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Application of ceramic membranes for seawater reverse osmosis (SWRO) pre-treatment

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ABSTRACT

Low-pressure (microfiltration/ultrafiltration (MF/UF)) membranes are being increasingly used as pre-treatment, prior to seawater reverse osmosis (SWRO). The objective of pre-treatment before reverse osmosis (RO) membranes is to remove undesirable and particulate fouling materials (algae, suspended and colloidal particles). Also, a pre-treatment barrier reduces organics and provides better feed water quality for RO membranes. MF and UF pre-treatment prior to SWRO provides Low Silt Density Index (SDI) values recommended for RO operation. Ceramic membranes are more attractive as they made of more chemically resistant materials, which allow for more stable operation and aggressive backwashing (BW) and cleaning.

A pilot plant with a monolith ceramic MF membrane (0.1 μm pore size) from METAWATER was used to carry out the study. Red Sea water pumped from a distance of 700 m offshore from Thuwal (Kingdom of Saudi Arabia) was used as feed water. The pilot plant was operated automatically at constant flux of 150 LMH that involved BW, air flushing and forward flushing at the end of filtration cycle. Seawater permeates were used for hydraulic BW, while sodium hypochlorite, citric acid and sodium hydroxide were used for chemical cleaning (CIP) to restore the membrane permeability after use. Filtration cycles of 2.5 h were adopted for initial experiments. Aggressive BW flux of 1,800 LMH for 15 s, air flushing of 4 bars for 10 s and forward flushing of 300 LMH for 40 s were applied for regular membrane hydraulic cleaning. The increase of membrane resistances over time was monitored. Further studies were also performed by using Anopore ceramic membranes AAO100 (pore sizes of 0.1 μm) using a constant pressure bench-scale set-up. The feed water and permeate were analysed using an SDI unit, flow cytometre (FCM) and liquid chromatography with organic carbon detection (LC–OCD).

The results showed that ceramic membrane filtration reduced the SDI_{15} of seawater from 6.1 to 2.1 which conform to the requirement of $\mathrm{SDI} < 3$ needed for SWRO feed. The removal of bacteria corresponded to 3.7 log removal, while turbidity improved from 0.6 NTU (feed) to 0.05 NTU (permeate). However, ceramic membranes showed low recovery after BW and significant increase of trans-membrane pressure (TMP) during operation with the membrane

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alone, without coagulation. This increase of TMP can be related to the presence of sticky polysaccharide-like material called transparent exopolymers particles (TEP) that are known to be in abundance in seawater and contribute to organic fouling and eventually bio fouling. TEP showed resistance and stickiness on the membrane surface (AAO100) even after aggressive BW. This may be responsible for the low flux recovery observed after BW in both bench-scale and pilot experiments.

To improve membrane filtration, coagulation was performed by using iron III chloride. Continuous addition of iron III chloride (4 mg/L Fe) through inline coagulation showed almost complete control of irreversible fouling and reduces reversible fouling after 30 h of operation, based on 2.5 h intervals of filtration cycle. Also, biopolymers removal improved to 51–71%, with improved removal at low pH, while for stabilization of flux, a dose of 1 mg/L Fe^{3+} was sufficient. Reduction of high molecular weight Natural organic matters (NOM) is essential for controlling or reducing irreversible fouling. Therefore, coagulation is recommended for smooth operation of ceramic membranes and for provision of low-fouling feed water, prior to SWRO membranes.

Keywords: Ceramic membranes; Membrane resistance; Silt Density Index (SDI); Fouling and flux recovery

1. Introduction

Seawater reverse osmosis (SWRO) is still expensive process due to excessive use of energy during operation and later fouling development [1]. The performance of SWRO membranes highly depends on the excellency of pre-treatment methods [2]. Conventional pre-treatment methods are still dominating in desalination [3]; however, the use of integrated membrane systems in cooperating low pressure membranes (LPM) seemed to be the best option for SWRO pre-treatments [4]. The purpose of pre-treatment is to provide better and stable feed quality water to reverse osmosis (RO) membranes [5] with less potential of fouling [6].

Fouling of SWRO membranes can take place in the form of colloidal/particulates, organic, inorganic (scaling) or biological (biofouling) [7]. Adequate pre-treatments can reduce the risk of SWRO fouling, improve production and reduce the frequency of chemical usage for membrane cleaning [8]. Normal colloidal and particulate matters, if not well eliminated with pre-treatment, tend to stay on the membrane surface and form cake layer fouling [9]; dissolved organic may cause pore blocking, which is the worst form of fouling [6]. Natural organic matters (NOM) also facilitate bio fouling in the presence of bacteria [10]. Scaling is not a common problem to LPM, but is severe problem to high-pressure membranes.

Almost all membranes customers adopt Silt Density Index (SDI) as a measure of feed water needed for RO membranes. SDI measurement is covering the colloidal and particulate retained in the 0.45-μm filters. The SDI range of 4–5 is acceptable, although for smooth performance of RO membranes, SDI of <3 is preferable [11]. Colloidal and particulate fouling can be easily controlled in LPM by hydraulic backwashing (BW). But the most challenging form of fouling in LPM is organic fouling, which is difficult to be removed and eventually cause irreversible fouling. The rest of the dissolved organic matters that escape from pre-treatment step are considered as a threat to RO membranes. Thus, organic fouling is a major problem for both low-pressure and high-pressure membranes.

