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# A comparative study on in-line flocculation and spiral flocculation followed by media filtration as a pre-treatment of seawater

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ABSTRACT

In this study the efficiency of two different flocculation systems namely in-line flocculation and spiral flocculation followed by media filtration (sand or anthracite) have been investigated as a pre-treatment of seawater to reverse osmosis. The performances of these filtration systems were assessed in terms of turbidity removal, head loss development, ultra filter-modified fouling index (UF-MFI) and organic matters removal. Both systems showed 60–70% removal of turbidity. In-line flocculation and filtration showed 2–3 times higher head loss development than spiral flocculation filtration. These filtration systems helped to reduce the fouling potential (in terms of UF-MFI) by 50–73%, whereas dissolved organic carbon-removal efficiency was 30–45%. The fractionation of organic matter showed that both systems removed 70% of hydrophobic organic matters. The removals of hydrophilic organics were around 30–40%. Among the hydrophilic compounds, the removal of biopolymer and lower molecular weight neutrals and acid were higher than that of humic substances' and building blocks'.

*Keywords:* Pre-treatment; Turbidity; Organic removal; Fouling index; LC-OCD

## 1. Introduction

Water scarcity is becoming a major problem in the world. Many countries in the world suffer from a shortage of natural freshwater. A rapidly increasing population is placing pressure on existing water resources. As a result of rises in population rates and enhanced living standards, together with the expansion of industrial and agriculture activities, increasing amounts of freshwater will be needed in the future. Water management and water reclamation is not the only solution to ensure an adequate water source. To mitigate the water demand it is necessary to create and find alternative sources of freshwater. Desalinated seawater presents such an alternative. However, raw seawater is unsuitable for human consumption and for industrial and agricultural uses. By removing salt from a virtually unlimited supply of seawater, desalination technologies including reverse osmosis (RO) have emerged as an important source of freshwater [1].

Membrane-based desalination technology such as RO is rapidly becoming an efficient alternative to conventional treatment for drinking water production from seawater. However, membrane fouling is a major

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concern in RO-based seawater desalination. The fouling on RO membrane deteriorates the performance of RO membranes and increases the energy consumption and even requires more frequent replacement of the membranes. Thus, membrane fouling is a major concern in RO-based seawater desalination. The main fouling mechanisms of RO membranes include (1) particulate and/or colloidal fouling resulting from accumulation of suspended solids and some metal-based hydroxide which can accumulate on the surface of the membrane over time and form cake fouling, (2) biofouling due to the formation of biofilms caused by the attachment and metabolism of biological matter which includes micro-organism and macro organism such as bacteria, fungus or algae which may also accelerate the chemical decomposition of RO membranes posing serious threats to the operation of RO plants, (3) inorganic fouling including scaling caused by exceeding the solubility of soluble salts such as $CaSO_4$, $BaSO_4$ and $MgSO_4$ which is considered less problematic and can be controlled by adjusting the pH and adding antiscalant and (4) organic fouling resulting from the deposition of organic matter such as humic and fulvic acids, polysaccharides and aromatic compounds on to membrane surface [2,3].

On the other hand, the organic matters are also an energy source for micro-organism leading to biofouling. Moreover, from literature it is found that seawater reverse osmosis (SWRO) foulants consist of biofouling (48%), inorganic colloids (18%), organic compounds (15%), silicites/silicates (13%), mineral deposits (6%) and coagulants (5%) [4].

Thus, it is necessary to have an effective pre-treatment to prevent fouling of RO membranes. The main objective of a pre-treatment system is to remove particulate, colloidal, organic, mineral and microbiological contaminants contained in the raw seawater and to protect the membranes from fouling in the downstream SWRO.

Pre-treatment such as bio-filtration, coagulation, adsorption, in-line flocculation, filtration and ozonation have been used to remove the natural organic matter (NOM) and to alleviate fouling [5–8]. Flocculation, coagulation and sedimentation have become important unit processes because of their low cost and easy application in the treatment of water and wastewater in conjunction with convectional mechanical, biological and physio-chemical plants.

