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New concept to characterize seawater quality for RO plant design and operation

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ABSTRACT

Characterization of seawater quality is crucial to determine the selection and design of pretreatment process as well as to manage membrane fouling in seawater reverse osmosis (SWRO) plants. In some cases, conventional seawater quality parameters are limited in explaining the regional variations of raw seawater and/or in predicting the extent of membrane fouling because of poor correlations between the amounts of impurities in seawater and the resultant membrane fouling. In this study, four seawater quality parameters (P-MFI, C-MFI, PROTEIN and HUMIC) are newly employed to investigate whether those parameters could overcome the current limitations of conventional parameters. Seawater samples have been collected periodically from five different SWRO plants and then analyzed by multiple membrane array system to obtain the two different MFI values and by fluorescence spectrophotometer for PROTEIN and HUMIC quantifications. Statistical analyses of seawater quality data from the SWRO plants showing the different extent of membrane fouling suggest that those parameters are useful to estimate membrane fouling by all types of impurities such as particles, colloids and organic matters in seawater. In addition, the four suggested parameters (P-MFI, C-MFI, PROTEIN and HUMIC) could better specify the regional differences of seawater quality and the changes of impurities from raw seawater to RO feedwater according to operating conditions, which would be the basis to establish the practical guidelines for a pretreatment design and an efficient operation of SWRO plants.

Keywords: Seawater reverse osmosis (SWRO); Seawater quality; Membrane fouling; Fouling index; SWRO plant operation

1. Introduction

Reverse osmosis (RO) is a well-established technology with many successful cases of industrial plant design and operation [1,2]. However, sometimes RO plant suffers from severe membrane fouling, which results in a reduced plant availability as well as an increased operational cost due to frequent shutdown for RO membrane cleaning and replacement [3,4]. Alternative design and/or operation strategies for pretreatment could minimize RO membrane fouling, while this will be only possible with reliable seawater quality parameters that correlate well with the extent of membrane fouling. There are several cases of severe RO membrane fouling reported even though the feed water quality to RO membrane in terms of conventional water quality parameters meet the guidelines of RO membrane

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manufacturers [4–6]. In these cases, it is difficult to find out the reasons for membrane fouling because conventional water quality parameters might be less useful as barometers for plant design and operation. Therefore, it is very important to develop better seawater quality parameters to mitigate the limitations of conventional water quality parameters.

With conventional seawater quality parameters, it is sometimes difficult to quantify how much impurities exist in seawater and thus it is difficult to expect how much membrane fouling would occur [7–10]. For particulate matters mostly larger than 0.45 μm in seawater, the typical conventional parameters are total suspended solid (TSS), nephelometric turbidity unit (NTU), and silt density index (SDI). These three parameters are important to evaluate the performance of pretreatment processes, but there are known limits. TSS measurement has high error for seawater samples typically found at the intake of a desalination plant because their particle content is below the reliable quantification ranges of TSS [11,12]. SDI measurements correlate well with particle concentration, only if the particle content is very low [13]. Raw seawater frequently exceeds the quantification ranges of SDI measurements. Turbidity is a simple and fast measurement for particle content in seawater but the value differs according to the characteristics of particles in seawater, such as size and composition [14]. Therefore, the evaluation of seawater quality by the conventional parameters might lead to an inadequate design of the pretreatment configuration due to misunderstanding of the regional and/or seasonal variations of particle contents in seawater. On the other hand, these parameters are not correlated (in linear or any other function theoretically based) with the extent of RO membrane fouling because they are not based on any filtration or fouling mechanisms [13,15].

For organic contents in seawater, total organic carbon (TOC) and ultraviolet at 254 nm (UV254) are usually employed. However, several reports have indicated that the two parameters are not enough to predict membrane fouling in RO by organic matters [7,10,16–18]. The type of organic matters is more critical in membrane fouling rather than the amount of organic matters (such as TOC) [19]. So, several analytical methods have been suggested alternatively to predict a RO membrane fouling by organic matters: transparent exopolymeric particle, biopolymer, building block, humic acid, low molecular weight acid and assimilable organic carbon [7,18,20]. In some cases, these parameters showed close correlation to RO membrane fouling. However, employing these parameters for RO plant operation might be a bit difficult, because the measurements require expensive instruments and specialized analysts.

In order to complement the limitations of the conventional seawater quality parameters for RO plants, four different seawater quality parameters are proposed in this study to estimate the membrane fouling potential by particles, colloids and organic matters in seawater. First, multiple membrane array system (MMAS) provides two modified fouling indices (MFIs), which are particle-MFI (P-MFI) and colloid-MFI (C-MFI), by filtering seawater in series through 0.45 μm and 100 kDa pore-sized membrane filters, respectively [21]. MFI is based on the cake filtration theory, which measures a resistance of membrane filtration resulted from the foulants in seawater, thus they are linear to the concentration of the foulants [9,22]. P-MFI is measured by the resistance formed on the first microfiltration membrane during the seawater filtration. The filtered water is then fed to the second ultrafiltration (UF) membrane filter to obtain C-MFI value that stands for the resistance caused by the foulants that passed through the first membrane. This approach provides for both the separation of foulants and the evaluation of the fouling potential as particle (P-MFI) and colloid (C-MFI). In addition, excitation emission matrix (EEM) and parallel factor (PARAFAC) analysis are employed to quantify the organic matters in seawater as HUMIC and PROTEIN [23]. These two parameters are good candidates to understand the origins of organic matters (terrestrial or biological) as well as the effect of organic fouling on membrane [19]. Whether the four different parameters could represent a seasonal and regional variations of seawater quality and what could be the appropriate concentration of those parameters to mitigate RO membrane fouling are the interests of this paper. The results could be also used as a basis for optimizing some operating conditions as well as for designing a reliable plant with a minimized risk of membrane fouling.

2. Materials and methods

2.1. Plant descriptions

Three different full-scale commercial RO plants (plant A, plant B and plant C) and two different pilot-scale plants (plant D and plant E) are investigated in this study (Table 1). Plant A is located in South Korea and the others are in the Middle East. Two different pretreatment processes are installed in parallel at plant A and plant D. In particular, UF at plant D have three independent systems from different suppliers in parallel. Periodically, raw seawater has been collected from the sampling line after a seawater intake pump, and RO feedwater has been collected from the sampling lines after the outlets of dual media filtration (DMF) or UF for all the five RO plants.