The efficient use of LPM can be achieved by combining their uses with other pre-treatment techniques, like coagulation. Coagulant doses of iron III chloride ranged between 1 and 10 mg/l as Fe are commonly used, which depends on the quality of feed water [12]. Coagulation process in LPM system is typically targeting colloidal particles and NOM removal [3]. The advantages of hybrid pre-treatment process are enhancement of removal of dissolved organic, maintaining of stable long operation of LPM and reduction in fouling [8]. Ceramic membranes nourished with inorganic materials may be the best option due to high production supported by high flux operation [13].

Seawater, unlike surface water, are known to have massive contents of transparent exopolymers particles (TEP) with sticking behaviour [14] that make low-pressure membrane to suffer more from fouling. This kind of polysaccharide organics are evidenced to be very problematic, since they cannot be easily removed with BW. The nature of TEP allows them to stay on the surface of membranes or penetrate through the LPM pores, when vertical inclined [15].

LPM are also known to be good in removal of micro-organisms, like bacteria, due to their molecular weight cut-offs [16]. Bacteria are available in different forms like rod-like, sphere and irregular shapes and because of their flexible nature, some of them may go through the membranes. Seawater is rich in bacteria and therefore adequate removal with pre-treatment method is encouraged to reduce the risk of bio fouling in RO membrane.

This research aimed at assessing the performance of ceramic micro-filtration membranes in terms of SDI improvements, NOM removal and bacteria removal for better feed water quality of SWRO membranes. The study was further focused on improvement of ceramic membrane operation with the aid of coagulation. Bench-scale and pilot experiments were employed to achieve the goal.

2. Materials and methods

2.1. Source water

Red Sea water from the Thuwal area of Saudi Arabia was used to conduct both bench-scale and pilot experiments. The characteristics of the Red Sea water are shown Table 1 below.

The ionic composition of Red Sea water is shown in Table 2.

2.2. Membrane characteristics

Flat-sheet anopore ceramic membranes (AAO100) with a pore size of 0.1 μm and monolith ceramic membrane of the same pore size from METAWATER were used to conduct experiments. Both membranes are hydrophilic and made up of alumina with different fabrications. While the METAWATER membrane was fabricated by sintering at very high temperature, AAO100 membrane was fabricated by electrolysis.

2.3. Coagulant

Iron III chloride ($FeCl_3.6H_2O$), obtained from Aldrich-Sigma Company, was used as a coagulant.

Table 1
Feed water quality–Red Sea water

DOC (mg/l)	1–1.5
UV (cm^{-1})	0.012–0.02
SUVA (L/mg-m)	1.2–1.5
Turbidity (NTU)	2.34 ± 0.12
pH	8.1 ± 0.1
Conductivity (ms/cm)	60–70
TDS (g/l)	30–39
Alkalinity (meq/L) $CaCO_3$	7.6–11

2.4. NOM, membrane characterizations, micro-organisms and fouling assessment

Characterizations of NOM composition was done by using liquid chromatography with organic carbon detection (LC–OCD). Characterization of the membranes focused on TEP visualization. Flat-sheet membranes were stained with alcian blue, a specific dye for acidic polysaccharides, to determine the presence of TEP retained from membrane surface using Epifluorescence microscopy, as described in the protocol at Section 2.6.4. Micro-organisms, in particular bacteria, were analysed using a Flow Cytometer (FCM) from Accuri, as defined in Section 2.6.3.

Fouling was assessed by flux decline (bench scale) and trans-membrane press (TMP) increase (pilot plant). The SDI test was performed according to the ASTM methods (see Section 2.6.1.).

2.5. Experimental set-up

The pilot plant from KWR (the Netherlands), equipped with ceramic microfiltration membrane from METAWATER (Japan), was used to conduct the experiments (Fig. 1). The pilot was operated at constant flux mode with filtration cycles that can be adjusted automatically. The system is equipped with a BW vessel and 4 bar nitrogen gas that is used for operation and air flushing. One cycle of filtration is composed of filtration, BW, air flushing and forward flushing. Filtration cycles of 2.5 h were adopted for initial experiments. An aggressive BW flux of 1,800 LMH for 15 s was applied for regular membrane hydraulic cleaning. This was followed by air flushing of 4 bars for 10 and forward flushing of 300 LMH for 40 s to remove entrapped air. Sodium hypochlorite, citric acid and sodium hydroxide were used for chemical cleaning (CIP) to restore the membrane permeability.

For bench-scale experiments, an Amicon stirred cell was employed (Fig. 2). The feed water was placed in a pressure vessel and nitrogen gas was used to pressurize the feed water through the membrane. The permeate water was collected in a beaker placed on a digital balance, recording the weight of the permeate water.

