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Impact of high turbidity on reverse osmosis: evaluation of pretreatment processes

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ABSTRACT

This study evaluates the performance of sand filtration (SF) and ultra-filtration (UF) as pretreatment processes for reverse osmosis (RO) for seawater with turbidities of 4.8, 23.2, and 99.7 NTU. For seawater with a turbidity of 4.8 and 23.2 NTU, the average membrane flux and the water recovery rate in the RO process did not improve significantly by pretreating the seawater using SF or UF. However, when the turbidity of seawater was 99.7 NTU, pretreating the seawater with UF improved the average membrane flux and the water recovery rate in the RO process by 5 LMH and 1.7%, respectively. Pretreatment of seawater with a turbidity of 99.7 NTU with UF reduces the specific energy demand and increases the average membrane flux and water recovery rate.

Keywords: Reverse osmosis; Pretreatment; Ultrafiltration; Sand filtration; Turbidity removal; Desalination

1. Introduction

Around 40% of the world population resides in areas with severe water scarcity [1]. Due to rapid industrialization and population growth, the number of people suffering from water scarcity is expected to reach 60% by 2023 [1]. Currently, almost 95 million m^3 of potable water is being produced from seawater, using around 15,906 desalination plants distributed all over the world [2,3]. Nearly 70% of these desalination plants use reverse osmosis (RO) membrane technology [2,4]. The RO process has several advantages such as high recovery rate, high rejection to solutes, the capability to desalinate a wide range of feed salinities, and moderate energy requirements compared to the thermal processes. Despite the advantages of the RO process, it has significant drawbacks represented by membrane fouling [5].

Membrane fouling is caused by the accumulation, deposition, and adsorption of foulants on the membrane surface/pores resulting in a reduced permeate flux and reduced water recovery rate [6]. Consequently, pretreatment methods consisting of breakpoint chlorination, inline coagulation–flocculation, and multimedia filtration have been used [7–9]. Other technologies, including dissolved air flotation (DAF) and sludge blanket clarifiers (SBC) have also been used for inline pretreatment of the feed to RO [10]. However, these practices suffer from drawbacks associated with high chemical usage, high workforce requirement, and high operating cost [11]. Thus, membrane-based processes have been devised as alternatives to conventional pretreatment methods. Chua et al. [12] used microfiltration (MF) and ultrafiltration (UF) for pretreating seawater before the RO process. The initial slit density index (SDI_{15}) of the seawater varied from 6.1 to 6.5. Both UF and MF processes

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were operated with 1–1.4 bar hydraulic pressure. The membrane pore size of UF and MF membrane was 0.01 and 0.1 μm, respectively. After UF and MF, the SDI reduced to 1.2 and 3.0, respectively, which was within the required limit for the RO process [12]. Castaing et al. [13] used submerged MF and UF to pretreat microalgae rich seawater. The membrane filtration was operated using 10, 4.8 kDa, and 0.2 μm membranes. The transmembrane pressure was maintained at 0.3 bar and operated for 180 min. The initial concentration of microalgae and turbidity of the seawater were 30,000 cells/mL and 10.5 NTU. All three tested membranes were able to reduce the microalgae concentration and turbidity by 99% [13]. A pilot-scale study conducted by Xu et al. [14] showed that, the turbidity of seawater could be reduced from 10 to 0 NTU using ultrafiltration. The UF membrane had a pore size of 0.02 μm and the applied pressure in UF was 2.5 bar. Zhang et al. [15] evaluated the performance of UF as a pretreatment process prior to RO for high turbidity seawater desalination. The results showed that UF provided permeate water with high quality regardless of the feed water turbidity, the permeate water SDI was maintained below three. Corral et al. [16] compared the performance of slow sand filtration and microfiltration as pretreatment processes for RO inland desalination. Slow sand filtration always produced permeate water with SDI less than five which was acceptable for RO. However, microfiltration always produced permeate water with SDI less than three that significantly improved the RO performance over the years.

So far, pretreatment processes for the RO process have been studied for seawater with low turbidities. However, the Arabian Gulf, from which 47.5% of the total desalinated water of the world is produced, suffers from poor water quality in terms of high salinity and high turbidity. Besides, the Arabian Gulf suffers from red tide phenomena. The red tide or harmful algal bloom is caused by the proliferation of toxic algae species [17]. The Arabian Gulf is shallow, semi-closed, and surrounded by arid regions. This results in higher salinity of the water [18]. The high salinity and the warm waters of the Arabian Gulf intensify the growth of the harmful algal bloom [19]. The regular outbreak of the red tide increases seawater turbidity in the Arabian Gulf and the 4,826 desalination plants that depends its water suffer from excessive membrane fouling [2].