2.2. Seawater quality analysis

Seawater (20 L) is regularly collected to measure the conventional seawater qualities, MMAS and fluorescence. Some portion of the collected water is first analyzed for turbidity using a turbidity meter (2100P, Hach, USA)

Table 1
Configurations and sampling duration of five different RO plants investigated in this study

Plant	Pretreatment process	SWRO process	Sampling duration
A	DAF + UF, DAF + DMF	Partial two pass	Aug 2014 – Aug 2015
B	DAF + DMF	Partial two pass	Mar 2017 – Dec 2017
C	DAF + UF	Partial two pass	July 2014 – July 2016
D	DAF + DMF, DAF + UF	Single pass	Jan 2017 – Dec 2017
E	DAF + UF	None	Apr 2017 – Oct 2017

and for UV_{254} using a UV spectrophotometer according to a standard method [5]. In addition, MMAS is employed to measure the SDI, P-MFI and C-MFI values with about 15 L of the collected seawater [21]. MFI measurements are carried out according to the ASTM test method D4189. P-MFI is obtained by filtering a seawater sample through 0.45 μm pore sized membrane (Millipore Corp., HAWP, mixed cellulose esters) under 2.07 bar. The filtrated water is then fed to the 100 kDa pore sized membrane (Millipore Corp., PLHK, regenerated cellulose) under 12.4 bar to obtain C-MFI values. The filtered water by 0.45 μm membrane is also analyzed to obtain an EEM by a HORIBA Jobin Yvon AquaLog fluorometer (Horiba Scientific, USA). Fluorescence emission wavelengths are 240–600 nm (increment about 2 nm) and excitation wavelengths are 220–500 nm (increment 5 nm). The obtained fluorescence data are processed with MATLAB using PARAFAC tools in the N-way toolbox [24]. HUMIC and PROTEIN are quantified by converting EEMs based on the established PARAFAC model [24].

2.3. Data collection and analytical methods

Seawater quality data (turbidity, SDI, P-MFI, C-MFI, PROTEIN and HUMIC) obtained from five different plants are analyzed by Origin software (OriginLab, Northampton, MA). Plant operation data (differential pressure increase of RO train, filtration flux of UF system, loading rates of DMF system, ferric dosing rates, etc.) are obtained from each plant. Statistical analyses are carried out to evaluate the correlation between the seawater quality and the plant operating parameters by the Origin software.

3. Results and discussion

3.1. Comparison of seawater quality parameters

P-MFI is compared with the conventional seawater quality parameters (SDI_{15} and turbidity). The three parameters were measured at the same time for the samples collected from plant C and D. P-MFI values have relatively linear correlation with those of SDI_{15} only when $SDI_{15} < 5$ (inset in Fig. 1(A)). In the region of $SDI_{15} > 5$, the increment of P-MFI values is much higher compared with that of SDI_{15} (Fig. 1(A)), which indicates that P-MFI has better resolution for seawater quality than SDI_{15} in the range. Similarly, P-MFI values have linear correlation with those of turbidity in the range from 0.4 to 10 NTU which is typically found in raw seawater of seawater reverse osmosis (SWRO) plants (Fig. 1(B)). P-MFI values are highly varied ranging from 1 to 10 when turbidity values are in the range of 0.1 to 0.3 NTU. These results strongly suggest that P-MFI could be the substitute for both SDI_{15}