Jar test has been used for since a long time and it is an effective method to determine the suitability for different types and amount of flocculants on coagulation/flocculation and sedimentation process for raw water. Despite its popularity, the jar test has a number of disadvantages. The jar test is not standardized and as result there are difficulties in making comparisons. It is a batch test, whereas full-scale plants are flow through units, therefore the results obtained from the jar test may not correspond with the results obtained from full-scale plants. Whereas spiral flocculator is more rapid and uses a smaller volume of water than jar tests in providing information on optimum chemical dosage. It provides results which are more closely related to flocculation performance in an actual flocculation plant [9]. From previous studies it is also found that in-line flocculation filtration effectively reduced membrane fouling. For example, Johir et al. [8] found lower membrane fouling of RO after an inline-flocculation-dual media filtration than without pre-treatment. Another study by Chinu et al. [10] showed that the flux decline of MF without any pre-treatment of seawater was 45%, it was about 42% after pre-treatment of $FeCl_3$ flocculation, 24% after pre-treatment of sand filtration with in-line coagulation and 22% after pre-treatment of dual media filtration (sand and anthracite), respectively. Similarly Lee et al. [11] found 50% lower fouling of membrane filtration when in-line flocculation fibre media filtration was used. All of these studies revealed that the in-line flocculation filtration can effectively reduce membrane fouling by removing particulate matters as well as colloidal and dissolved organic matters.

In this study in-line flocculation and spiral flocculation followed by media filtration (sand or anthracite) was investigated as a pre-treatment to seawater RO. In our subsequent discussion, we refer to rapid mixing followed by media filtration (sand or anthracite) as in-line flocculation filtration; and rapid mixing with spiral flocculation and then by media filtration as spiral flocculation filtration. A comparison of filter performances was made between sand and anthracite medium filters. Short-term (6 h) experiments were carried out with in-line flocculation filtration and spiral flocculation filtration at a velocity of 5 m/h and 10 m/hand a flocculent dose of 0–5 mg-$Fe^{3+}$/L. The efficiencies of these pre-treatments were carried out in terms of ultra filtration-modified fouling index (UF-MFI), head loss development, and turbidity and organic matter removal.

## 2. Materials and methods

### 2.1. Characteristics of seawater and filter media

Seawater used in this study was collected from Chowder Bay, Mosman, Sydney. The average pH, turbidity, dissolved organic carbon (DOC) and UF-MFI values of seawater were 8.01, 0.42–0.44 NTU, 2.07–2.79 mg/L and11589 s/$L^2$, respectively.

The physical properties of anthracite and sand used in this study are given in Table 1. The anthracite and sand were obtained from James Cumming and Sons P/L and Riversands P/L, respectively. Sand and anthracite were washed with distilled water then dried at 103°C and desiccated prior to their use.

### 2.2. In-line flocculation filtration and spiral flocculation filtration systems

Short-term in-line flocculation filtration and spiral flocculation filtration was conducted (Fig. 1(a) and (b)). The filter columns were made of transparent acrylic filter columns which have a length of 135 cm and internal diameter of 1.8 cm. These columns have sampling ports along its length and at the bottom. Prepared filter media (anthracite or sand) were packed up to a depth of 90 cm in these columns. Seawater was pumped from a feeding tank and coagulant was added using a dosing pump (Fig. 1).

The flocculant used was $Fe_2(SO_4)_3$ and it was fed at a dose of 1–5 mg-$Fe^{3+}$/L. The rapid mixing device was a 20 cm tube, 3 mm in diameter and wound around a tube of 5 cm. It was used for uniform mixing of seawater with coagulant for 10 s.

In the case of in-line flocculation filtration system, the seawater was passed through the media filter just after rapid mixing of raw seawater with flocculants for 10 s. The flocculation and solid liquid separation occur in the filter.

In the case of spiral-flocculation filtration, after the rapid mixing of seawater with flocculants it was then passed through the spiral flocculation. The spiral flocculation was made by winding a tube of 25 m length and 6 mm in diameter around a cylindrical column of 9 cm in diameter. The head loss and thus the velocity gradient was measured using the piezometric arrangement across the two ends of the spiral flocculation. Seawater after the flocculation through the spiral flocculation was passed through a filter bed with down flow filtration at velocities of 5 m/h and 10 m/h. The effluent samples were collected on a regular basis from the bottom of the filter column for analysis. An overflow chamber was in place at the top of the filter bed to maintain a constant head. The head loss was measured every hour using a piezometer.

Table 1
Physical properties of anthracite and sand

| Parameter | Anthracite | Sand |
|---|---|---|
| Effective size (mm) | 1.0–1.1 | 0.5–0.6 |
| Bulk density (kg/m$^3$) | 660–720 | 1,500 |
| Uniformity coefficient | 1.3 | <1.5 |
| Acid solubility | 1% | <2% |
| Specific gravity | 1.45 | 2.65 |

