Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.822632

52 (2014) 6325–6332
October

Taylor & Francis
Taylor & Francis Group

Seawater biofiltration pre-treatment system: comparison of filter media performance

A. Shrestha, S. Jeong, S. Vigneswaran*, J. Kandasamy

Faculty of Engineering and IT, University of Technology, P.O. Box 123, Broadway, Sydney, NSW 2007, Australia
Tel. +61 2 95142641; Fax: +61 2 95142633; email: s.vigneswaran@uts.edu.au

Received 6 August 2012; Accepted 18 June 2013

ABSTRACT

Biological filtration is an effective pre-treatment method to remove organic matter and particulate matter from seawater. Three biofilter columns were operated packed with granular-activated carbon (GAC), anthracite and sand as a filter media. The biofilters were run for 120 d at a slow filtration velocity of 0.12 m/h. Biofiltration performances were evaluated in terms of turbidity, different fouling indices, and dissolved organic carbon (DOC). The removal efficiencies of turbidity by the three biofilters were similar with low headloss development. The fouling potential of treated seawater (filtrate) was evaluated using three different fouling indices such as microfiltration, ultrafiltration, and microfiltration at a cross flow. The analyses of three different fouling indices showed that the reduction in fouling potential was the following order GAC > sand > anthracite. In terms of DOC removal efficiency, GAC biofilter showed higher and stable removal efficiency (41–88%), than sand biofilter (7–76%) and anthracite biofilter (3–71%). All biofilters used in this study removed most of hydrophobic organic compounds (around 94%). On the other hand, hydrophilic organic removal varied depending on the media filter. GAC biofilter removed more organic biopolymers (51%), humic substances (75%) and building blocks (50%) compared with sand and anthracite biofilters. Therefore, GAC biofiltration can be used as an effective pre-treatment to alleviate organic fouling.

Keywords: Anthracite; Biofilter; Granular activated carbon; Pre-treatment; Sand; Seawater

1. Introduction

Seawater pre-treatment is a major component of a desalination plant [1]. The main objective of pre-treatment system is to remove particulate, colloidal, organic, mineral, and microbiological contaminants contained in raw seawater and to protect the downstream seawater reverse osmosis membranes from fouling. The selection of a pre-treatment method is very significant since it can influence the overall performance and determine the success or failure of the plant. In traditional pre-treatment, suspended materials are removed by deep bed filtration coupled with flocculation or extensive use of chemical treatment [2]. Even though conventional pre-treatment methods can remove a small portion of dissolved organic matter, it is not sufficient to overcome the organic fouling in reverse osmosis (RO). Previous research [3–5] showed that a biofilter can remove a majority of organic matter from water and wastewater, resulting in less

*Corresponding author.

1944-3994/1944-3986

operation and maintenance requirements. It can effectively remove organic substances by utilizing activities of micro-organisms attached on the filter media through a biodegradation process. Both aerobic and anaerobic microbes in suspended or attached forms can be used in the biological processes. The microbes convert biodegradable organic substances present in the influent into biomass and inorganic carbon through their metabolisms. In addition to this, it can also remove small fractions of organic matter which cannot be removed by other conventional treatment processes. Moreover, biological filtration is economical and safe to the environment in comparison to other physical and chemical treatment methods.

In this study, three deep bed filters were operated at a slow filtration velocity using three different media: granular activated carbon (GAC), anthracite, and sand, respectively. The performance of biofilter with different media was compared to evaluate the effectiveness of the pre-treatment to RO. The use of GAC, anthracite, and sand as a biofilter media has several advantages. GAC possesses an extremely large and irregular surface of the order of several 100 m^2/g of carbon and offer a large number of available sites for the adsorption of organic substrates and micro-organisms [4]. Further, Naidu et al. [6] showed the reduction in biofouling potential with stable microbial activity in the GAC filter bed. During biofilter operation, the GAC structure also protects microbes from shear loss. On the other hand, anthracite and sand are cheaper compared to GAC. Thus, sand and anthracite were used single or dual as a conventional granular media in water industry [7].