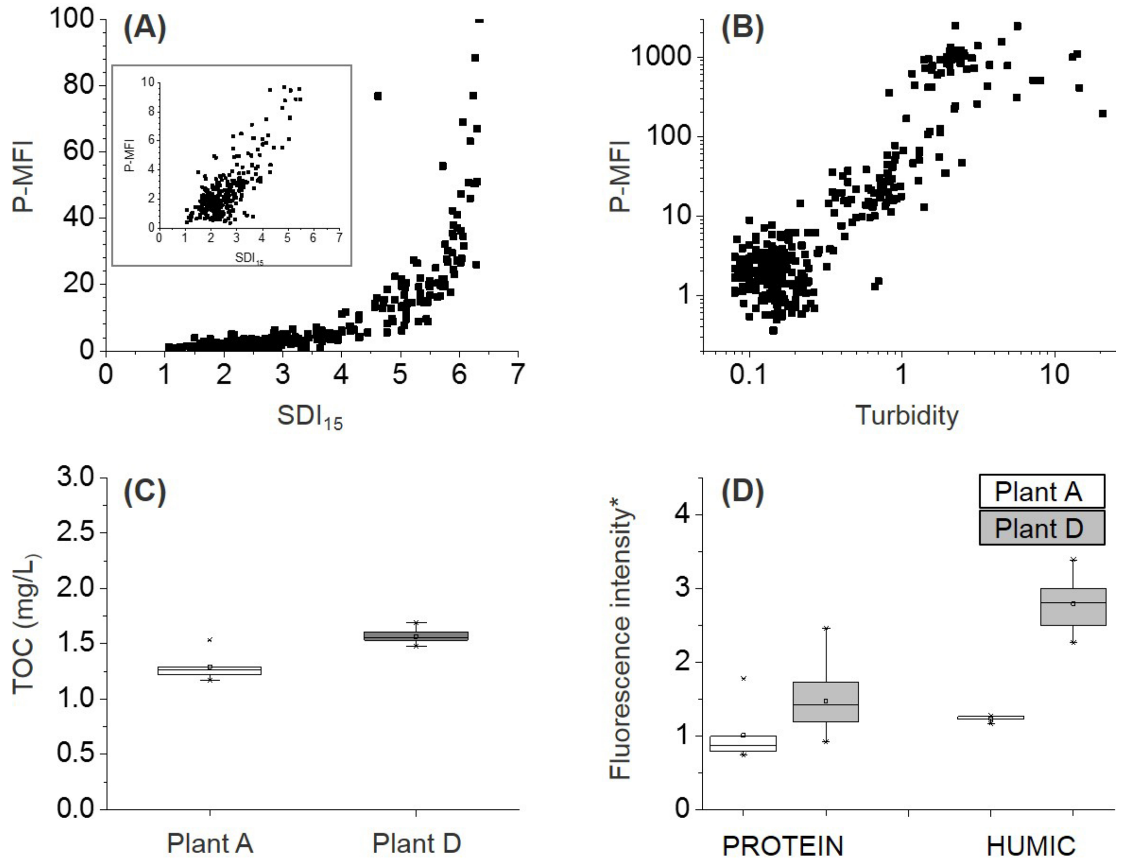

Fig. 1. Comparison of the seawater quality parameters obtained from SWRO plants. P-MFI and SDI values from plant D are plotted in (A). P-MFI and turbidity values from plant C are plotted in (B). TOC and fluorescence intensity as HUMIC and PROTEIN from plant A and D were compared in (C) and (D), respectively. Inset in (A) is the enlarged view of the region where P-MFI and SDI shows a linear correlation. *Fluorescence intensity (counts per seconds) represents a peak volume of 3D-EEM (excitation emission matrix).

and turbidity as well as that seawater quality could be traced from raw seawater to RO feedwater by P-MFI due to its wide quantification range. On the other hand, comparison of both MFI and SDI_{15} in terms of membrane fouling was reported in several studies [8,9].

TOC values are compared with those of PROTEIN and HUMIC (Figs. 1(C) and (D)). All measurements were carried out with the samples collected from plant A and D during Jan and Feb 2017. The values of the three different parameters are higher at plant D than at plant A. The difference of PROTEIN and HUMIC values at both plants is more distinct compared with that of TOC. PROTEIN could be a parameter showing the extent of microbially-derived organic matters (MOM) which are composed of biopolymer, building block and a low molecular weight acid because some fractions of MOM include protein molecules [16,19]. Although PROTEIN parameter cannot cover non-protein fraction of MOM, it could serve as a surrogate for MOM once protein content of MOM is not significantly varied. HUMIC is a dominate fraction of terrestrially derived organic matters [19]. This approach allows for the separation of organic matters according to their origins closely related to the properties (molecular weight, polarity and charge density) that are important factors in membrane fouling.

3.2. RO feedwater quality guidelines by the four different water quality parameters

RO feedwater quality guidelines are aimed to define an appropriate level of impurities that could secure an RO membrane from severe membrane fouling. In order to establish the guidelines by the four proposed seawater quality parameters (P-MFI, C-MFI, PROTEIN and HUMIC), RO feedwater quality is analyzed at four different SWRO plants (plant A, plant B, plant C and plant D), showing the different extent of RO membrane fouling (Fig. 2). The extent of the membrane fouling in the SWRO plants is classified by three different grades according to the number of clean-in-place (CIP) operations carried out in RO membrane for a year operation: low fouling (CIP < 2 times per year, plant A and plant B), moderate fouling (CIP = 2–4 times per year, plant D), and heavy fouling (CIP > 10 times per year, plant C). The number of CIP could be used as a rough index for membrane fouling, because the CIP has been carried out when the normalized pressure drop (DP) between the feed and concentrate headers reaches to usually 150% of the initial DP due to membrane fouling. Pretreated water quality is regularly analyzed for P-MFI, C-MFI, PROTEIN and HUMIC at the four SWRO plants. Comparing the pretreated water qualities from the