2.6. Methodology

2.6.1. SDI test

A membrane filters from Millipore (HWAP) with a 0.45-μm pore size was used. After placing the membrane, the pressure of the SDI unit was adjusted to 30

Table 2
Red Sea water ionic strength

Ions	Concentration	Ions	Concentration	Ions	Concentration
Na^+	12,470 mg/L	Cl^-	22,199 mg/L	Br^-	67.8 mg/L
Mg^{2+}	1,436 mg/L	SO_4^{2-}	3,330 mg/L	Silica (as SiO_2)	4 mg/L
Ca^{2+}	527 mg/L	Fe^{2+}	1.0 mg/L	Ba^{2+}	6 μg/L
Sr^{2+}	7.99 mg/L	Cu^{2+}	10 μg/L	Al^{3+}	90 μg/L

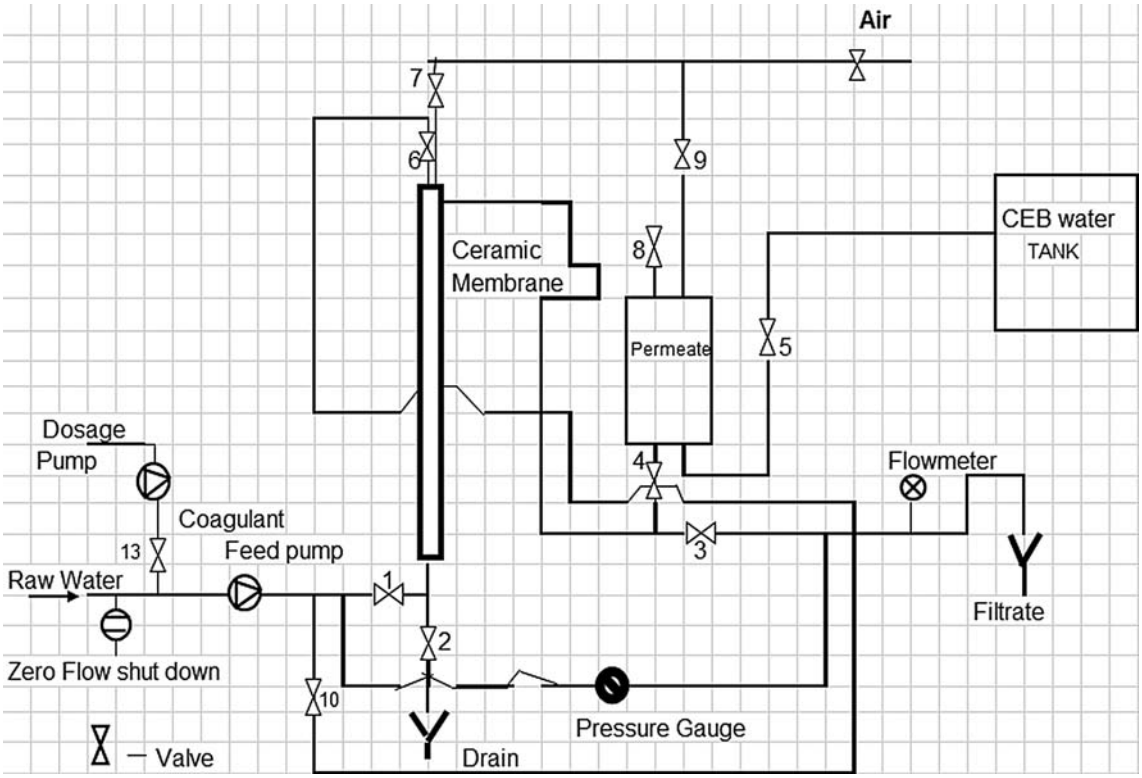

Fig. 1. Layout of the ceramic pilot plant.

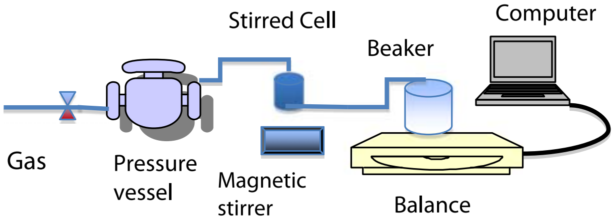

Fig. 2. Schematic layout of amicon stirred cell.

psi (2.1 bars) and pure water was flushed on the membrane for few seconds to check and remove air bubbles in the system, as well as to open the membrane pores. SDI testing was started after satisfying system performance. The time to fill the first filtrate of 500 mL was recorded. More samples of 500 mL were collected after 5, 10 and 15 min of operation and the times taken were recorded to mark the values of SDI_5, SDI_{10} and SDI_{15}. The following equation governs calculations for SDI:

$$SDI = \left[1 - \frac{T_i}{T_{15}}\right] \times 100/15$$

whereas T_i = time used to collect first 500 mL, T_{15} = time used to collect 500 mL after 15 min and the variable number 15 can be changed to 10 or 5 depending on measured value of SDI (SD_{I5}, SDI_{10} or SDI_5).

2.6.2. Coagulation protocol

2.6.2.1. Bench-scale experiments. Two litres of seawater was prepared and 1–10 mg/L Fe coagulant was added as a dose. The solution was then placed in a jar test unit (Phipps & Bird Stirrer). Rapid mixing of 300 rpm was applied for 45 s. The mixing solution was then transferred to the bench-scale system to start filtration. If pH adjustment was needed, then addition of coagulant was followed by addition of sodium hydroxide or hydrochloric acid to set the required pH before starting rapid mixing.