In this study, a slow filtration velocity is used to mimic the natural infiltration like a beach well system. In certain cases, it may be constrained by shorter depths and residence times. By contrast, beach wells (a technology similar to riverbank filtration) can provide longer travel times and distances (>10 days and >10 m) and can be used as a biofiltration. The beach well constitutes a natural biological filter and achieves effective removal of biodegradable organic carbon and assimilable organic carbon. It also reduces bio- and organic fouling, and colloidal fouling. It has the advantage of providing a seawater intake system [8]. It eliminates the need for complex intake structures that protrude into the sea and the problem of organism impingement/entrainment at intakes. This system appeals to large desalination plants which use open sea intake.

Presently, little information is available for detailed particulates and organic matter removal using a long-term biofiltration with different media. Therefore, this detailed knowledge on the filtration performance would significantly contribute to a more efficient application of biofilter for seawater pre-treatment. The aim is to develop a cost-effective biofilter with a high potential to remove the dissolved organic matter to prevent fouling of RO membranes.

2. Materials and methods

2.1. Seawater and filter media

Biofiltration experiment was conducted on-site at Sydney Institute of Marine Science, Chowder Bay, Sydney, Australia. Seawater was collected from 1 m below the sea surface level and continuously fed into biofilter. The characteristics of seawater were monitored regularly during the biofiltration experiments. Biofilter packed with different media; GAC, anthracite and sand was operated in parallel. GAC and anthracite used were manufactured from Australian coal seam by James Cumming and Sons P/L, Australia. The most important characteristic of GAC is extremely large surface area (more than 1,000 m^2/g GAC). It has a relatively small nominal size of 0.3 mm with a bulk density of 748 kg/m^3. This ability makes GAC suitable for adsorbing of substances and micro-organisms presented in seawater. Sand used in this study was sourced by Riversands P/L Australia. The physical properties of GAC, anthracite and sand used are presented in Table 1. GAC, sand and anthracite were washed with distilled water, then dried at 103°C and desiccated prior to use.

Table 1
Physical properties of anthracite, GAC and sand

Parameter	Anthracite	GAC	Sand
Specification	Estimated value	Estimated value	Estimated value
Effective size (mm)	1.05	0.3	0.6
Bulk density (kg/m^3)	660–720	748	1,500
Uniformity coefficient	1.3	1.3	<1.5
Specific surface (mg/gm)	NA	1,000	NA

Note: NA—not available and these values are very small as compared to that of GAC.

2.2. Biofiltration

Biofiltration experiment was conducted using transparent acrylic filter columns which have a length of 150 cm and a diameter of 9.5 cm as shown in Fig. 1. These columns have sampling ports along the length as well as at the bottom of the column. Prepared filter media (GAC, anthracite and sand) were packed up to a depth of 80 cm from the bottom of the columns and biofilters were connected in parallel. Seawater was pumped from feeding tank to the top of the columns and then passed through the filter bed at filtration velocity of 0.12 m/h. An overflow outlet was placed above the filter bed in the column to maintain a constant velocity. Backwashing was applied to remove particles and excess biomass in the filter bed that cause biofilter clogging during experiments. Backwashing was conducted with tap water in the up-flow direction from the bottom of the column and the filter bed expanded up to 30% during a backwash of 2 min. The entire filtration period was 120 d. Effluent samples (filtrates) were collected from the bottom of the column for further analyses.

2.3. Analytical methods

The turbidity of the influent (seawater) and effluent was measured in terms of nephelometric turbidity units (NTU) using 2100P turbidity meter (HACH, USA). The pH was measured using a potable pH meter (Model-920A, Orion). Both turbidity and pH were measured daily for the first week and afterwards measured twice a week till the end of the experimental period.

Liquid chromatography-organic carbon detection (LC-OCD) categorizes and fractionates the classes of organic compounds in water [9]. It gives qualitative results regarding molecular size distribution of organic matter as well as quantitative information on natural organic matter. 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 [10]. Therefore, large molecules elute first followed by the smaller compounds. In addition to the organic carbon detector, LC-OCD uses UV detection and determination of the spectral absorption coefficient at 254 nm to complete the information about the water samples. In this study, dissolved organic carbon (DOC) analysis was conducted on the samples