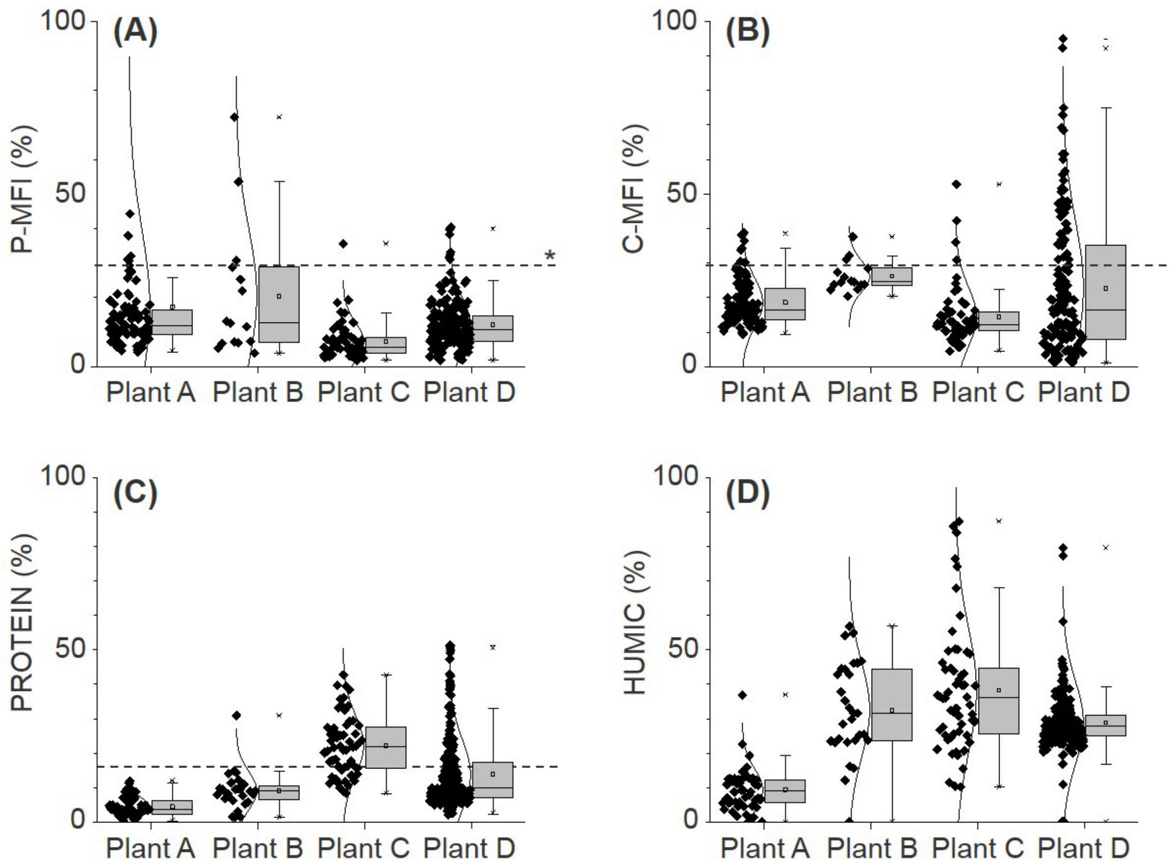

Fig. 2. RO feedwater quality as P-MFI (A), C-MFI (B), PROTEIN (C) and HUMIC (D) from the four different SWRO plants (Y axis is the relative values (%) of the four parameters and dots are the raw data. In the box plots, the lower and upper line of the box represents the values at 25th and 75th percent, the middle line is the average, and the small open square is the median of the data. Error bars represent 1.5 interquartile range from the 25th and 75th percentile. The curve stands for the normal distributions of the data. The dotted horizontal lines are the suggested guidelines of P-MFI, C-MFI and PROTEIN to prevent severe RO membrane fouling).

four SWRO plants with the actual RO membrane fouling in terms of DP increase, RO feedwater quality guidelines are suggested by P-MFI, C-MFI, PROTEIN and HUMIC as described in the following sub-sections.

3.2.1. Particulate and colloidal matters

P-MFI and C-MFI values obtained from the MMAS measurements of RO feedwater at the four SWRO plants are compared in Figs. 2(A) and (B), respectively. From the actual CIP frequency over a year, plant A and plant B are classified as a low fouling plant, where the MFI values for plant B are higher compared with those of plant A. So, the 75th percent value of plant B data is considered as the RO feedwater guidelines for P-MFI and C-MFI. Plant D, classified as moderate fouling, is the only plant exceeding this guideline for C-MFI. It is noted that the guideline could be revised once some other plants operating at low fouling but with higher MFI values at RO feedwater are reported.

The proposed P-MFI guideline value approximately corresponds to SDI_{15} = 4, from around 100 RO feedwater sample data when both P-MFI and SDI_{15} are measured at the same time (data not shown). SDI_{15} = 4 is the widely accepted value for RO plant operation to maintain the RO membrane condition at low fouling [25]. Though there has been no guideline proposed yet for C-MFI, as per the authors' knowledge, the correlation between C-MFI values and DP increase in RO was investigated also in the precedent study by analyzing full-scale RO plant data [5]. Therefore, maintaining the C-MFI value of RO feedwater below a certain guideline is recommended to minimize RO membrane fouling potential.

3.2.2. Organic matters

Protein and humic concentrations obtained from the fluorescent measurements of RO feedwater at the four SWRO plants are compared in Figs. 2(C) and (D), respectively. PROTEIN values at plant C could be considered as an unacceptable level, because the other concentrations of P-MFI, C-MFI and HUMIC at plant C (heavy fouling) are lower than or similar to those of plant A and B (low fouling). Therefore, the PROTEIN value at 25th percent of the plant C data, which is similar to the 75% percent value of plant D, is proposed as a RO feedwater guideline. From HUMIC values, it is found to be difficult to evaluate the potential of membrane fouling in this study, because plant B (low fouling) and plant C (heavy fouling) show a similar HUMIC value distribution.

In order to investigate the effects of PROTEIN and HUMIC values on membrane fouling, the correlation between the PROTEIN and HUMIC values and the DP increase at RO is analyzed using plant C data (Fig. 3). The multiple regressions of PROTEIN and HUMIC values as independent variables against the DP increase are plotted in Fig. 3(A). The correlation is statistically linear (R^2 = 0.480, p < 0.0008), which indicate that these parameters are related to the membrane fouling in plant C. The values of other parameters, SDI_{15}, P-MFI and C-MFI, are found to be similar to those values in plant A and plant B (low fouling). In addition, the accumulation of PROTEIN and HUMIC on RO membrane is evaluated by calculating the balance of PROTEIN and HUMIC in RO membrane (Fig. 3(B)). The results show that the relative accumulation of PROTEIN is about twice of that of HUMIC, which suggested that PROTEIN could more significantly affect the membrane fouling at plant C compared with HUMIC. The results are well correlated with