2.6.2.2. Pilot plant. A stock solution of 484 mg/L concentration of $FeCl_3.6H_2O$ was prepared and placed in dosing tank. A dosing rate of 40 mL/min was set using the dosing pump. Then, iron III chloride was dosed inline continuously to the feed pipe that pumped the feed water at a rate of 60 L/h to introduce an equivalent dose of 4 mg/L Fe to seawater that passed through the static mixer before being filtered in ceramic MF. If dose adjustment was required, then dosing rate or concentration of stock solution can be adjusted.

2.6.3. Bacteria protocol

One millilitre (1 mL) of sample was collected from the bulk of the sample. Ten microlitre (10 μL) of Na-EDTA was spiked to the sample and shaken well, followed by warming at 35˚C for 10 min. After warming the sample, SYBR Green I (10 μL) was added and mixed well before warming the sample again for 10 min. The sample was then transferred to the FCM for micro-organism analysis.

2.6.4. TEP protocol

TEP are transparent organic components originating from excretion of phytoplankton, and a special dye, like alcian blue, is needed to stain the TEP and make them visible. Alcian blue solution was prepared by dissolving the alcian blue powder-8GX (ordered from SIGMA-Aldrich) in Milli Q water. Acetic acid was added to the 400 mL of Milli Q to drop the pH to 2.5, before adding 0.1 g of alcian blue powder to make a solution of 0.025%. The fouled membrane was first soaked in water for 1 min and the soaked to the solution of alcian blue for 10 min before being soaked again in Milli Q water for about 5 min and examined with the Epi-fluorescence microscopy for TEP visualization in bright field.

3. Results and discussion

3.1. Measurement of SDI

The quality of feed water prior to SWRO membrane is defined by the SDI value. When SDI_{15} exceeds 4, pre-treatment is necessary [3]. The recommended SDI value for SWRO membranes feed is <3 [17]. The SDI_{15} of Red Sea water was measured and found to be an average of 6.1 after duplicate measurements (Fig. 3). This indicates that Red Sea water needs to undergo pre-treatment process before being used in a SWRO system. Ceramic microfiltration membranes, as a pre-treatment step, managed to lower the SDI_{15} value to an average of 2.1 that is acceptable for SWRO feed (Fig. 3). Hence, ceramic MF membrane achieved the requirements for SWRO feed per recommended SDI values. This complies with other studies that showed that microfiltration systems can reduce the SDI value to less than 3 [18]. Moreover, ceramic membrane filtration improved the turbidity of seawater from 0.6 NTU to 0.05 NTU (permeate).

3.2. Removal of micro-organisms

Micro-organisms are present in dry and wet environments. In water applications, micro-organisms are related to (bio) fouling. The size of bacteria in general ranges between 0.5 and 5 μm. MF and UF membranes can easily remove bacteria without pre-treatment [19]. With limited nutrients, bacteria sizes can be decreased to lower than 0.3 μm [20]. With the availability of nutrients, such as NOM, micro-organisms can multiply significantly and be part of biofilm formation and contribute to bio fouling. Bio fouling is known to be a serious problem for RO membranes, so pre-treatment strategies should focus on reducing or eradicating the

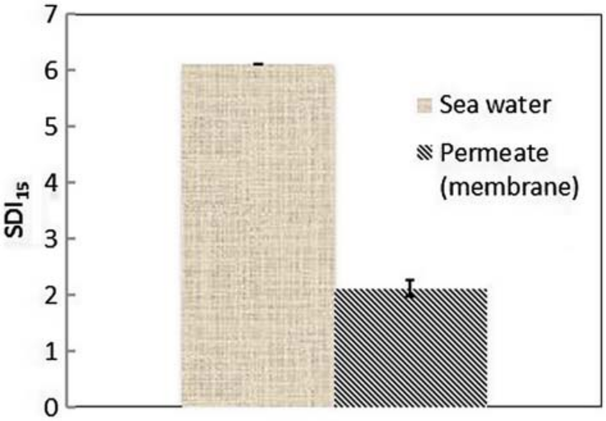

Fig. 3. Silt Density Index (SDI_{15}) measured for feed water (sea) and permeate.

micro-organisms and nutrients responsible for their growth. Several methods for analysing micro-organisms like heterotrophic plate count (HPC) and DAPI staining for Epi-fluorescence Microscopy visualization have been used for decades.

These techniques are just focused on visible colonies and consume considerable time for samples preparation and analysis [21]. Other techniques like real-time quantitative PCR, fluorescence in situ hybridization (FISH) and micro-array are commonly used nowadays [22]. However, FCM is a quick, simple and more accurate method for measuring micro-organisms [21]. This method use light-scattering method to count the number of stained micro-organisms, as describe in the methodology in Section 2.6.3. The figures and table below show micro-organisms removal, as assessed by using a FCM. The population of bacteria found in a Red Sea water is presented in Fig. 4.