Most of the previous studies investigated only the performance of the pretreatment process without studying the full hybrid system. This study investigates the efficiency of multimedia sand filtration (SF) and ultrafiltration (UF) for the treatment of seawater of varied turbidity before reverse osmosis as a hybrid system. Seawater with turbidities of 99.7, 23.2, and 4.8 NTU was used as feed for the RO process using SF and UF pretreatment. The recovery rate and water flux of the hybrid SR-RO and UF-RO systems were compared with those for the RO process without pretreatment. Moreover, the energy consumption in the RO, SF-RO, and UF-RO processes was investigated.

2. Materials and setup

2.1. Feed solution

Table 1 summarizes data collected from a reverse osmosis pilot plant in Qatar. Table 1 shows the average, maximum, and minimum turbidity values recorded for each month for 1 y. It can be seen from Table 1 that the turbidity of seawater is relatively low all year long with an average value around 4.8 NTU. However, in February and March the average turbidity is higher than the other months of the year with an average value of 23.2 and 8.3 NTU, respectively. It can be also seen from Table 1 that the maximum values of turbidity are high all year long with an average value of 76.1 NTU. Table 1 shows that the turbidity of seawater in the Arabian Gulf is highly variable where the turbidity values range between 0.4 and 99.7 NTU. Therefore, the impact of the changing turbidity of seawater on the RO process was investigated. The feed solution for the RO system was seawater with different initial turbidity values. Real seawater samples were collected from a beach in Doha. Three different initial turbidities, namely, 23.2 NTU (i.e., most frequent value), 4.8 NTU (i.e., average value), and 99.7 NTU (i.e., maximum value), were attained by adding clay colloidal particles into the collected seawater. The characteristics of the collected seawater along with the standard method of measurement are summarized in Table 2.

2.2. Experimental setup

Multimedia sand filtration and ultrafiltration have been used for the pretreatment of the reverse osmosis feed solution. Figs. 1a and b show the schematic diagram of the multimedia sand filter and the ultrafiltration system, respectively. Fig. 1c shows the schematic diagram of the reverse osmosis system.

The multimedia sand filter consists of 10 cm of activated carbon (anthracite) (0.8–1.6 mm), 23.2 cm of coarse sand (0.71–1.18 mm), 23.2 cm of fine sand (0.4–0.8 mm), and 5 cm of gravel. The filtration system has a diameter of 10.2 cm and a length of 122 cm. The filter can operate in two modes, the normal run mode and the backwash mode. The mode of operation can be switched by controlling the turbid water valve and backwash water valve. Water is pumped into the system using a single impeller pump (CEAM 70/5, Lowara Co., Italy). The system was backwashed using tap water for 20 min before running the

Table 1
Turbidity of seawater collected over the year

Month	January	February	March	April	May	June	July	August	September	October	November	December	Average
Average	3.4	23.2	8.3	4.7	1.9	3.7	1.3	1.4	1.3	1.4	2.6	4.0	4.8
Maximum	66.0	98.7	99.7	97.7	99.3	94.7	27.9	34.4	99.6	15.7	97.6	81.8	76.1
Minimum	0.7	0.5	0.6	0.4	0.4	0.3	0.4	0.3	0.2	0.4	0.3	0.8	0.4

Table 2
Characteristics of the feed solution (Seawater) to RO

Parameter (unit)	Seawater (feed solution)	Standard Method
Conductivity (mS/cm)	62.1	APHA 23.210 B. Conductivity
TDS (g/L)	45.1	APHA 23.240 C. Total dissolved solids dried at 180°C
Na^+ (ppm)	12,952.6	APHA 4.8120 metals by plasma emission spectroscopy
Cl^- (ppm)	22,184.87	

