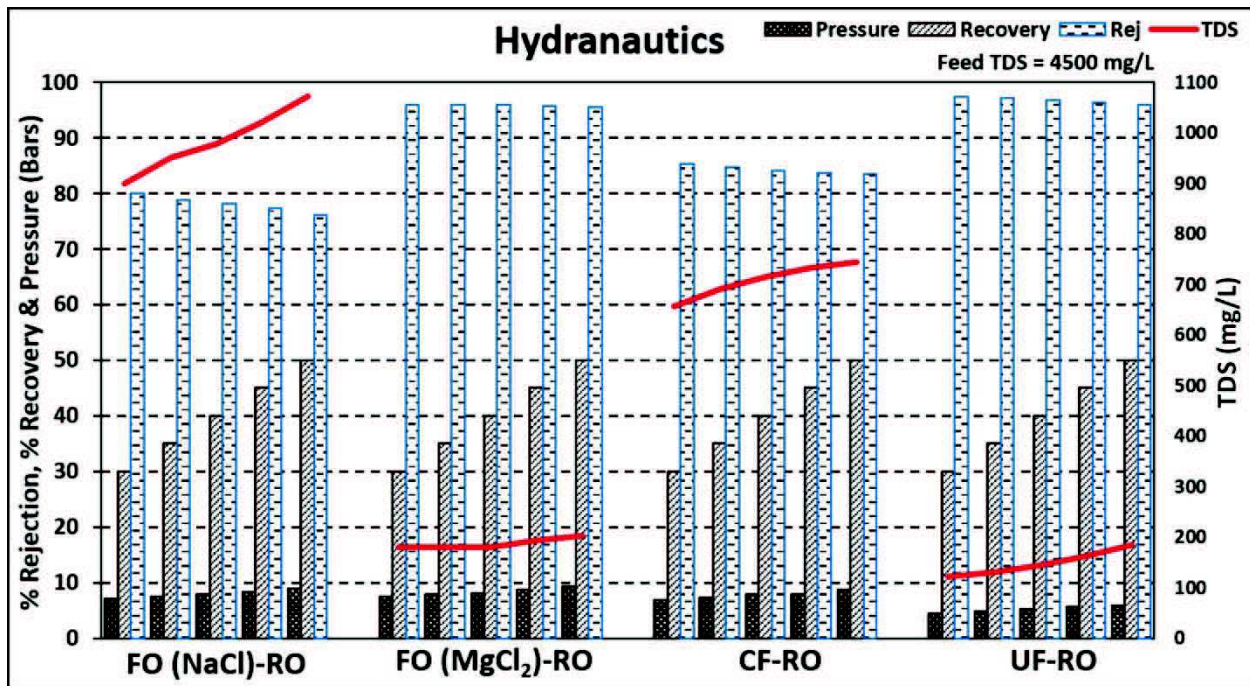


Fig. 8 Rejection and TDS at different recoveries and pressure for FO-RO, UF-RO & CF-RO system along with Filmtec membrane.

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4 1 Despite high rejection efficiency of UF-RO as compared with CF-RO and FO-RO (MgCl₂ as
5 2 DS), UF being high pressure pre-treatment option may experience high fouling tendency over
6 3 long term operation as compared to FO operated under natural osmotic concentration gradient.
7 4 Zaviska et al. [29] reported that the fouling potential of UF membrane was higher as compared
8 5 with FO membrane due to its high pressure application and less removal of scaling agents (i.e.
9 6 sulfate and carbonate).
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11 8 Figs. 8 and 9 shows the percent rejection performance of RO membranes for the feed condition III
12 9 i.e. 4500 mg/L. Under feed condition III, pressure drop and decline in flux across the UF membrane
13 10 was observed over the passage of time for high TDS feed condition indicating its fouling
14 11 characteristics. On the contrary, FO-RO arrangement with MgCl₂ as DS offered relatively lower
15 12 pressure drop and sustained flux. FO membrane operation offers limited deposition of scaling and
16 13 fouling agents and extracts water under natural gradient which results in reversible, uncompact
17 14 fouling on membrane surface due to concentration polarization only [29]. Furthermore, fouling on
18 15 FO membrane surface does not significantly affect membrane flux due to its uncompact structure
19 16 and can be easily removed by rinsing with di-ionized (DI) water [29].



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18 **Fig. 9** Rejection and TDS at different recoveries and pressure for FO-RO, UF-RO & CF-RO
19 system along with Hydranautics membrane.

20 Considering all three feed TDS conditions, the optimum water recovery was found to be 40% for
21 Hydranautics membrane and 45% for Filmtec membrane. It was also observed that the initial
22 permeability i.e., permeability for pure water (DI water) of both membranes decreased during the
23 filtration test with brackish water, although no irreversible fouling was observed after each test
24 with forward membrane flushing. Teychene et al. [33] reported that 30% decrease in permeability
25 for Energy-Saving Polyamide-Boron (ESPAB) membrane while an average 10% decrease for
26 other sea and brackish water membrane was observed. On average, our study revealed 13%
27 decrease in permeability for Filmtec membrane whereas 10% decrease in permeability for

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4 1 Hydranautics membrane over two-hour operation due to concentration polarization on the
5 2 membrane surface.

7 3 4. Conclusions

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9 5 Ultrafiltration (UF) and Forward Osmosis (FO) was found as an effective pre-treatment with less
10 6 fouling characteristic to avoid membrane cleaning frequencies but at high operating cost in term
11 7 of high operating pressure for UF and MgCl₂ as DS for FO process. Operating cost of FO can be
12 8 justified for the brackish water having complex constituents and varying concentrations posing
13 9 high fouling tendencies. MgCl₂ as draw solution presented better results as compared to NaCl due
14 10 to its divalent structure and osmotic potential. Filmtec membrane LC-LE-4040 provided better
15 11 performance than Hydranautics membrane CPA5-LD-4040 over a wide range of pressure and TDS
16 12 conditions. 40 and 45% recoveries for Hydranautics from Filmtec membranes were found as an
17 13 optimum value for all the feed conditions.

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25 17 support for the research project.

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