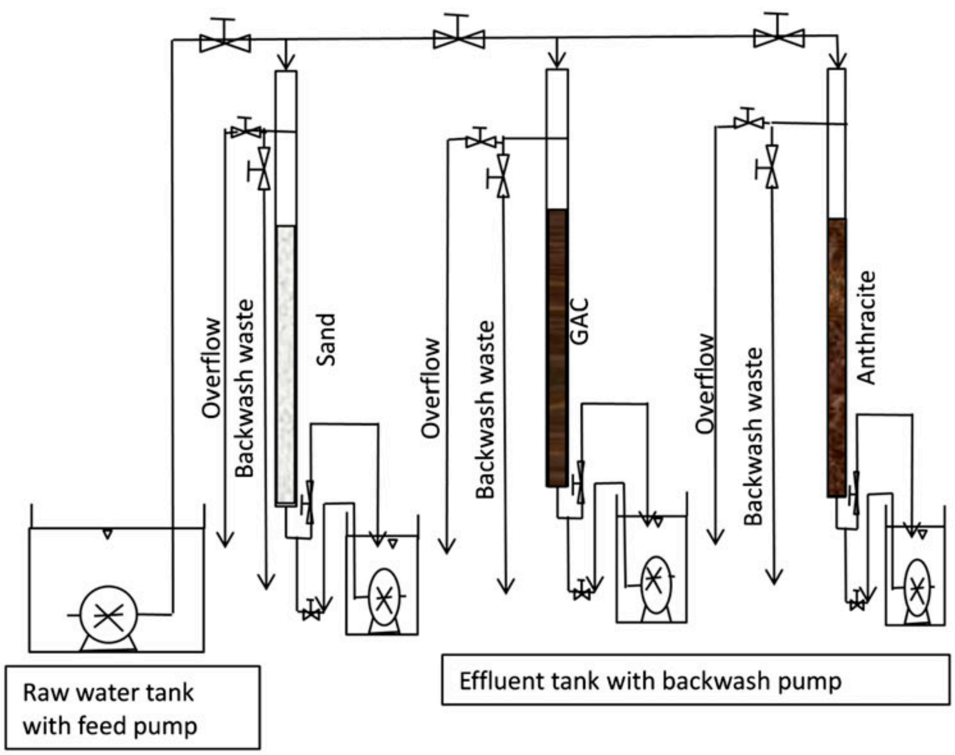


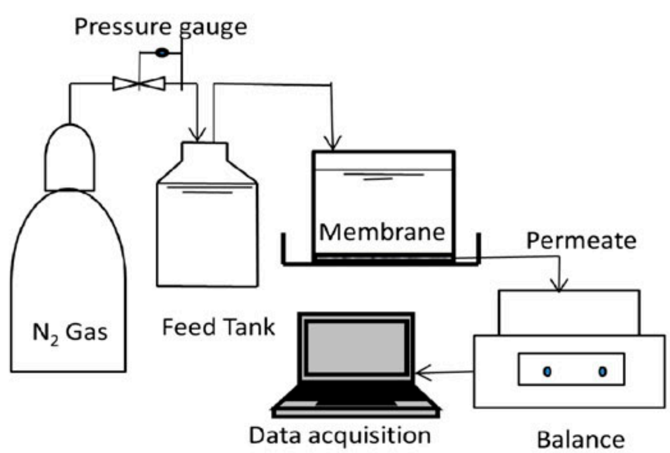
Fig. 1. Schematic diagram of biofiltration column.

collected before and after biofiltration (pre-treatment) of seawater twice a week for first week and afterwards samples were analysed once a week for the reminder of the experimental period. All samples were filtered through a 0.45 μm micro-filter (MF-MFI) prior to the LC-OCD. The measurements of turbidity and the DOC were made in duplicate for at least 30% of the samples. The deviation was less than 5%.