Bacteria removal by the membrane alone was 99.23% after 5 min of starting of filtration with suspicious pipe contamination (Fig. 5 and Table 3). When pipes were well flushed with permeate and the fouling started to build up after one hour, bacteria removal increased to 99.98%, which is equivalent to 3.7 log removal (Fig. 6 and Table 3). These results confirm that microfiltration membranes can remove bacteria to a significant level [5]. Ceramic microfiltration system showed even better removal, compared with other research findings that found bacteria removal to be 3.26 log after filtration with a 0.1 μm MF membrane [20]. The removal of total coliforms bacteria from a combined system of plastic media pre-filter (PP) operated at 208 LMH and a hollow fibre microfiltration membrane (0.1 μm pore sizes) operated at 58 LMH was 99% [7], as measured by most probable number (MPN/100 mL) method. Therefore, ceramic membrane filtration showed outstanding performance in removal of bacteria that play a role in bio fouling in RO membranes.

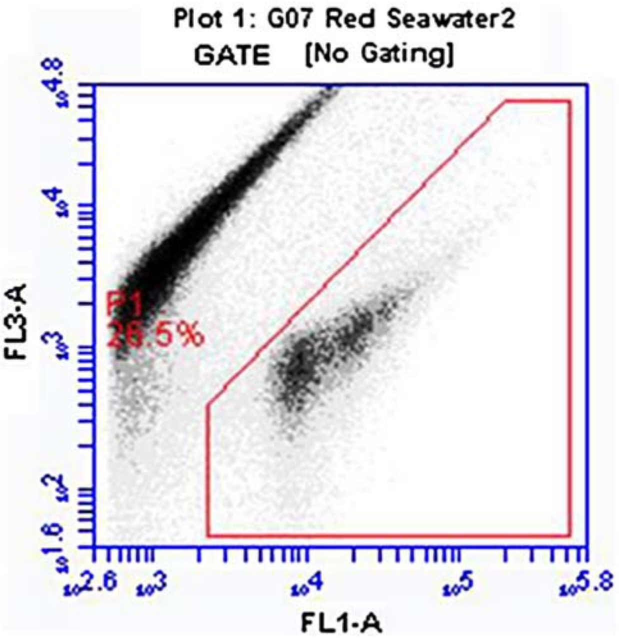

Fig. 4. Feed–Red Sea water.

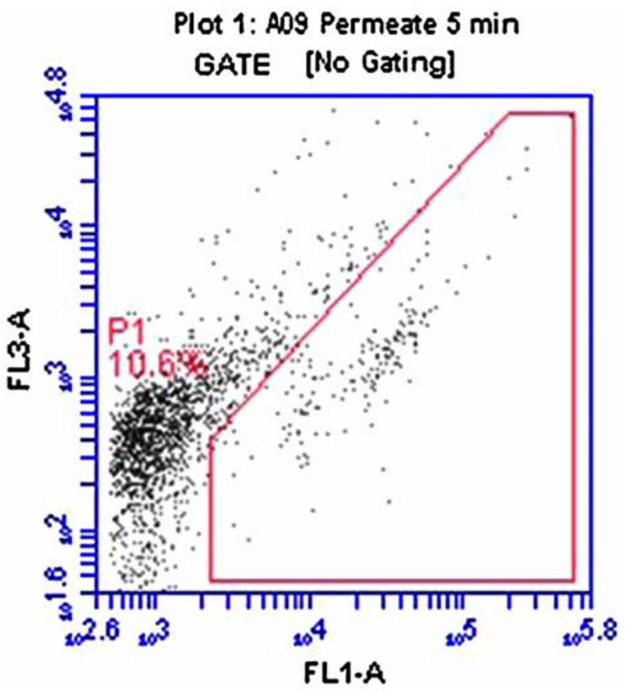

Fig. 5. Permeate after 5 min.

3.3. *Fouling of ceramic membrane: increase in membrane resistances*

The ceramic membrane suffered from fouling, despite good performance on bacteria removal and particulates/colloidal removal. Fig. 7 shows an increase in membrane resistances with low performance of BW, despite using a high BW flux. Membrane resistance was calculated by the following equation:

$$R_m = \frac{\Delta P}{\mu j}$$

where R_m = membrane resistance, J = flux and μ = viscosity of water.

The calculated flux recovery after BW was ranged between 33 and 44%, while membrane resistance

Table 3
Number of bacteria counted per millilitre

	Seawater (No./mL)	Permeate (No./mL) after 5 min	Permeate 2 (No./mL) – after 1 h
Test 1	454,411	3,433	140
Test 2	439,142	3,440	80
Average	*446,777*	*3,437*	*110*

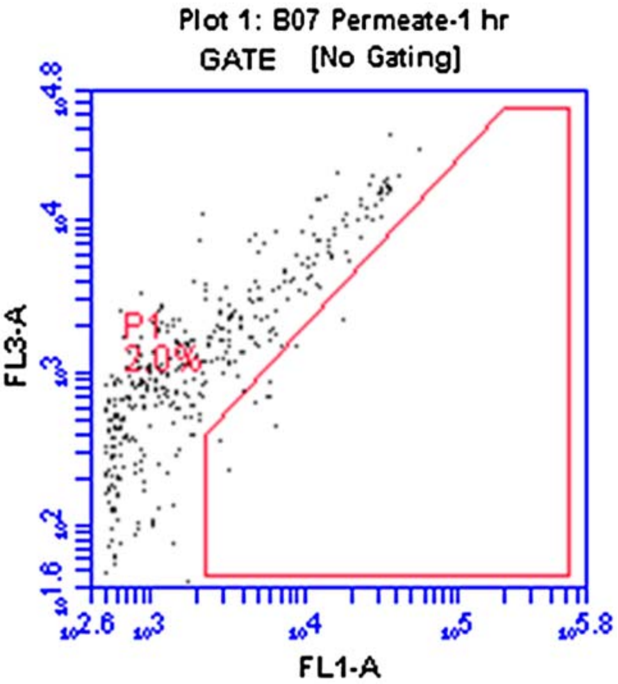

Fig. 6. Permeate after 1 h.