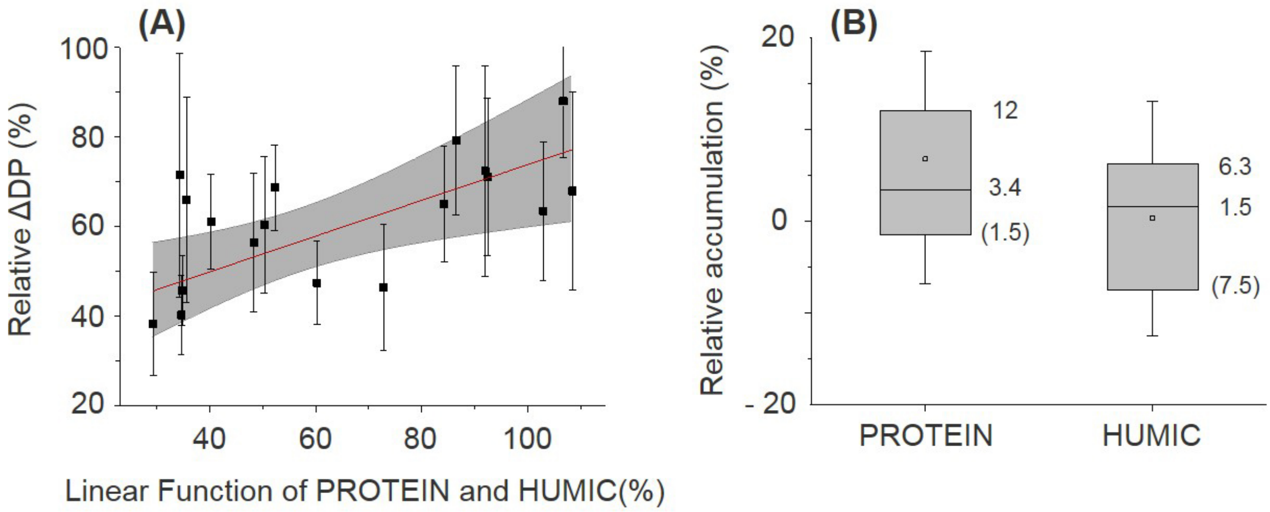

Fig. 3. Linear regression of RO membrane fouling represented by the daily increment of differential pressures in RO trains and the linear functions of PROTEIN and HUMIC (A) and the relative accumulation (%) of PROTEIN and HUMIC on RO membrane at plant C (B) (The linear functions of PROTEIN and HUMIC are obtained from the multiple regressions between the daily DP increment and PROTEIN and HUMIC. The values from the linear functions of PROTEIN and HUMIC are normalized and expressed in percent values. The relative accumulation (%) is calculated from the difference of the mass flow rates of PROTEIN and HUMIC at RO feedwater and those of concentrate and permeate. The mass flow rates are obtained by multiplying the measured concentrations of PROTEIN and HUMIC and the flow rates of feedwater, concentrate and permeate, respectively. Gray shading in (A) stands for 99% confidence band of ΔDP).

the theoretical and experimental evaluations for membrane fouling by organic matters [19].

3.3. Control of colloidal and organic matters

In order to employ the four suggested parameters in RO plant operation, the values of those parameters are examined from raw seawater to RO feedwater, according to the plant operating conditions. The reduction of particulate matters by pretreatment is already well established [25]. Here, of interest are (1) how the amount of colloidal and organic matters represented by C-MFI, PROTEIN and HUMIC might be changed according to the pretreatment and related operating conditions and (2) how the amount of colloidal and organic matters could be controlled below the suggested guidelines.

3.3.1. Colloidal control in seawater

Colloidal matters could be removed via coagulation and flocculation in water treatment processes. The colloidal removal efficiency in RO plant is currently evaluated by turbidity or SDI_{15} measured at the outlet of dissolved air flotation (DAF) and/or the subsequent filtration unit (DMF or UF). These conventional parameters, however, are not specialized to measure the amount of only colloidal matter in seawater, thus the optimization of coagulation and flocculation is difficult with the conventional parameters. In the UF system in plant D, which is directly receiving raw seawater, the removal of colloidal matters (reduction of C-MFI values after the pretreatment) is monitored according to the increase of $FeCl_3$ dosage rate for a month (Fig. 4). Reduction of C-MFI has been gradually improved with the increased $FeCl_3$ dosage and then the reduction rate is almost saturated when the $FeCl_3$ dosage rate reaches to about 1.2 ppm as Fe (Fig. 4(B)). During the experiment, SDI_{15} showed almost similar values regardless of $FeCl_3$ dosage rate (Fig. 4(A)). The results indicate that the colloidal removal could be monitored and the appropriate $FeCl_3$ dosage could be evaluated by C-MFI. Similarly, control logics could be employed at DAF system for optimal operation of coagulation and flocculation (data not shown). The results suggest that C-MFI could be used as a barometer to colloidal matters in design and operation of RO plant.

3.3.2. Control of organic matters in seawater

PROTEIN and HUMIC values are analyzed from raw seawater to RO feedwater in order to evaluate a pretreatment process. Approximately 30% of HUMIC is removed after DAF units compared with raw seawater while there has been no notable sign of PROTEIN removal at plant B and plant C (data not shown). In addition, during some operation periods without $FeCl_3$ dosage at plant A, no significant removal of HUMIC is observed. The results suggest that HUMIC could be reduced by proper coagulation and flocculation in DAF. Similar observations representing 20%–30% of TOC removal at DAF are reported in several studies [16,17,26].

The removal of PROTEIN through DMF is evaluated at plant B and plant D. More than 80% of PROTEIN is removed when DMF is operated with a slow filtration velocity of about 7 m/h. DMF at plant D operates with a high filtration velocity of more than 15 m/h, and less than 10% of PROTEIN removal is observed. No significant PROTEIN removal is observed through UF at plant C and plant D. The results suggest that an appropriate operation of DMF could reduce PROTEIN concentration in the treated seawater. There are studies reporting that DMF could eliminate organic matters under proper operating conditions [27,28]. The removal rate is related to mainly both filtration velocity and microbial acclimation at packing materials of DMF.

3.4. Applications to SWRO plant operation and design

3.4.1. SWRO plant operation with the four suggested seawater quality parameters

Several operating parameters could be determined in RO plant operation by monitoring the P-MFI, C-MFI, HUMIC and PROTEIN values (Fig. 5). First, the dosage rate of coagulant (such as $FeCl_3$) could be decided based on the C-MFI value of raw seawater. Similarly, the optimum $FeCl_3$ dosage rate could be determined by monitoring the C-MFI

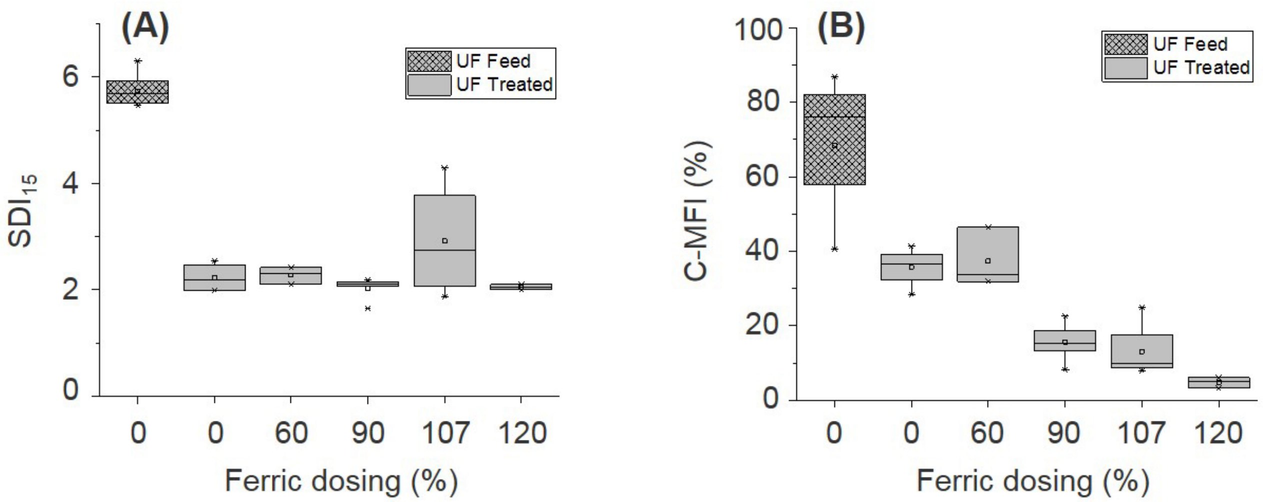

Fig. 4. Variations of SDI_{15} (A) and C-MFI (B) of UF-treated water according to the amounts of ferric added into UF feedwater.