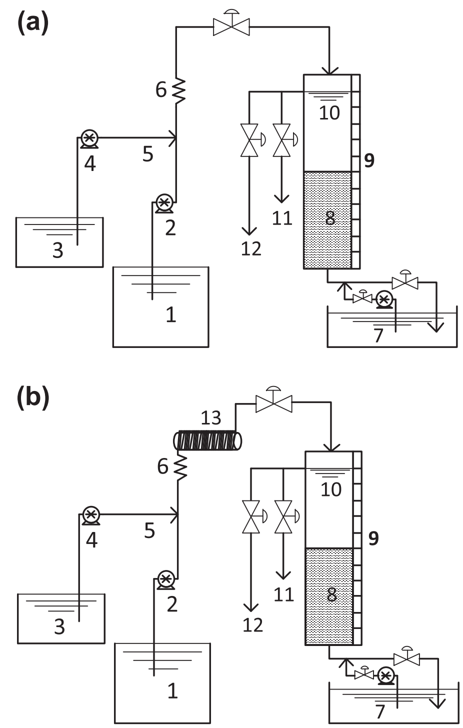


Fig. 1. Schematic diagram of (a) in-line flocculation filtration and (b) spiral flocculation filtration system.
Note: 1—feed tank, 2—feed pump, 3—coagulant tank, 4—dosing pump, 5—cogulant addition, 6—rapid mixing device, 7—effluent tank with backwash pump, 8—filter media, 9—manometer, 10—static head, 11—backwash water, 12—overflow, 13—spiral flocculator (slow mixing device).

### 2.3. Analytical methods

The turbidity of the influent and effluent was measured in terms of Nephelometric Turbidity Units (NTU) using a 2100P turbidity meter, HACH, USA. The influent and effluent turbidity was measured thrice for each sample and the mean value was recorded with the range.

The floc size was measured using Malvern Mastersizer 2000. The coagulated water suspension was drawn through the sample cell of the Mastersizer 2000 and back to the jar by a peristaltic pump located downstream of the Mastersizer to avoid the disturbance of flocs prior to measurement with a 5 mm internal diameter tube at a flow rate of 1.5 L/h.

Liquid chromatography-organic carbon detection (LC-OCD) was used to measure the DOC concentration of raw and treated seawater as well as to categorize the classes of organic compounds in water [12,13]. It gives qualitative results regarding molecular size distribution of organic matter as well as quantitative information on NOM. Quantification is done on the basis of carbon mass determination, similar to total organic carbon analysis which is performed with a special organic carbon detector. The qualitative analysis is based on size exclusion chromatography and it separates organic matter according to their molecular size. Water samples are injected into a column filled with a chromatographic gel material. Substances having small molecular sizes can access more of the internal pore volume than those having larger molecular sizes [14]. Therefore, large molecules elute first followed by the smaller compounds. In addition to the organic carbon detector, LC-OCD uses UV detection and determines the spectral absorption coefficient at 254 nm. In this study, DOC analysis was conducted for the samples collected before and after pre-treatment of seawater. All samples were filtered through a 0.45 μm microfilter before being analysed in the LC-OCD. The turbidity and the DOC of pre-treated water were measured thrice and the average value and range were reported.

UF-MFI was measured using a dead-end cell unit using an ultra filter membrane with a molecular weight cut-off 17.5 kDa. The fouling index experimental setup is shown in Fig. 2. Seawater before and after pre-treatment, was pressurized through a flat sheet membrane module (diameter of 47 mm). The operating transmembrane pressure (TMP) was controlled at 200 ± 3 kPa by means of a pressure regulating valve using high purity nitrogen gas. For each experiment, new membranes were used to avoid the effect of residual fouling and to compare the results obtained under different conditions.

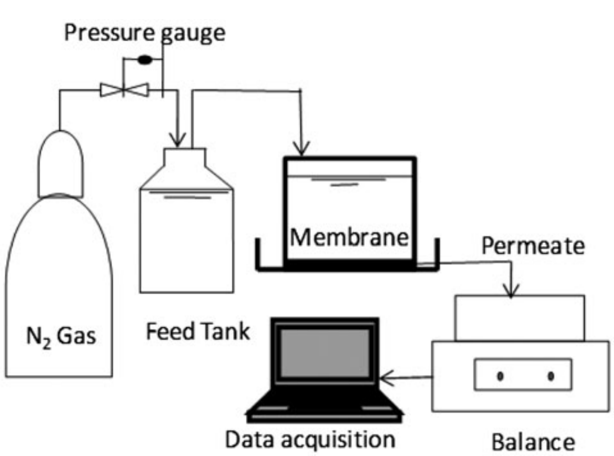


Fig. 2. UF-MFI experimental setup.