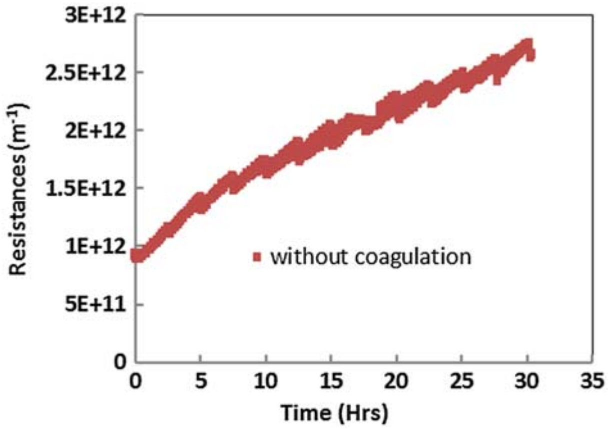

Fig. 7. Seawater filtered with monolith ceramic microfiltration system at constant flux of 150 LMH and BW interval of 2.5 h.

increased from 9.11E+11 to 2.66E+12 after 30 h of operation (Fig. 7). Despite good performance in bacteria removal and achieving the required SDI value, ceramic membranes, like any other membranes, were not exempted from fouling. Previous studies have shown that irreversible fouling can start even at early stage [2]. The dissolved organic compound (DOC) level of seawater is approximately 1 mg/L that raises a question about why BW alone is not effective to restore membrane permeability for seawater. Therefore, further study to assess backwash ability was performed at the bench scale, and membranes were characterized in particular to determine the fate of TEP before and after BW using Epi-fluorescence microscopy, as discussed below.

3.4. Assessments of BW performance and membrane characterization—Bench scale

Bench-scale experiments at constant pressure (0.2 bars) using flat-sheet ceramic microfiltration membranes (AAO100) were performed to further study BW and factors influence low performance of BW of ceramic membranes in seawater filtration. The membrane surface before and after BW was analysed. After the AAO100 membrane was backwashed at a high

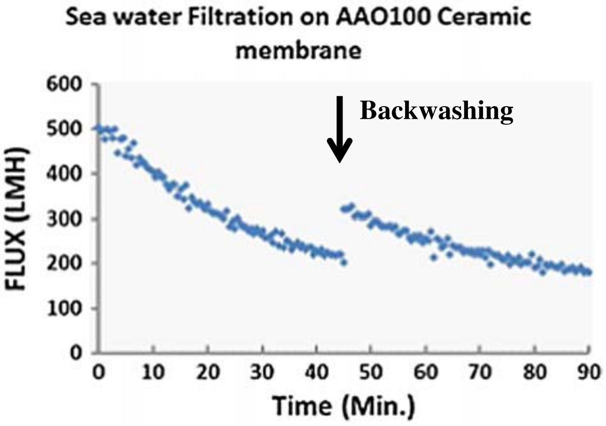

Fig. 8. Seawater filtration and BW.

flux of 1,500 LMH for 2 min, a flux recovery of 33% was achieved (Fig. 8).

When the membranes before and after BW were analysed by Epi-fluorescence microscopy (Figs. 9 and 10), the results revealed that TEP were persistent and remained attached tightly to the membrane surface even after aggressive hydraulic BW with Milli Q water. Dissolved organic matter originating from algae (like TEP) and humic substances have been identified as the cause of fouling in SWRO membranes [12]. Therefore, these qualitative results suggest that TEP is a major cause of low backwash ability of ceramic membranes that may increase operational cost and maintenance cost, due to increasing of frequency of chemical cleaning.

In addition, the effectiveness of BW depends on the BW flux. The results in Fig. 11 shows that the Anopore membrane (AAO100) operated at a constant pressure of 0.1 bar showed negligible flux recovery (3%) when backwashed with twice the pressure (0.2 bars). When the BW pressure was increased to five times and 10 times (0.5 and 1 bars), the flux recovery increased to 13 and 34%, respectively.

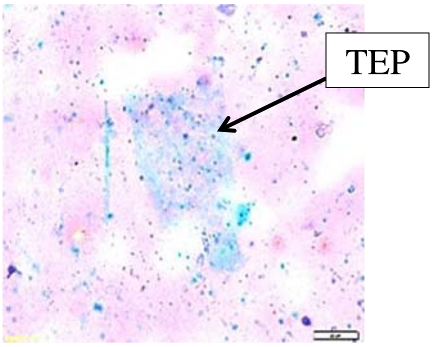

Fig. 9. TEP on AAO100 after Red Sea water filtration.