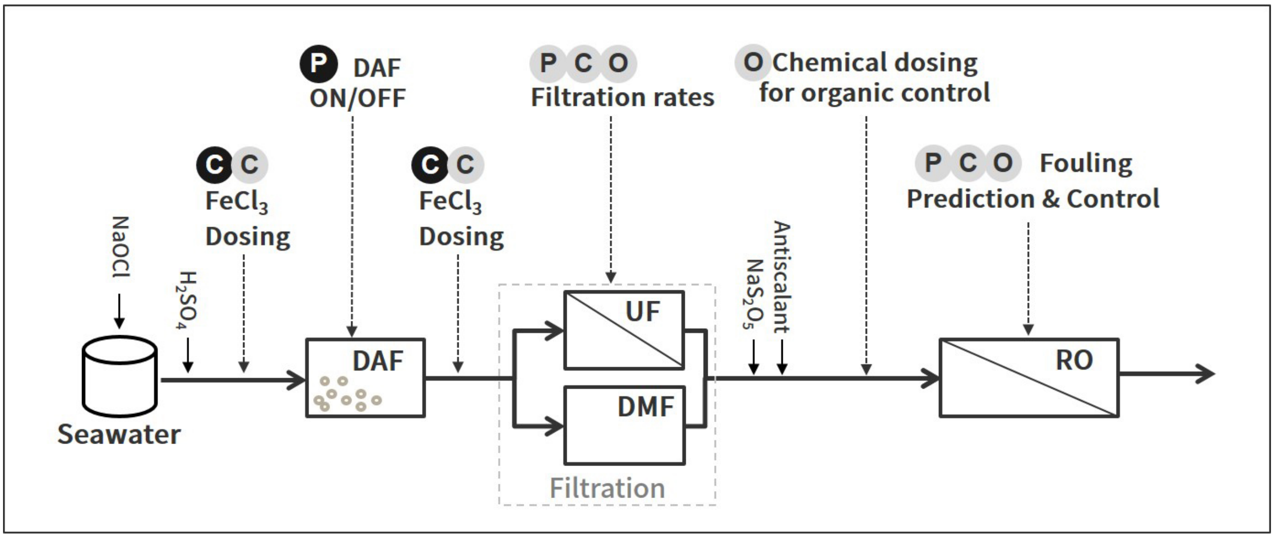

Fig. 5. Scheme for SWRO operation with the four suggested seawater quality parameters (P, C, O in the circles stand for P-MFI, C-MFI and PROTEIN in either raw seawater or RO feedwater. Black circle stands for those in raw seawater and gray circle for those in RO feedwater).

value at RO feedwater, to maintain the C-MFI value lower than the guideline. Second, if PROTEIN value exceeds the guideline, adjustment of DMF operating conditions could be considered to minimize RO membrane fouling. In case of SWRO plant employing a UF system, non-oxidative chemical dosing could be considered to mitigate membrane fouling [29,30]. Third, the potential of membrane fouling could be evaluated by P, C, O values in RO feed water, which could guide field operators to devise an appropriate pretreatment operating conditions. Lastly, P-MFI could serve as an index for DAF operation on and off. The role of DAF is to reduce the particle loading because the particle loading is a burden for all following filtration processes if it is too high. Once the appropriate particle loading for the subsequent filtration process is determined, DAF operation could be ceased when P-MFI value is below the set value.

3.4.2. Pretreatment design of SWRO plant

The role of pretreatment is to remove impurities, mainly particulate and colloidal matters, so the performance evaluation in terms of impurity removal is a key design factor for pretreatment processes. The impurity removal performances of four different filtration units at plant D are compared by P-MFI and C-MFI parameters (Fig. 6). All the treated water qualities from the four filtration units are found to meet the guideline of P-MFI, while the UF (type 3) and DMF could not satisfy the guideline of C-MFI. This failure could not be observed by P-MFI or SDI_{15}. The results indicate that employing both P-MFI and C-MFI would be essential to select a proper pretreatment process and to evaluate the performance.

Seawater quality is a crucial factor to determine the capacity of pretreatment. For the same type of pretreatment process, the capacity should be increased with the increased amount of impurities in seawater. The P-MFI and C-MFI parameters described in this study are found to distinguish well the regional variations of seawater quality for the four RO plants at different locations (Figs. 7(A) and (B)). Turbidity and TSS values obtained from each plant are plotted in Figs. 7(C) and (D). Variations of turbidity among plants B–E are similar to those of P-MFI and C-MFI, but the regional variations by turbidity is quite a bit obscure. Plant A shows relatively high values of turbidity even though those of P-MFI and C-MFI are very low, which might be due to different characteristics of particles in seawater, such as size and composition that can affect turbidity [14]. TSS values of plant B and plant D are significantly high compared with the other plants but the reason is not clarified in this study. One of possible reasons is that particle content in the raw seawater samples from five plants is below the reliable quantification ranges of TSS, which might cause the errors for TSS measurement [11,12]. The results suggest that the evaluation of regional variations of seawater quality in terms of MFI values could provide better comparison of the particulate and colloidal impurities at different plants, which could mitigate the risk of failures in design of the pretreatment configuration due to misunderstanding of the seawater quality variations.

4. Conclusions

Four new seawater quality parameters, P-MFI, C-MFI, PROTEIN and HUMIC, could improve the characterization of seawater quality in relation to RO membrane fouling potential by several key types of impurities, which are particles, colloids and organic matters. Employing the four parameters could provide several advantages over the conventional water quality parameters:

- P-MFI shows a wide range of quantification of particulate matters in seawater compared with SDI_{15}, turbidity and TSS, which enables to trace the changes of impurities concentrations from raw seawater to RO feedwater according to different pretreatment systems and operating condition. The property of P-MFI is beneficial to estimate the performance of pretreatment processes.