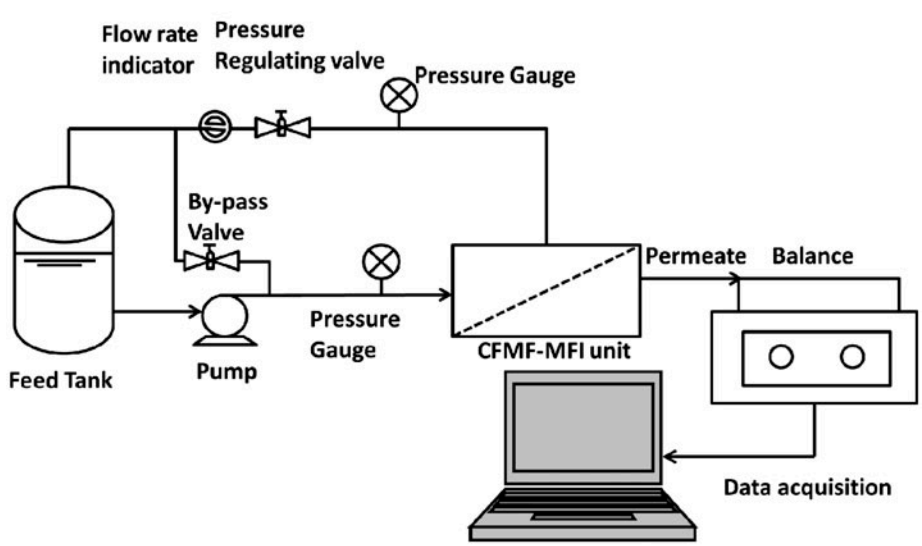
Modified Fouling Index (MFI) was measured using dead-end cell unit with a 0.45-μm MF-MFI and a 17.5 KDa (molecular weight cut-off) ultra-filter (UF-MFI). The fouling index experimental set-up of MF-MFI and UF-MFI is shown in Fig. 2(a). Seawater before and after pre-treatment were pressurized using N_2 gas through a flat-sheet membrane module (a diameter of 47 mm) at a feed water temperature of 20˚C. The operating trans-membrane pressure was controlled at 207 ± 3 kPa by means of a pressure-regulating valve. In each experiment, new membranes were used to avoid the effect of residual fouling and to allow a comparison of results obtained under different conditions.

The fouling index experimental set-up of cross-flow unit with MF membrane (CFMF-MFI) is shown in Fig. 2(b). The raw and pre-treated seawater were pressurized at 10 kPa through a 0.45-μm MF membrane at a cross-flow velocity of 4.3 m/h. A temperature controller was used to maintain the temperature at 29˚C. The cross-flow velocity and trans-membrane pressures were controlled by bypass and regulating valves.

MFI was calculated according to the method by Schippers and Verdouw [11]. The MFI is determined from the gradient of the general cake filtration



(a) UF-MFI or MF-MFI



(b) CFMF-MFI

Fig. 2. Fouling Index experimental set-up: (a) MF-MFI and UF-MFI; (b) CFMF-MFI.

equation at constant pressure by plotting t/V vs. V using Eq. (1).

$$\frac{t}{V} = \frac{\eta R_m}{\Delta PA} + \frac{\eta \alpha C_b}{2\Delta PA^2} V \leftrightarrow MFI \quad (1)$$

where V = total permeate volume (L); R_m = membrane resistance ($1/m$); t = filtration time (s); ΔP = applied trans-membrane pressure (Pa); η = water viscosity at 20˚C (N.s/m^2); α = the specific resistance of the cake deposited; C_b = the concentration of particles in a feed water (mg/L); A = the membrane surface area (m^2).

Fouling indices are used to measure and predict the fouling potential of the feed water to membrane filtration systems. The Silt Density Index (SDI) is the only standard method presently used yet it has many shortcomings as they often fail to reflect the true fouling strength of the seawater or pre-treated seawater. In this study, the reduction in the fouling potential of raw seawater arising from biofilters with different media was studied.

In addition to MF-MFI, UF-MFI was conducted to study the fouling potential in this study. This was because in many cases MF-MFI does not provide a good representation of organic fouling due to the relatively large pore size of MF membrane compared to a UF membrane [12]. Thus, the use of UF-MFI could give better information on some of the larger molecular weight organics than MF-MFI. Thus, UF-MFI was conducted for only a few samples as a representative result during an operational period of 92–120 d.

In dead-end filtration used in measuring MF-MFI and UF-MFI, foulants in the feed are deposited on or pass through the membrane surface, whereas in cross-flow filtration, foulants are fractioned by selective deposition. The hydrodynamics effects of cross-flow filtration, which were not simulated in SDI and MFI tests, can be considered in a cross-flow sampler unit. It is critical since the cross-flow velocity in the cross-flow sampler unit influences the particle concentration and the particle size distribution in its permeate [13,14]. Thus, Modified Fouling Index using a CFMF-MFI was conducted to closely simulate the hydrodynamic conditions of a cross-flow RO unit (Fig. 2(b)). A few samples were tested on CFMF-MFI to obtain a representative result during the operational period of between 21 and 50 d.