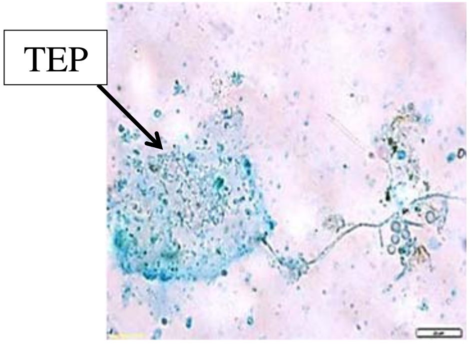

Fig. 10. TEP on AAO100 after BW with Milli Q water.

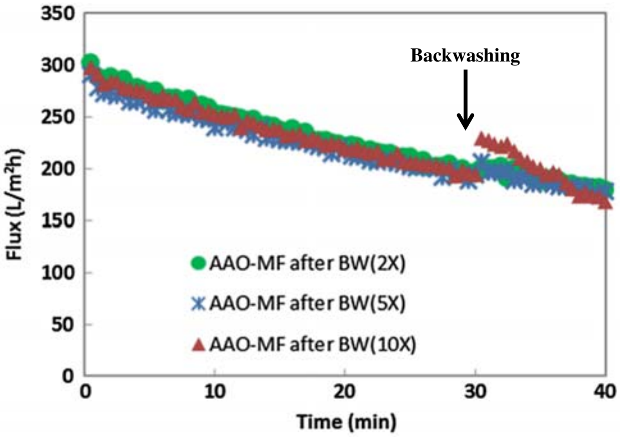

Fig. 11. Influence of BW flux on flux recovery (AAO100)–Seawater filtration.

3.5. Coagulation optimization: dose and pH using iron III chloride

The optimum dose and pH for coagulation (Iron III chloride) was determined by bench-scale experiments under constant pressure mode. The study was focused on removal of high molecular weight NOM (biopolymers and humic substances). The DOC level of Red Sea used to conduct experiments was 1.12 mg/L, including biopolymers content of 0.143 mg/L and humic substances of 0.39 mg/L, as measured by LC–OCD.

The optimum dose of coagulant was found to be 4 mg/L Fe^{3+} as there were no significant changes observed in terms of biopolymers and humic substances removal above this dose (Fig. 12). Previous studies have shown that Iron III chloride removed

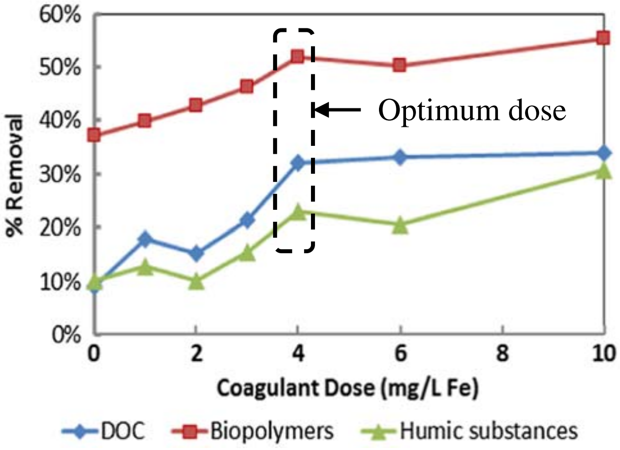

Fig. 12. High molecular weight NOM removal from ceramic anopore MF membrane (AAO100) at different coagulant doses (Jo ≈ 500 LMH)–Bench.

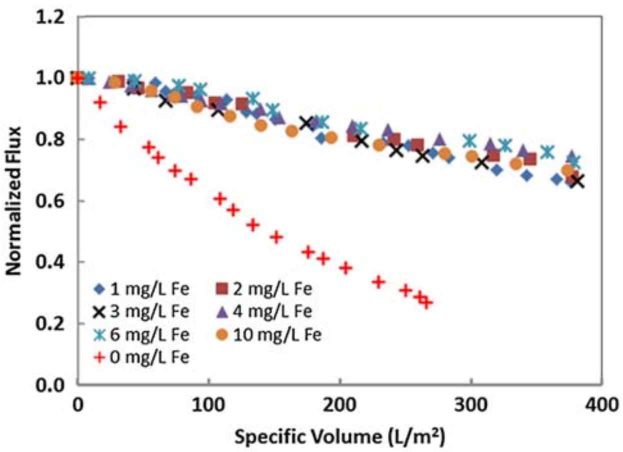

Fig. 13. Flux decline of AAO100 membranes at different coagulant doses—Seawater.

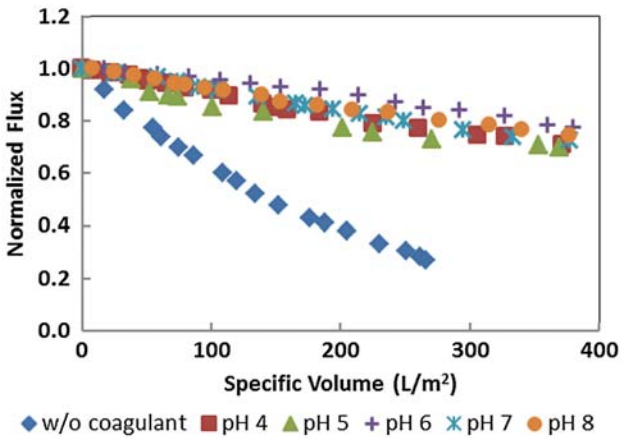

Fig. 14. Flux decline of AAO100 membranes at different pH conditions with 4 mg/l Fe coagulant.

more biopolymers than humic substances [1]. However, this study showed that both biopolymers and humic substances from seawater are moderately removed by coagulation combined with ceramic membranes.