The MFI was calculated according to the method described by Schippers and Verdouw [15]. The MFI was determined from the gradient of the general cake filtration equation at constant by plotting $t/V$ vs. $V$ using the Eq. (1).

$$\frac{t}{V} = \frac{\eta R_m}{\Delta P A} + \underbrace{\frac{\eta \alpha C_b}{2\Delta P A^2}}_{MFI} V \qquad (1)$$

where $V$ = total permeate volume (L), $R_m$ = membrane resistance (1/m), $t$ = filtration time (s), $\Delta P$ = applied TMP (Pa), $\eta$ = water viscosity at 20°C (N s/m$^2$), $\alpha$ = the specific resistance of the cake deposited, $C_b$ = the concentration of particles in a feed water (mg/L) and $A$ = the membrane surface area (m$^2$).

MFI is defined as the gradient of the linear region of a $t/V$ vs. $V$ plot normalized to standard TMP reference values of 200 ± 3 kPa, a feed water temperature of 20°C and UF with a surface area of 47 mm diameter.

## 4. Results and discussion

### 4.1. Calculation of velocity gradient for spiral flocculation system

First of all, the velocity gradient of a spiral flocculation during the passage of suspension was determined by measuring the head loss across the length of spiral tube. The relationship between head loss and the velocity gradient is given by Eq. (2).

$$G = \sqrt{\left(\frac{g}{v}\right)\left(\frac{Q}{V}\right)\Delta H} \qquad (2)$$

where $G$ = velocity gradient, 1/s, $g$ = gravitational acceleration, cm$^2$/s, $v$= kinematic viscosity, cm$^2$/s, $Q$ = flow rate, cm$^3$/s, $V$ = volume of the flocculator (in this case, tube volume), cm$^3$, $\Delta H$ = head loss through the flocculator, cm.

Based on the experimental conditions, the velocity gradients were found to be 13.6 and 27.2/s, respectively, when the filtration velocity was 5 and 10 m/h. The higher the velocity gradient, the smaller will be the floc size [9]; however, this difference in floc size could be significant after the growth phase.

### 4.2. Turbidity removal

The removal of turbidity by in-line flocculation filtration (sand or anthracite filtration) is presented in Table 2. The filters were operated at two filtration velocities of 5 and 10 m/h with and without the

Table 2
Performance summary of in-line flocculation filtration and spiral flocculation filtration (depth of filter media = 90 cm; seawater turbidity = 0.42–0.44 NTU; Seawater UF-MFI = 11,589 s/L$^2$)

| Filter media | Flocculant dose (mg-$Fe^{3+}$/L) | Velocity (m/h) | Turbidity removal (%) | Final head loss development (cm) | UM-MFI reduction (%) |
|---|---|---|---|---|---|
| *In-line flocculation filtration* | | | | | |
| Sand | 0 | 5 | 47.6 ± 8.1 | 3.5 | 46.5 ± 1.3 |
| | 1 | 5 | 51.7 ± 6.3 | 23.0 | 60.2 ± 2.8 |
| | 3 | 5 | 67.4 ± 6.9 | 38.5 | 69.3 ± 1.7 |
| | 5 | 5 | 71.4 ± 4.7 | 151.5 | 63.2 ± 5.5 |
| | 3 | 10 | 64.4 ± 3.3 | 228.5 | 67.2 ± 9.6 |
| Anthracite | 0 | 5 | 39.5 ± 6.9 | 1.5 | 50.8 ± 3.1 |
| | 1 | 5 | 48.2 ± 5.4 | 30.0 | 70.4 ± 2.8 |
| | 3 | 5 | 63.9 ± 8.1 | 52.0 | 65.6 ± 2.0 |
| | 5 | 5 | 64.2 ± 7.1 | 58.0 | 76.5 ± 8.9 |
| | 3 | 10 | 58.8 ± 4.4 | 105.5 | 65.0 ± 7.4 |
| *Spiral flocculation filtration* | | | | | |
| Sand | 3 | 5 | 71.9 ± 9.5 | 17.5 | 60.2 ± 10 |
| | | 10 | 69.5 ± 7.1 | 52.0 | 61.0 ± 5.3 |
| Anthracite | | 5 | 67.1 ± 4.2 | 2.5 | 65.4 ± 9.2 |
| | | 10 | 60.0 ± 6.2 | 16.0 | 62.4 ± 2.5 |

addition of coagulant dose of 0–5 mg-$Fe^{3+}$/L. The average turbidity of raw seawater was 0.42–0.44 NTU. From Table 2, it is found that the removal of turbidity without the addition of coagulant was in the ranges of 40–50%. The lower removal of turbidity without the addition of coagulant is due to the fact that colloidal suspended particle could easily get through the filter media. Thus, it is important to use the flocculation or coagulation prior to the filtration system which will help to aggregate the colloidal as well as organic matter, and will improve turbidity-removal efficiency. Therefore, the remaining sets of experiments were conducted with the addition of coagulant to investigate the effect of coagulation on turbidity removal.