3. Results and discussion

Biofilters were operated on-site for the duration of 120 d. The variation of seawater temperature and turbidity was monitored during the entire operation. The turbidity of raw seawater was relatively consistent in the range of 0.40–0.65 NTU (Fig. 3). Turbidity increased slightly up to 0.78NTU during the rainy period. The turbidity of filtrates (effluents) from the GAC, sand and anthracite biofilters was found to be 0.16–0.41, 0.16–0.40 and 0.19–0.43 NTU, respectively. Temperature of seawater was fairly uniform at around 20˚C during the experimental period (Fig. 4(a)). There was no significant change in pH over the entire duration of the experiment. Except for the first 10 days, the pH was relatively stable between 7.75 and 8.50 till the end of experiment for both seawaters before and after filtration (Fig. 4(b)). Seawater pre-treated with GAC biofilter showed slightly lower pH in comparison with seawaters followed by sand and anthracite biofilters.

The measurement of fouling potential using MF-MFI showed that raw seawater varied in the range of 4.2–9.7 s/L^2. MF-MFI was mainly carried out to see the fouling reduction by colloidal particles. After filtration through GAC, sand and anthracite biofilters, MF-MFI value decreased to 1.2–3.7, 1.9–5.9 and

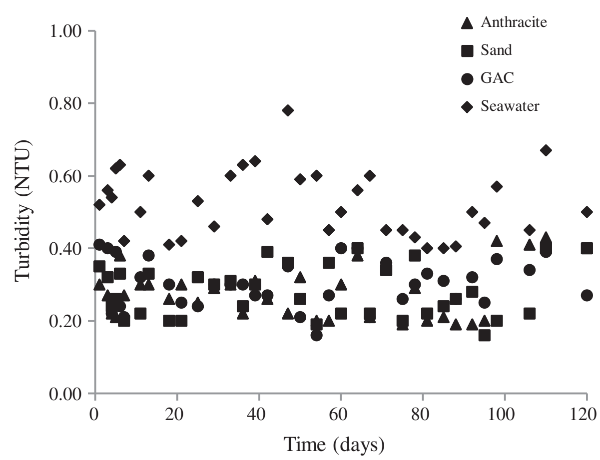


Fig. 3. Turbidity removals with biofilters.

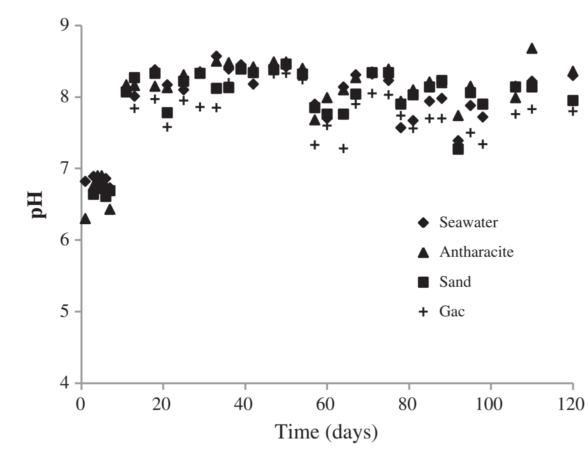


Fig. 4. Variation of pH during experimental period.

2.1–8.2 s/L^2, respectively (Fig. 5(a)). This indicated that the GAC biofilter could reduce a majority of fouling potential during the experimental period of 120 days compared to sand and anthracite biofilters. In the case of sand and anthracite biofilters, the MF-MFI value decreased gradually after the beginning of experiment (13–30 d of operation) till the period between 33 and 64 days of operation. After 64 d of operation, the MF-MFI values (in the case of sand and anthracite biofilters) fluctuated between 2.0 and 8.2 s/L^2, even though during this period, the MF-MFI value of raw seawater fluctuated between 4.4 and 9.7 s/L^2. This could be due to the unsteady removal of colloidal and particulate organic matters by sand and anthracite biofilters.