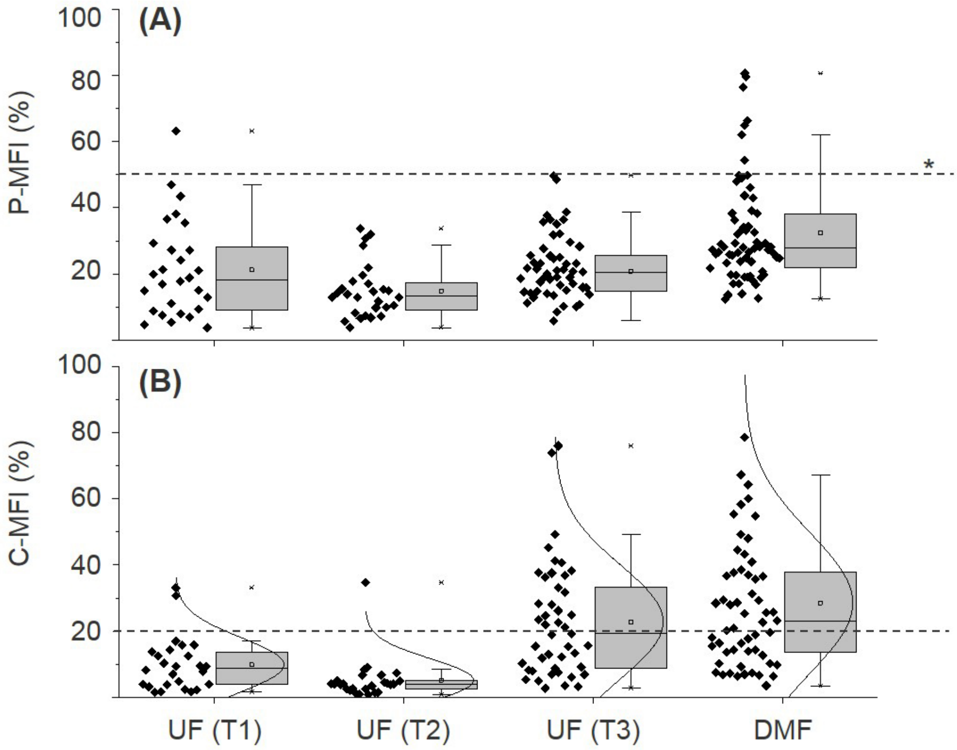

Fig. 6. Treated water quality by four different types of filtration units at plant D (X axis stands for three different UF (T1, T2, and T3) and one DMF process. The dotted horizontal lines represent the suggested guidelines of P-MFI and C-MFI to prevent severe RO membrane fouling).

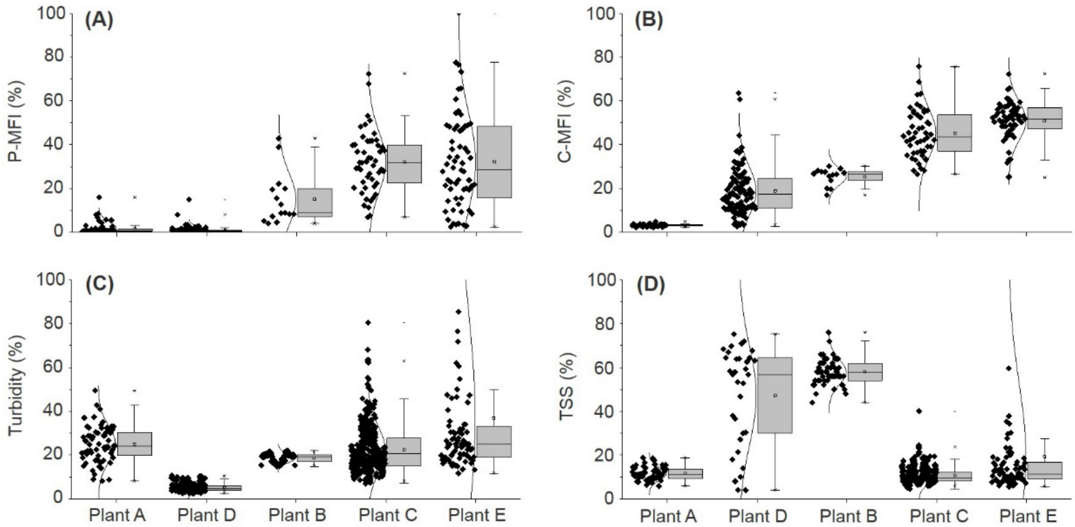

Fig. 7. Variations of seawater quality in terms of P-MFI (A), C-MFI (B), turbidity (C) and TSS (D) at five SWRO plants A to E.

- C-MFI is specialized to measure the amount of only colloidal matter in seawater, which allow for both the optimization of coagulation and flocculation and the comparison of pretreatment performances in terms of colloidal removal, which are not determined by P-MFI or SDI_{15}.
- PROTEIN and HUMIC can quantify amounts of organic matters from two different origins (microbially- or terrestrially-derived, respectively). This classification is beneficial to evaluate the fate of organic matters during pretreatment processes as well as the membrane fouling because the two different origins are closely related to their chemical properties of molecular weight, polarity and charge density that are important factors in several physicochemical processes in SWRO plants including membrane fouling.

In addition, appropriate guidelines of the four parameters are suggested to prevent severe membrane fouling by comparing RO feedwater quality at four SWRO plants which show different extent of membrane fouling. The parameters also successfully described the regional variation of seawater quality as well as the changes of impurities concentrations from raw seawater to RO feedwater according to different pretreatment systems and operating conditions. Therefore, the new suggested parameters could be used as barometers for a reliable RO plant design and operation with minimized RO membrane potential.