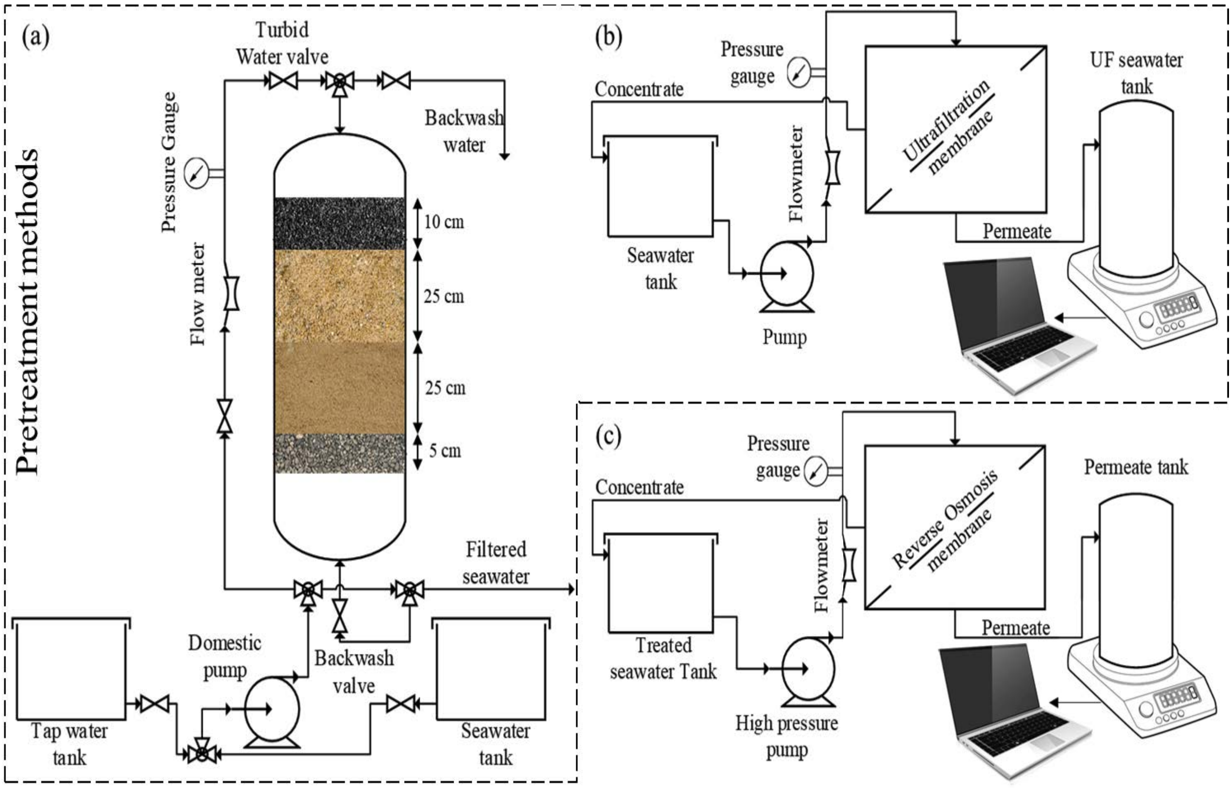

Fig. 1. Schematic diagram of (a) multimedia sand filter, (b) ultrafiltration, and (c) reverse osmosis setup.

multimedia filter. Then a constant seawater flow to the filter at a flowrate of 2.5 LPM was permitted by opening the turbid water valve. After the filtration stage, water was collected from the effluent sampling port and used as a feed solution in the reverse osmosis system.

A CF042D crossflow cell assembly manufactured by Sterlitec, was used for the ultrafiltration system. The dimensions of the cell were 12.7 cm × 8.4.8 cm × 10 cm with active inner dimensions of 4.6 cm × 9.2 cm. Two tanks were used to store the feed and the permeate solutions. The feed was pressurized using an M-04.8S HYDRACELL pump (24.80 V, 50 HZ, 4.8 PH, 6.7 LPM). The water flow through the system and regulation of the pressure was controlled by a concentrate/back pressure control valve assembly. The flow rates at specific points in the system were measured by flow meters (Sterlitech Site Read Panel Mount Flow Meter, USA). A digital balance (Mettler Toledo—ICS 241, USA) connected to a computer was used for measuring the permeate flux in the system. NADIR PM UP 150 membrane was used in the ultrafiltration process. The applied pressure in the ultrafiltration system was 2 bar. The UF setup was washed for 30 min with distilled water before use for pre-conditioning and removal of any impurities from the surface of the membrane.