The UF-MFI was measured mainly to see the fouling reduction by larger organic matter (such proteins, polysaccharides and humics) in addition to the colloidal particles. This is vital in seawater pre-treatment. It was found from the UF-MFI result that the all biofilters showed superior reduction in fouling potential. The UF-MFI of raw seawater was between 9,500 and 10,900 s/L^2. The UF-MFI values of filtrate seawater treated with GAC, sand and anthracite biofilters varied between 1,500–4,800 s/L^2, 2,200–6,600 s/L^2, and 1,500–8,000 s/L^2, respectively (Fig. 5(b)). GAC biofilter showed a better reduction in the UF-MFI compared to sand and anthracite biofilters. In a similar result to the MF-MFI, the GAC biofilter showed an almost steady reduction in UF-MFI values till the end of experimental period of 120 d. This is due to better removal of organic matters with GAC biofilter. The DOC value of GAC biofilter effluent was relatively stable and lower than that of sand and anthracite biofilter effluent (Fig. 6).

CFMF-MFI result also showed a similar trend with UF-MFI. The CFMF-MFI value for raw seawater varied between 49.6 and 56.7 s/L^2 (Fig. 5(c)). The CFMF-MFI values for effluent filtered through GAC, sand and anthracite biofilters varied between 4.2–12.0 s/L^2, 7.5–15.0 s/L^2, and 4.4–20.0 s/L^2, respectively. GAC biofilter showed a better reduction in the CFMF-MFI in comparison with sand and anthracite biofilters. In results similar to MF-MFI and UF-MFI, the GAC biofilter showed an almost steady reduction during a period between 21 and 50 days. This suggests that it is possible to decrease the fouling potential (particulates, organic matter and foulant deposit by cross-flow) to the RO membrane using the biofilters studied in this study.

Fig. 6 presents the reduction in DOC after filtration with GAC, sand and anthracite biofilters. This shows a significant amount of dissolved organic matter was removed by biofilter pre-treatment. GAC biofilter had a better removal efficiency of between 41 and 88%,

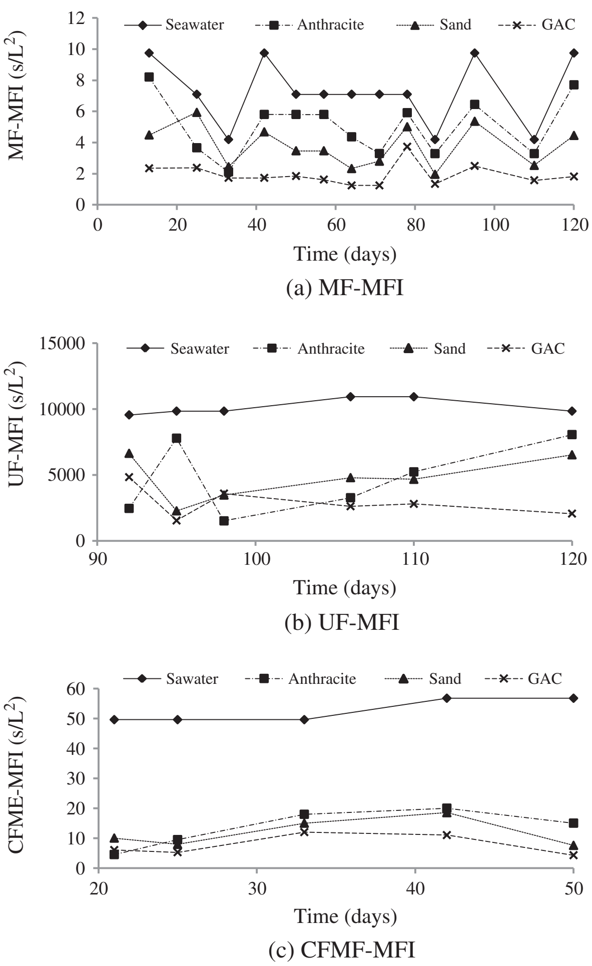


Fig. 5. The MFI values of seawater and effluents through biofilters: (a) MF-MFI; (b) UF-MFI; and (c) CFMF-MFI.