From the results presented in Table 2, it is found that the addition of coagulant helped to reduce the turbidly of the filtrate water resulting in more removal of turbidity by up to 70% at higher flocculent doses of 3 and 5 mg-$Fe^{3+}$/L. The increase in removal of turbidity with the addition of coagulant is due to the aggregation of colloidal particle by the coagulant which was then captured by the media filter.

In the case of the effect of filtration velocity, a lower filtration velocity of 5 m/h showed higher turbidity-removal efficiency of up to 71% compared with a higher filtration velocity of 10 m/h where the removal was slightly lower (up to 66%) (Table 2). In addition, among the two different filter media namely sand and anthracite, the removal efficiency of turbidity by sand filter was slightly higher than that of the anthracite filter's (Table 2). The slightly higher removal of turbidity by sand filter was due the smaller particle size of sand used in this study. This could be due to the change in physical properties of these two filter media used in this study. From the physical characteristics of sand and anthracite (presented in Table 1) the effective size of the anthracite filter media (1.05 mm) is almost 1.5 times larger than the sand filter (0.6 mm). This can be validated from the previous study which showed higher removal (%) with finer filter [8].

In addition, the turbidity removal by spiral flocculation filtration systems was also investigated. In all cases, it was found that the spiral flocculation filtration also showed almost similar removal efficiency of turbidity (Table 2). Hence, it can be concluded that both of the filtration systems showed good removal of turbidity thus both types of filtration produced almost same quality of water in terms of turbidity reduction.

### 4.3. Head loss development

The total head loss development of in-line flocculation filtration system after a filter operation of 6 h is presented in Table 2. From Table 2 it is found that the application of coagulant increased the head loss development. The head loss development without the addition of coagulant was only 3.5 cm (for sand filter) and 1.5 (for anthracite filter). However, in both cases (sand and anthracite) when in-line coagulation was applied the head loss development increased significantly (84–97%). The higher head loss development with the application of coagulant is because of the creation of floc particles resulting from the aggregation of colloidal and organic matter. These floc particles are then captured by the filter media which led to a faster blocking of the filter media resulting in higher head loss development.

In terms of filtration velocity and filter media, higher filtration velocity (10 m/h) and finer filter medium (sand) resulted in higher head loss compared with a lower filtration velocity of 5 m/h and a coarser filter medium (anthracite) at the same coagulant dose (Table 2).

The higher head loss development with finer filter media of sand could be due to the smaller particle size of sand than anthracite used in this study. Thus, the void space between sand filter (smaller particle size) was clogged more by the flocculated particle or colloidal particle than by particles of larger size (here anthracite filter). Similarly, at a higher filtration velocity (10 m/h) the higher head loss was likely due to the faster rate of deposition of floc/colloidal particle inside the pores of the filter bed.

In addition, the total head loss development of spiral flocculation filtration system is also presented in Table 2. A comparison between the two different filtration systems, shows that the in-line flocculation filtration system had almost 2–3 times higher head loss development than the spiral flocculation filtration system (Table 2) when operated at the same filtration velocity and coagulant dose.

For the in-line flocculation filtration system, the coagulant was mixed with seawater for only 10 s. This resulted in destabilization of particles and formation of very small flocs which then passed through the filter and was trapped within the media filter. The small flocs could easily penetrate through the filter medium and quickly clogged the filter media. Further there is additional flocculation of destabilised particles during the passage of the particles through the filter. On the other hand, in the case of spiral flocculation filtration after rapid mixing of 10 s, the mixed flocculated seawater was passed through spiral flocculation for slow mixing (i.e. flocculation) for 16.6–33.33 min. Thus, the spiral flocculation provided additional contact time for the aggregation of colloidal and organic matter with the coagulant which produced relatively larger flocs than the in-line flocculation filtration system before the suspension passes through the filter. Thus, the relatively larger flocs entering the system caused an increase in head loss development.

In summary, based on the turbidity removal both the filtration systems had almost similar performances, but the result of head loss development showed that the spiral flocculation filtration system had a lower tendency to clog compared to in-line flocculation filtration system. This shows the benefit of using short-term spiral flocculation, in addition to rapid mixing and in-line flocculation filtration.