The reverse osmosis setup was similar to the UF setup (Fig. 1c). A SW30HR membrane was used in the reverse osmosis process (manufactured by DOW chemicals, USA). The applied pressure in the reverse osmosis was 50 bars. Before each run, the setup was washed for 30 min using distilled water for pre-conditioning and removal of any impurities from the surface of the membrane.

3. Results and discussion

3.1. Removal of turbidity by multimedia sand filtration and ultrafiltration

The turbidity removal performance of multimedia sand filtration (SF) and ultra-filtration (UF) was evaluated for seawater with turbidity of 4.8, 23.2, and 99.7 NTU. In sand filtration, the flowrate of the feed was 2.5 LPM and the pressure was 0.5 bar. In the ultra-filtration process, the flowrate was 2.5 LPM and the pressure was 2 bar. The results from the pretreatment processes are summarized in Table 3.

Table 3 shows the turbidity of seawater after SF and UF. When the initial turbidity of seawater was 4.8 NTU the turbidity after SF and UF were 4.8 and 2 NTU, respectively. When seawater had initial turbidity of 23.2 NTU, the turbidity after SF and UF was 4 and 1 NTU, respectively. Finally, when the turbidity of seawater was 99.7 NTU the turbidity after SF and UF were 12 and 2 NTU, respectively. Both systems showed high efficiency in reducing the high turbidity of seawater. The multimedia sand filter can remove colloidal particles larger than 15–20 μm [20]. Whereas ultrafiltration can remove colloidal particles larger than 5–20 nm [21]. The performance of the RO system was evaluated using sand-filtered, ultra-filtered, and untreated seawater.

3.2. Reverse osmosis

The untreated seawater (SW) along with sand filtrated seawater (SFSW) and ultra-filtrated seawater (UFSW) were used separately as feed solution to the RO process. The reverse osmosis process was operated at a pressure of 50 bar and a feed flowrate of 3 LPM for 240 min.

Fig. 2 shows the average membrane flux obtained from the RO process using SW, SFSW, and UFSW as a feed solution (FS). According to Fig. 2, when seawater with turbidity of 4.8 NTU was the feed in the RO process, the obtained average membrane flux was 22.0 LMH. When the same seawater was filtered using SF and UF then used as feed to the RO process, the average membrane flux in the RO process was 21.2 and 21.8 LMH for the SFSW and UFSW, respectively. When seawater with turbidity of 23.2 NTU was the feed in the RO process, the obtained average membrane flux was 20.9 LMH. When the same seawater was pre-filtered using SF and UF the average membrane flux in the RO process was 20.8 and 20.9 LMH, respectively. The results show that at turbidities of 4.8 and 23.2 NTU sand filtration and ultrafiltration have almost no impact on the improvement of the RO process. However, when seawater with turbidity of 99.7 NTU was the feed in the RO process, an average membrane flux of 17.5 LMH was obtained. Pretreated FS with SF and UF increased the average membrane flux in the RO process to 18.7 and 22.5 LMH, respectively. This is because when the turbidity of the seawater is high, excessive fouling occurs on the membrane surface which is expected to reduce the membrane flux. After SF and UF, the turbidity of the SW was reduced to 12 and 2 NTU, respectively. At lower turbidity less fouling occurs, hence, the membrane flux is sustained for longer. The fouling of the RO membrane can be confirmed by the SEM images. Fig. 3 shows SEM images of the active layer of the RO membrane at different initial turbidities of seawater. Fig. 3a shows the clean RO membrane surface. Figs. 3b–d show the active layer of the RO membrane surface after filtering different seawaters with an initial turbidity of 4.8, 23.2, and 99.7 NTU, respectively. It can be noticed from Figs. 3b–d that, when the turbidity of the feed solution increases, the accumulation of foulants on the membrane surface increases. However, Figs. 3e and f show that pretreating the seawater with turbidity of 99.7 NTU using sand filtration and ultra-filtration decreases the fouling propensity of the RO membrane.