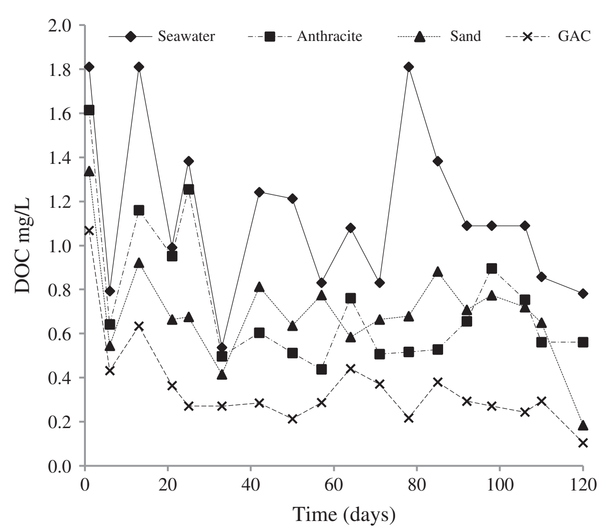


Fig. 6. Variation of DOC concentration of seawater and effluents through biofilters during the experimental period.

whereas the DOC removal efficiency of sand and anthracite biofilters in seawater was lower (7–76 and 3–71%, respectively). As discussed above, GAC produced a steady and superior quality of effluent. LC-OCD chromatograms of seawater and effluents through three different media biofilters are shown in Fig. 7 and their detailed organic fractions are given in Table 2. The seawater used in this study comprised of more hydrophilic compounds (79%) causing severe organic fouling on the RO membrane. The removal efficiency of DOC in seawater by GAC biofilter was superior at more than 69%. As can be seen from Table 2, all biofilters tested in this study removed most (94%) of the hydrophobic organic compounds. On the other hand, hydrophilic organic removals varied depending on the different media filters. GAC biofilter removed more organic biopolymers (51%) than sand and anthracite biofilter. Also, a higher amount of building blocks (as humic substances-hydrolysates with molecular weights between 300 and 450 g/mol) were removed by the GAC biofilter (50.0%). In particular, the removal efficiency of humic substances by GAC biofilter was 74.5%, whereas both anthracite biofilter and sand biofilter could not remove as much. This shows that GAC biofiltration is effective pretreatment to reduce organic fouling.

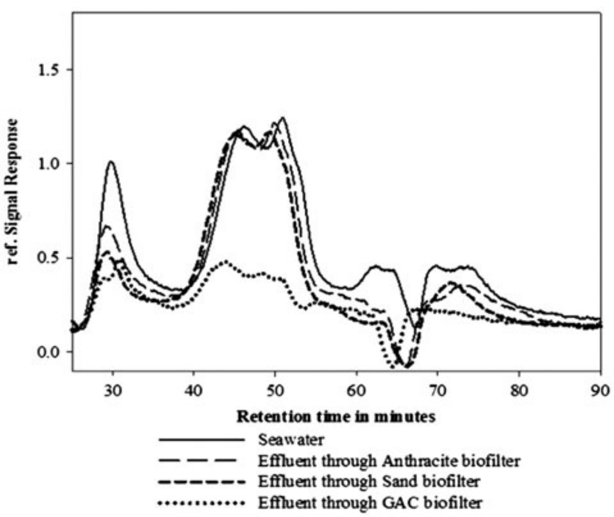


Fig. 7. LC-OCD chromatogram of seawater and effluents through biofilters.

4. Conclusion

The experimental results indicate that biofiltration pre-treatment systems reduced organic matter and particulate matter. It is expected that biofilter can lower fouling to a subsequent RO process in desalination plant. The biofiltration performance of GAC biofilter was significantly better than that of conventional media such as sand and anthracite. All the biofilters had almost similar turbidity removal efficiency. The results measured by various fouling indices showed that the filtrate (effluent) from the GAC biofilter had lower fouling potential compared to sand and anthracite biofilters. In terms of DOC removal efficiency, GAC biofilter had better and consistent removal efficiency compared to sand and anthracite. All biofilters tested in this study removed most of the hydrophobic organic compounds. On the other hand, removal of hydrophilic organic varied depending on the different media filters. GAC removed more organic biopolymer

Table 2
Removal of different organic fractions by different media biofilters

Sample	DOC	Hydrophobic	Hydrophilic	Biopolymer	Humics	Building blocks	LMW neutrals
Seawater (mg/L)[a]	1.65	0.34	1.31	0.35	0.47	0.14	0.35
Effluent through GAC biofilter (mg/L)[a]	0.51	0.02	0.49	0.17	0.12	0.07	0.13
Removal efficiency (%)[b]	69.1	94.1	62.6	51.4	74.5	50.0	62.9
Effluent through sand biofilter (mg/L)[a]	0.90	0.02	0.88	0.19	0.46	0.10	0.13
Removal efficiency (%)[b]	45.5	94.1	32.8	45.7	2.1	28.6	62.9
Effluent through anthracite biofilter (mg/L)[a]	1.06	0.02	1.04	0.26	0.46	0.12	0.20
Removal efficiency (%)[b]	35.8	94.1	20.6	25.7	2.1	14.3	42.9