### 4.4. Fouling reduction

The fouling potential was also measured in terms of UF-MFI for the raw seawater and for the effluent from both filters operated at a filtration velocity of 5 and 10 m/h with a coagulant doses of 0–5 mg-$Fe^{3+}$/L (Table 2). The UF-MFI value for raw seawater was 11,589 s/$L^2$. The fouling potential in terms of UF-MFI index showed that both the filtration systems reduced the UF fouling. The UF-MFI of the filter effluent without the addition of coagulant reduced by 40–50%, whereas with the addition of coagulant the UF fouling reduced by 60–70%. The fouling of UF membrane could be due to the deposition of colloidal matter and to some extent the deposition of organic matter. Thus, the higher reduction of UF-MFI with the addition of coagulant is due to the removal of both colloidal and organic matter by the coagulant. The filtration velocity and filter media type (or size) had almost no effect on the UF-MFI fouling reduction. Both the filtration systems (in-line flocculation filtration and spiral flocculation filtration) showed almost the same reduction in fouling potential.

### 4.5. Organic removal and characterization of organic matter

The removal of DOC by in-line flocculation filtration and spiral flocculation filtration is presented in Tables 3 and 4. DOC was measured for filters operated at a filtration velocity of 5 and 10 m/h with and without the addition of coagulant. From Table 3 it is found that the removal of DOC without the addition of coagulant was low (13–21%). The addition of coagulant increased the DOC-removal efficiency (35–47%). The DOC-removal efficiency increased with increasing larger doses of coagulant from 1 to 5 mg-$Fe^{3+}$/L for both in-line flocculation filtration and spiral flocculation filtration (sand or anthracite filter). From literature it is also found that the removal of organic by $Fe^{3+}$ is due to the complexation of Fe [16] (here $Fe_2(SO_4)_3$ as source of $Fe^{3+}$). Both the in-line flocculation filtration and spiral flocculation filtration showed almost same performance in terms of DOC removal (Tables 3 and 4)

A detailed organic characterization of raw seawater and filtrate seawater was also done using LC-OCD

Table 3
DOC removal and fractionation of organic matter presented in seawater and effluent from different in-line flocculation filtration

| Filter media | Velocity (m/h) | Flocculant dose (mg-$Fe^{3+}$/L | DOC (mg/L) | HOC (mg/L) | CDOC (mg/L) | Bio-polymers (mg/L) | Humic substances (mg/L) | Building blocks (mg/L) | LMW neutrals and acids (mg/L) |
|---|---|---|---|---|---|---|---|---|---|
| Raw seawater | | | 2.79 | 0.98 | 1.82 | 0.11 | 0.44 | 0.08 | 1.19 |
| Sand | 5 | 0 | 2.41 ± 0.29 | 0.78 ± 0.02 | 1.63 ± 0.31 | 0.07 ± 0.01 | 0.44 ± 0.02 | 0.08 ± 0.03 | 1.05 ± 0.30 |
| | | | (13.75 ± 10.3) | (20.58 ± 1.92) | (10.07 ± 16.9) | (36.07 ± 7.4) | (0.51 ± 5.04) | (7.22 ± 30.9) | (11.5 ± 25.2) |
| | | 1 | 2.07 ± 0.07 | 0.51 ± 0.04 | 1.56 ± 0.03 | 0.11 ± 0.04 | 0.48 ± 0.04 | 0.17 ± 0.02 | 0.81 ± 0.03) |
| | | | (25.76 ± 2.51) | (47.33 ± 4.09) | (14.16 ± 1.67) | (3.42 ± 35.04) | (-) | (-) | (31.90 ± 2.83) |
| | | 3 | 1.45 ± 0.14 | 0.34 ± 0.02 | 1.12 ± 0.12 | 0.07 ± 0.01 | 0.37 ± 0.00 | 0.10 ± 0.02 | 0.58 ± 0.11 |
| | | | (47.96 ± 5.08) | (65.55 ± 2.44) | (38.50 ± 6.50) | (35.73 ± 7.28) | (16.51 ± 0.69) | (-) | (51.18 ± 9.05) |
| | | 5 | 1.55 ± 0.02 | 0.41 ± 0.01 | 1.14 ± 0.00 | 0.07 ± 0.01 | 0.54 ± 0.04 | 0.09 ± 0.01 | 0.45 ± 0.04 |
| | | | (44.45 ± 0.60) | (58.17 ± 1.33) | (37.08 ± 0.21) | (40.31 ± 7.73) | (-) | (-) | (62.34 ± 3.31) |
| | 10 | 3 | 1.80 ± 0.06 | 0.32 ± 0.05 | 1.48 ± 0.01 | 0.04 ± 0.01 | 0.56 ± 0.03 | 0.09 ± 0.02 | 0.76 ± 0.04 |
| | | | (35.38 ± 2.12) | (67.10 ± 5.36) | (18.32 ± 0.38) | (63.62 ± 9.09) | (-) | (-) | (36.37 ± 2.95) |
| Anthracite | 5 | 0 | 2.19 ± 0.03 | 0.68 ± 0.0.01 | 1.51 ± 0.02 | 0.09 ± 0.01 | 0.40 ± 0.01 | 0.08 ± 0.01 | 0.96 ± 0.01 |
| | | | (21.6 ± 1.14) | (30.84 ± 1.54) | (16.64 ± 0.92) | (22.7 ± 4.55) | (8.68 ± 2.28) | (1.04 ± 12.07) | (15.51 ± 0.42) |
| | | 1 | 1.78 ± 0.13 | 0.53 ± 0.15 | 1.25 ± 0.02 | 0.07 ± 0.01 | 0.38 ± 0.00 | 0.14 ± 0.01 | 0.66 ± 0.03 |
| | | | (36.35 ± 4.58) | (45.87 ± 15.49) | (31.23 ± 1.29) | (37.58 ± 7.92) | (12.72 ± 1.00) | (-) | (44.26 ± 2.18) |
| | | 3 | 1.68 ± 0.08 | 0.47 ± 0.11 | 1.21 ± 0.03 | 0.06 ± 0.00 | 0.41 ± 0.06 | 0.12 ± 0.01 | 0.62 ± 0.09 |
| | | | (39.74 ± 2.98) | (51.74 ± 11.37) | (33.29 ± 1.53) | (48.91 ± 1.77) | (6.15 ± 14.06) | (-) | (47.56 ± 7.93) |
| | | 5 | 1.62 ± 0.01 | 0.38 ± 0.16 | 1.24 ± 0.15 | 0.07 ± 0.00 | 0.50 ± 0.05 | 0.12 ± 0.00 | 0.55 ± 0.10 |
| | | | (42.10 ± 0.47) | (61.06 ± 16.43) | (31.90 ± 8.12) | (34.45 ± 3.31) | (-) | (-) | (54.03 ± 8.53) |
| | 10 | 3 | 1.59 ± 0.17 | 0.23 ± 0.01 | 1.37 ± 0.16 | 0.06 ± 0.00 | 0.55 ± 0.05 | 0.08 ± 0.01 | 0.68 ± 0.12 |
| | | | (42.89 ± 6.17) | (76.93 ± 1.37) | (24.59 ± 8.76) | (45.31 ± 0.08) | (-) | (2.41 ± 9.40) | (42.70 ± 9.95) |