Table 3
Characteristics of the pre-treated feed solution using sand-filtration and ultrafiltration

Pretreatment	Sand-filtration			Ultrafiltration		
Initial turbidity (NTU)	4.8	23.2	99.7	4.8	23.2	99.7
Final turbidity (NTU)	4.8	4	12	2	1	2
Turbidity removal (%)	0	84	88	59	96	98

3.3. Water recovery from feed solution

The water recovery rate (%R) in the RO system is calculated using Eq. (1) [22]:

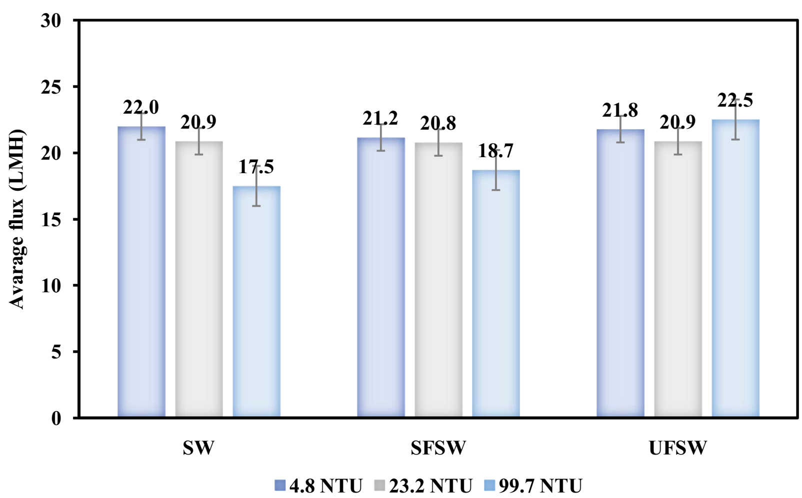

Fig. 2. Average RO membrane flux seawater with different turbidities before and after pretreatment.