Notes: [a]Concentrations of the different organic fractions in water samples.
[b]Removal efficiencies of different organic fractions in seawater after the pre-treatment.

and building blocks than sand and anthracite biofilters. In particular, the removal efficiency of humic substances by the GAC biofilter was 74.5%, whereas both sand and anthracite biofilter could not remove as much. Thus, the GAC filter was the best medium to provide the lowest fouling potential as it showed the highest removal efficiency of DOC, including hydrophilic, humic, building blocks and biopolymer. The lowest efficiency was found for anthracite medium.

Acknowledgements

The authors acknowledge the financial support of the National Centre of Excellence in Desalination Australia which is funded by the Australian Government through the Water for the Future initiative. The supplementary scholarship given by the National Centre for Excellence for Desalination to the first author is acknowledged.

References

[1] N. Voutchkov, SWRO pre-treatment systems: Choosing between conventional and membrane filtration, Filtr. Sep. 46 (Suppl. 1) (2010) 5–8.
[2] K.J. Chinu, A.H. Johir, S. Vigneswaran, H.K. Shon, J. Kandasamy, Biofilter as pretreatment to membrane based desalination: Evaluation in terms of fouling index, Desalination 247 (2009) 77–84.
[3] R.M. Clark, B.K. Boutin, Controlling Disinfection By-Products and Microbial Contaminant in Drinking Water, US, EPA, Columbus, OH, 2001.
[4] G. McKay, Use of Adsorbents for the Removal of Pollutants from Wasterwater, CRC Press, Boca Raton, FL, 1996.
[5] T. Hoang, S. Vigneswaran, H. Ngo, J. Kandasamy, W. Shim, D. Chaudhary, P. Gotety, P. Peiris, Performance evaluation and mathematical modelling of granular activated carbon biofiltration in wastewater treatment, Korean J. Chem. Eng. 25(2) (2008) 259–267.
[6] G. Naidu, S. Jeong, S. Vigneswaran, S.A. Rice, Microbial activity in biofilter used as a pretreatment for seawater desalination, Desalination 309 (2013) 254–260.
[7] H. Bae, H. Kim, S. Jeong, S. Lee, Changes in the relative abundance of biofilm-forming bacteria by conventional sandfiltration and microfiltration as pretreatments for seawater reverse osmosis desalination, Desalination 273 (2011) 258–266.
[8] V. Bonnelye, M.A. Sanz, J.P. Durand, L. Plasse, F. Gueguen, P. Mazounie, Reverse osmosis on open intake seawater: Pre-treatment strategy, Desalination 167 (2004) 191–200.
[9] S.A. Huber, A. Balz, M. Abert, W. Pronk, Characterisation of aquatic humic and non-humic matter with size-exclusion chromatography–organic carbon detection–organic nitrogen detection (LC-OCD-OND), Water Res. 45(2) (2011) 879–885.
[10] C. Pelekani, G. Newcombe, V.L. Snoeyink, C. Hepplewhite, S. Assemi, R. Beckett, Characterization of natural organic matter using high performance size exclusion chromatography, Environ. Sci. Technol. 33(16) (1999) 2807–2813.
[11] J.C. Schippers, J. Verdouw, The modified fouling index, a method of determining the fouling characteristics of water, Desalination 32 (1980) 137–148.
[12] S.F.E. Boerlage, M. Kennedy, M.P. Aniye, J.C. Schippers, Applications of the MFI-UF to measure and predict particulate fouling in RO systems, J. Membr. Sci. 220 (2003) 97–116.
[13] L.N. Sim, Y. Ye, V. Chen, A.G. Fane, Crossflow sampler modified fouling index ultrafiltration (CFS-MFIUF) an alternative fouling index, J. Membr. Sci. 360 (2010) 174–184.
[14] L.N. Sim, Y. Ye, V. Chen, A.G. Fane, Comparison of MFI-UF constant pressure, MFI-UF constant flux and crossflow sampler-modified fouling index ultrafiltration (CFS-MFI_{UF}), Water Res. 45(4) (2011) 1639–1650.