Note: % removal is in bracket ( ); HOC: Hydrophobic organic carbon; CDOC: Hydrophilic organic carbon.

Table 4
DOC removal and fractionation of organic matter presented in seawater and effluent from different spiral flocculation filtration

| Filter media | Velocity (m/h) | Flocculant dose (mg-$Fe^{3+}$/L) | DOC (mg/L) | HOC (mg/L) | CDOC (mg/L) | Bio-polymers (mg/L) | Humic substances (mg/L) | Building blocks (mg/L) | LMW neutrals and acids (mg/L) |
|---|---|---|---|---|---|---|---|---|---|
| Raw seawater | | | 2.07 | 0.38 | 1.69 | 0.21 | 0.58 | 0.14 | 0.76 |
| Sand | 5 | 3 | 1.33 ± 0.04 | 0.08 ± 0.02 | 1.26 ± 0.06 | 0.07 ± 0.01 | 0.52 ± 0.00 | 0.11 ± 0.00 | 0.56 ± 0.05 |
| | | | (35.73 ± 1.98) | (80.47 ± 3.98) | (25.52 ± 3.34) | (67.81 ± 3.41) | (10.40 ± 0.18) | (18.69 ± 0.19) | (26.59 ± 6.35) |
| | 10 | | 1.26 ± 0.13 | 0.10 ± 0.01 | 1.16 ± 0.12 | 0.07 ± 0.01 | 0.51 ± 0.02 | 0.07 ± 0.01 | 0.51 ± 0.08 |
| | | | (39.08 ± 6.40) | (73.39 ± 3.69) | (31.12 ± 7.02) | (64.75 ± 3.73) | (11.86 ± 3.41) | (48.93 ± 10.87) | (33.27 ± 9.97) |
| Anthracite | 5 | 3 | 1.22 ± 0.04 | 0.11 ± 0.01 | 1.11 ± 0.03 | 0.06 ± 0.01 | 0.50 ± 0.03 | 0.05 ± 0.00 | 0.51 ± 0.00 |
| | | | (41.29 ± 1.77) | (72.17 ± 1.74) | (34.25 ± 1.78) | (73.11 ± 3.55) | (14.22 ± 5.06) | (60.30 ± 3.21) | (33.40 ± 0.36) |
| | 10 | | 1.12 ± 0.06 | 0.09 ± 0.01 | 1.04 ± 0.05 | 0.04 ± 0.00 | 0.45 ± 0.03 | 0.07 ± 0.00 | 0.48 ± 0.08 |
| | | | (45.67 ± 2.94) | (76.88 ± 2.68) | (38.55 ± 3.00) | (81.13 ± 2.35) | (21.64 ± 5.47) | (50.97 ± 3.16) | (37.42 ± 10.87) |