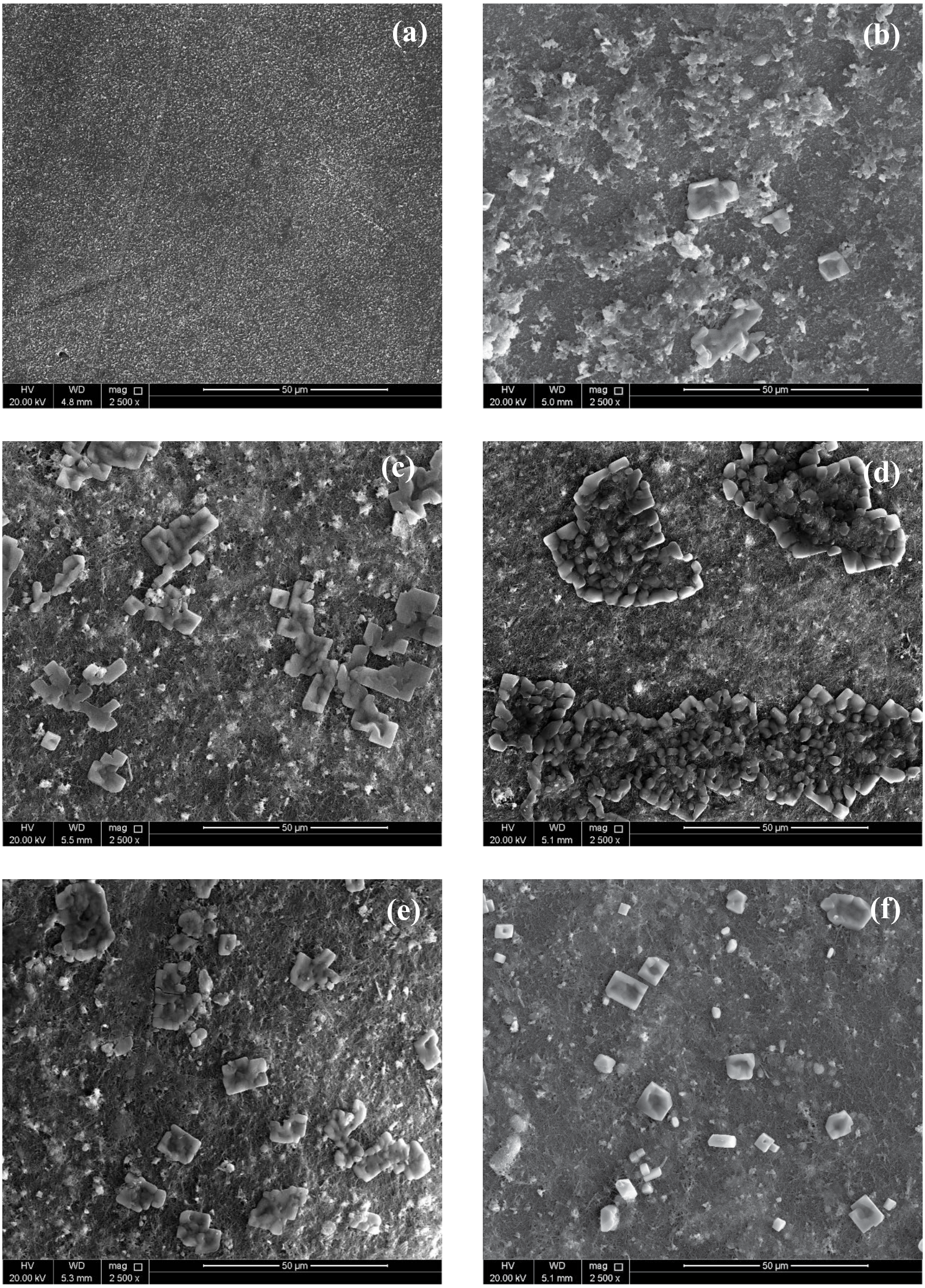

Fig. 3. SEM images of (a) clean RO membrane, RO membrane after RO process using seawater with a turbidity of (b) 4.8 NTU, (c) 23.2 NTU, (d) 99.7 NTU as feed and the active layer of RO membrane after RO process using, (e) sand filtered seawater (99.7 NTU) and (f) ultra-filtrated seawater (99.7 NTU).

$$\%R = \left(\frac{V_P}{V_F}\right) \times 100\% \quad (1)$$

where V_P and V_F are volume of the permeate and the feed, respectively. Fig. 4 shows the recovery rate for the RO process using untreated seawater, sand filtered seawater, and ultra-filtered seawater. When seawater with turbidity of 4.8 NTU was used as FS, the water recovery percentage from the RO process was 9.6%. Pretreating the 4.8 NTU seawater with SF and UF did not improve the recovery rate in the RO process significantly and resulted in 9.6% and 9.5% water recovery, respectively. When seawater with turbidity of 23.2 NTU was the feed to the RO process, the water recovery rate was 8.8%. Pretreating the 23.2 NTU seawater with SF and UF slightly improved the recovery rate by 0.5% and 0.6%, respectively. When seawater with turbidity of 99.7 NTU was used as FS, the water recovery from the RO process was 7.8%. Pretreating the 99.7 NTU seawater with SF and UF improved the recovery rate by 3% and 1.7%, respectively. This enhancement in the recovery rate is due to the reduction of turbidity after the used pre-treatment process. However, to further evaluate the performance of the pretreatment processes energy consumption of the combined systems has been performed.

3.4. Energy consumption

The specific power consumption is calculated for the RO, UF, and SF systems using Eq. (2) [23]:

$$E_s = \frac{P_f \times Q_f}{n \times Q_p} \quad (2)$$

where E_s is specific power consumption in (kWh/m$^{4.8}$), P_f is the feed pressure (bar), n is the pump efficiency, Q_f is the feed flow rate (L/h), and Q_p is the permeate flow rate (L/h). Fig. 5 shows the energy consumption of the reverse osmosis (RO) process, sand filtration-reverse osmosis (SFRO), and ultra-filtration-reverse osmosis (UFRO) for seawater with the three different turbidities. When the seawater with turbidity of 4.8 NTU is used, the specific energy consumption is 6.51 kW/m^3. Using sand filtration as pre-treatment did not increase the energy consumption of the process. However, using ultra-filtration as a pretreatment process increases the overall energy consumption of the process to 7.10 kW/m^3. The extra energy needed for the ultra-filtration process is responsible for the increased specific energy demand of UFRO. It is to be noted that, the water recovery rate was not improved by ultrafiltration when the turbidity of seawater was 4.8 NTU. When seawater with turbidity of 23.2 NTU was the feed in the RO process, the specific power consumption is 7.10 kWh/m^3. Using SF before RO reduced the specific energy demand by 5.5%. However, using UF before RO did not affect the specific energy demand significantly. The energy demand in SFRO was lower because the water recovery rate after SF was higher. On the other hand, the energy demand in UFRO was higher because of the extra energy consumed by the UF process. When seawater with turbidity of 99.7 NTU was used, the specific energy demand for RO was 7.44 kWh/m^3. After combining the RO process with SF and UF, the energy demand was reduced by 4.6% and 16.0%, respectively. For the RO process, specific energy consumption increased with increasing turbidity. However, the increased water recovery rate from SFRO and UFRO reduced the energy demand significantly.