Flux decline improved significantly when iron coagulant was used even at a low dose of 1 mg/L Fe (Fig. 13). When the optimum dose was tested at different pH conditions, the removal of biopolymers and humic substances was increased as the pH decreased. The removal was significantly increased for humic substances from 20% at pH 8–60% at pH 4 (Table 4). Also, biopolymers removal increased from 55% at pH 8–71% at pH 4 (Table 4). Removal mechanisms are pH dependent; at low pH, precipitation is dominant, while at high pH, the adsorption mechanism is dominant [23]. Coagulation causes compression of the electrical double layer and aggregating the particles and increases the possibility of removal for both NOM and particles [12]. The study conducted by [24] using humic acid as a model contaminant confirms that the removal of humic acid depends on coagulant dose and pH.

Acidic conditions for the feed water not only have an advantage in the coagulation process (i.e. removal of high molecular weight NOM), but can also play an important role in reducing scaling in RO system. The flux decline based on pH trends was not significant (Fig. 14). Low flux decline was observed at pH 6. Therefore, it can be concluded that the coagulation process at pH 4–5 improved the removal of high molecular weight NOM, in particular humic substances, and yet maintains the flux decline close to a minimum value obtained at pH 6.

3.6. Inline coagulation with pilot plant

The optimum dose of 4 mg/l Fe^{3+} obtained from bench-scale experiments was adopted for pilot-scale experiments. The results showed that reversible fouling was almost controlled and the BW was very effective (Fig. 15). The advantage of Iron III chloride over

Table 4
Effect of pH in seawater coagulation (4 mg/L Fe), in terms of NOM removal in AAO100 membrane flitration

	DOC (mg/l)	Biop. (ppm)	Humics (ppm)	% Removal DOC	% Removal biopolymers	% Removal humics
Red seawater	1.12	144	389			
pH 4	0.79	48	159	29	67	59
pH 5	0.63	61	150	44	58	61
pH 6	0.69	63	208	38	56	47
pH 7	0.78	75	268	30	48	31
pH 8	0.82	73	327	27	49	16
AAO100 permeate	1.03	95	365	8	34	6

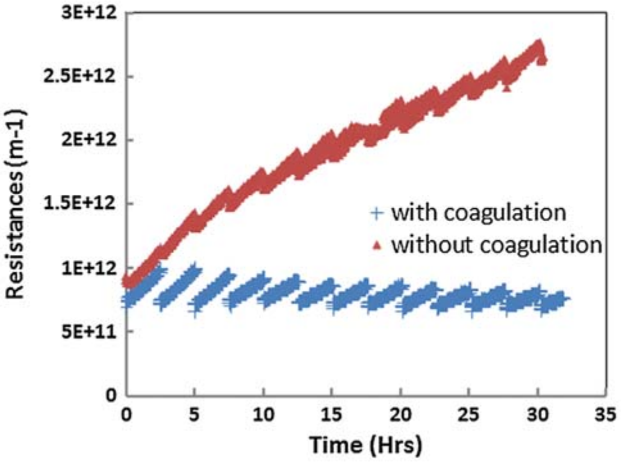

Fig. 15. Influence of coagulation (4 mg/L Fe) in reducing membrane fouling from seawater.

aluminium sulphate as a coagulant is that its solubility is low over a wide range of temperature and pH [12].

The use of coagulation significantly reduces the fouling and maintains stable operation, and hence reduces the use of chemicals for membrane cleaning. Previous studies also found that coagulation, even at a low dose of 1 mg/L Fe can maintain steady operation for more than one week [25]. This will reduce the operating cost of ceramic membrane if used as a pre-treatment process and also provide better feed for an RO membrane with less loading of high molecular weight NOM.

4. Conclusions and recommendations

Ceramic microfiltration (MF) membranes have the potential to produce the required feed water for RO membranes that meet the required SDI_{15} value. The average SDI_{15} value of 2.1 was measured from the seawater permeate after ceramic MF membrane filtration, and hence meets the recommended value of <3. In addition, bacteria removal of 3.7 logs was achieved by ceramic membrane filtration as pre-treatment prior to SWRO membrane, while turbidity improved from 0.6 to 0.05 NTU. For more stable operation of ceramic membranes and more reliable feed water quality for SWRO membrane inline coagulation using Iron III chloride is recommended. The optimum dose of 4 mg/L Fe was obtained for coagulation and good performance of coagulation, in terms of removal of high molecular weight NOM, was found at low pH (4–5). However, flux stabilization was achieved by a low dose of 1 mg/L Fe^{3+}. TEP was found to be persistent against hydraulic BW that is related to low flux recovery of ceramic MF membranes. The flux recovery improved with the increasing of BW flux intensity. Membrane resistances were precisely controlled with coagulation practice. Moreover, coagulation enhanced removal of high-molecular-weight NOM that is important for reducing bio fouling of SWRO membranes. Further studies to optimize operational conditions and doses for ceramic membrane filtration are recommended.

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