Note: % removal is in bracket ( ); HOC: Hydrophobic organic carbon; CDOC: Hydrophilic organic carbon.

which provides detailed quantitative as well as qualitative data of different organic matters removed. The LC-OCD results of raw seawater and filtrate are presented in Tables 3 and 4. The results show that the seawater used in this study had a DOC concentration of 2.07–2.79 mg/L among which more hydrophilic compounds (1.69–1.82 mg/L; 65.2–81.4%) were present than hydrophobic compounds (0.38–0.98 mg/L; 18.6–34.8%). This is responsible for organic fouling on the membrane. The hydrophilic compounds contain biopolymers, humic substances, building block, low molecular weight (LMW) neutrals and LMW acids. The concentration of biopolymers present in raw seawater was 0.11–0.21 mg/L (3.9–10.1% of total DOC), whereas the portion of humic substances, building block, LMW neutrals and LMW acids present in seawater was 14.4–24.0, 6.6–8.2 and 40.7–46.9% of the DOC, respectively. Their concentrations were 0.44–0.5, 0.08–0.14 and 0.76–1.19 mg/L, respectively.

From Tables 3 and 4, it can be seen that the filtration system used in this study could help to remove majority of hydrophobic type of substances. In the case of in-line flocculation filtration (sand or anthracite filter), the removal of hydrophobic compound (45–76%) was higher than that of hydrophilic compounds' (18–37%). Among the hydrophilic compound the removal of biopolymers was higher than that of humic and building blocks' which showed very low removal (less than 10%). In all cases, the removal of LMW neutrals and acids were 31–62%.

Spiral flocculation filtration (sand or anthracite) also showed almost similar trend of hydrophobic and hydrophilic organic removal to that of in-line flocculation filtration system. In spiral flocculation filtration system, the concentration of biopolymers after filtration was reduced to 0.05–0.09 mg/L (from 0.21 mg/L) which is around 2.7–5.8% of total DOC of filtrate water. The removal of humic substances was less than 10% and the amount of humic substances present in filtrate water was 22–36% of DOC present in filtrate water (around 0.38–0.60 mg/L). After filtration, the concentration of building block-type substances reduced from 0.14 mg/L (in raw seawater) to 0.05–0.09 mg/L(3.8–6.3% of DOC). After filtration, the concentration of LMW neutrals reduced from 0.84 to 0.38–0.56 mg/L (23–47% reduction). It could be concluded that both the tested filtration systems can remove 30–40% of the hydrophilic compounds which comprises biopolymer, building blocks, LMW neutrals and acids. However, both filters removed more hydrophobic compounds as expected. The removal of hydrophilic substances may be by complexation mechanism [16].

## 5. Conclusion

In this study the performance of in-line flocculation and spiral flocculation with single media filters (sand or anthracite) were investigated as pre-treatment to SWRO. The efficiency was studied in terms of turbidity removal, head loss development, UF-MFI and organic matter removal. From this study the following conclusion could be derived:

- Both in-line flocculation filtration and spiral flocculation filtration showed good removal efficiency of solids in terms of turbidity (up to 71%).
- In-line flocculation filtration showed relatively higher head loss development than that of spiral flocculation filtration system which was 2–3 times lower than the former. Moreover, the finer media of sand filter showed higher head loss development than coarser anthracite filter media. Thus, the spiral flocculation filtration is better in terms of lower head loss development.
- Both the filtration systems reduced the fouling propensity by 70%. The UF-MFI reduction was 63–70% for sand as medium in the presence of the flocculent whereas it was 65–76% for anthracite. In terms of fouling propensity (UF-MFI) both media behaved in a similar manner.
- Both filtration systems helped to remove more hydrophobic substances than hydrophilic substances. Both media in the presence of flocculent (3 mg/L $Fe^{3+}$) led to 50–65% removal of hydrophobic organics. The hydrophilic organic removal was around 30–38%. The predominant portion of hydrophilic removal was humic substances which had a poor removal. In general, sand filter gave a higher removal than anthracite filter.

In conclusion, the spiral flocculation filtration process was better than the in-line flocculation filtration system in terms of on head loss development which can be an attractive pre-treatment for seawater desalination.

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