Although the average specific energy consumption of the RO process decreased when it is coupled with the SF, the average membrane flux and water recovery rate does not improve significantly. On the other hand, the specific energy consumption increased when the UF is used to pretreat seawater with turbidity of 4.8 and 23.2 NTU. But the average membrane flux and water recovery rate increases after pretreatment. Moreover, pretreatment of seawater with turbidity of 99.7 NTU with UF reduces the specific energy demand and increases the average membrane flux and water recovery rate.

4. Conclusions

In this paper, seawater with turbidities of 4.8, 23.2, and 99.7 NTU were treated using reverse osmosis (RO),

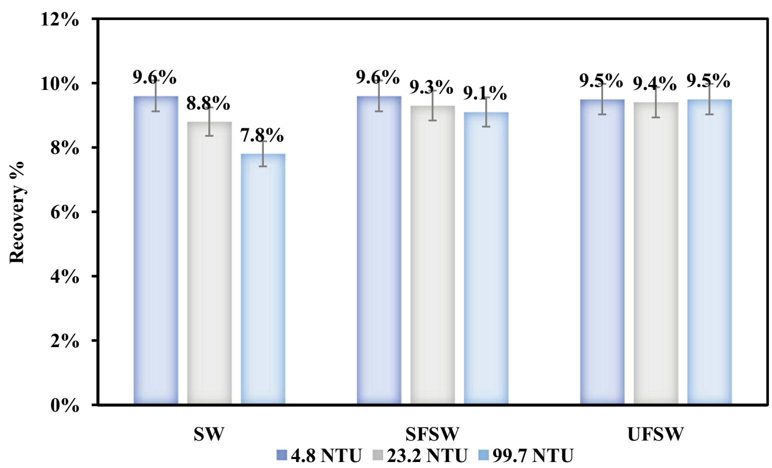

Fig. 4. Recovery rate using different feed solutions in RO.

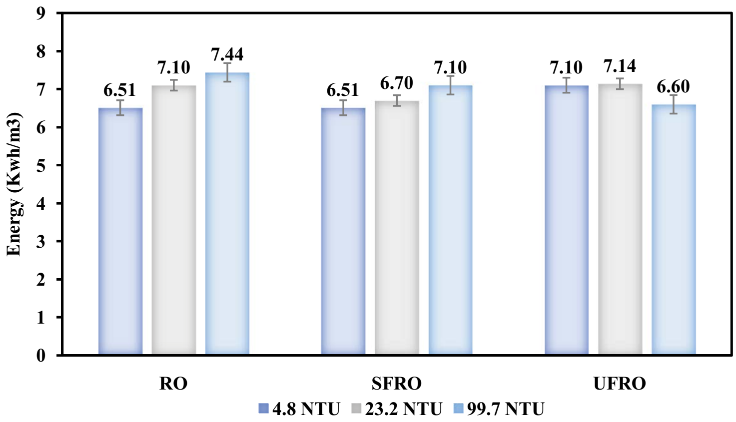

Fig. 5. Energy consumption during pre-treatment of feed solution.

sand filtration (SF) coupled with RO, and ultra-filtration (UF) coupled with RO. When the turbidity of seawater was 4.8 NTU, the average membrane flux and the water recovery rate did not improve after pretreatment with SF and UF. When the turbidity of seawater was 23.2 NTU, the average membrane flux in the RO process did not improve significantly; however, the water recovery rate increased by 0.5% and 0.4% after pretreatment with SF and UF, respectively. When the turbidity of seawater was 99.7 NTU, pretreatment by UF improved the average membrane flux by 5 LMH and the water recovery rate by 1.1%. Energy analysis showed that pretreatment of feed solution using SF and UF increased the specific energy of the system when the seawater had an initial turbidity of 4.8 and 23.2 NTU. However, at a high turbidity value of 99.7 NTU, the specific energy consumption decreased by 11.3% when the RO process was coupled with ultra-filtration and 4.6% when the RO process was coupled with sand filtration.

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