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References

[1] B. Penate, L. Garcia-Rodriguez, Current trends and future prospects in the design of seawater reverse osmosis desalination technology, Desalination, 284 (2012) 1–8.
[2] P.S. Goh, T. Matsuura, A.F. Ismail, B.C. Ng, The water-energy nexus: solutions towards energy-efficient desalination, Energy Technol., 5 (2017) 1136–1155.
[3] L.O. Villacorte, S.A.A. Tabatabai, D.M. Anderson, G.L. Amy, J.C. Schippers, M.D. Kennedy, Seawater reverse osmosis desalination and (harmful) algal blooms, Desalination, 360 (2015) 61–80.
[4] J.S. Vrouwenvelder, S.A. Manolarakis, J.P.v.d. Hoek, J.A.M.v. Paassen, W.G.J.v.d. Meer, J.M.C.v. Agtmaal, H.D.M. Prummel, J.C. Kruithof, M.C.M.v. Loosdrecht, Quantitative biofouling diagnosis in full scale nanofiltration and reverse osmosis installations, Water Res., 42 (2008) 4856–4868.
[5] Y. Jin, H. Lee, Y.O. Jin, S. Hong, Application of multiple modified fouling index (MFI) measurements at full-scale SWRO plant, Desalination, 407 (2017) 24–32.
[6] T. Miyoshi, M. Hayashi, K. Shimamura, H. Matsuyama, Important fractions of organic matter causing fouling of seawater reverse osmosis (SWRO) membranes, Desalination, 390 (2016) 72–80.
[7] N. Her, G. Amy, D. Foss, J. Cho, Y. Yoon, P. Kosenka, Optimization of method for detecting and characterizing NOM by HPLC - Size exclusion chromatography with UV and on-line DOC detection, Environ. Sci. Technol., 36 (2002) 1069–1076.
[8] K. Hong, S. Lee, S. Choi, Y. Yu, S. Hong, J. Moon, J. Sohn, J. Yang, Assessment of various membrane fouling indexes under seawater conditions, Desalination, 247 (2009) 247–259.
[9] Y. Jin, Y. Ju, H. Lee, S. Hong, Fouling potential evaluation by cake fouling index: theoretical development, measurements, and its implications for fouling mechanisms, J. Membr. Sci., 490 (2015) 57–64.
[10] M.D. Kennedy, J. Kamanyi, B.G.J. Heijman, G. Amy, Colloidal organic matter fouling of UF membranes: role of NOM composition & size, Desalination, 220 (2008) 200–213.
[11] Total suspended solids (TSS) in EPA Method 160.2 (1999), US Environmental Protection Agency (EPA), Washington, DC.
[12] Standard method 2540 solids in standard methods for the examination of water and wastewater 19th Ed. (1995), American Public Health Association (APHA), Washington, DC.
[13] A. Alhadidi, A.J.B. Kemperman, B. Blankert, J.C. Schippers, M. Wessling, W.G.J.v.d. Meer, Silt density index and modified fouling index relation, and effect of pressure, temperature and membrane resistance, Desalination, 273 (2011) 48–56.
[14] A. Rymszewicz, J.J. O'Sullivan, M. Bruen, J.N. Turner, D.M. Lawler, E. Conroy, M. Kelly-Quinn, Measurement differences between turbidity instruments, and their implications for suspended sediment concentration and load calculations: a sensor inter-comparison study, J. Environ. Manage., 199 (2017) 99–108.
[15] J.K. Edzwald, J. Haarhoff, Seawater pretreatment for reverse osmosis: chemistry, contaminants, and coagulation, Water Res., 45 (2011) 5428–5440.
[16] H.K. Shon, S.H. Kim, S. Vigneswaran, R.B. Aim, S. Lee, J. Cho, Physicochemical pretreatment of seawater: fouling reduction and membrane characterization, Desalination, 238 (2009) 10–21.
[17] N. Her, G. Amy, J. Chung, J. Yoon, Y. Yoon, Characterizing dissolved organic matter and evaluating associated nanofiltration membrane fouling, Chemosphere, 70 (2008) 495–502.
[18] L.O. Villacorte, Y. Ekowati, T.R. Neu, J.M. Kleijn, H. Winters, G. Amy, J.C. Shippers, M.D. Kennedy, Characterisation of algal organic matter produced by bloom-forming marine and freshwater algae, Water Res., 73 (2015) 216–230.
[19] G. Amy, Fundamental understanding of organic matter fouling of membranes, Desalination, 231 (2008) 44–51.
[20] L.O. Villacorte, Y. Ekowati, H. Winters, G.L. Amy, J.C. Schippers, M.D. Kennedy, Characterization of transparent exopolymer particles (TEP) produced during algal bloom: a membrane treatment perspective, Desal. Wat. Treat., 5 (2013) 1021–1033.
[21] Y. Yu, S. Lee, K. Hong, S. Hong, Evaluation of membrane fouling potential by multiple membrane array system (MMAS): measurements and applications, J. Membr. Sci., 362 (2010) 279–288.
[22] S.F.E. Boerlage, M.D. Kennedy, M.p. Aniye, E.M. Abogrean, D.E.Y. El-Hodali, Z.S. Tarawneh, J.C. Shippers, Modified fouling index$_{ultrafiltration}$ to compare pretreatment process of reverse osmosis feedwater, Desalination, 131 (2000) 201–214.
[23] K.R. Murphy, C.A. Stedmon, D. Waite, G.M. Ruiz, Distinguishing between terrestrial and autochthonous organic matter sources in marine environments using fluorescence spectroscopy, Mar. Chem., 108 (2008) 40–58.
[24] K.R. Murphy, C.A. Stedmon, D. Graeber, R. Bro, Fluorescence spectroscopy and multi-way techniques. PARAFAC, Anal. Methods, 5 (2013) 6541–6882.
[25] N. Voutchkov, Desalination Engineering: Operation and Maintenance, McGraw Hill, 2014.
[26] S.-N. Nam, Characterization and Differentiation of Wastewater Effluent Organic Matter (EfOM) versus Drinking Water Natural Organic Matter (NOM): Implications for Indirect Potable Reuse, Department of Civil, Environmental, & Architectural Engineering, University of Colorado, 2011.
[27] E. Bar-Zeev, N. Belkin, B. Liberman, T. Berman, I. Berman-Frank, Rapid sand filtration pretreatment for SWRO: microbial maturation dynamics and filtration efficiency of organic matter, Desalination, 286 (2012) 120–130.
[28] C. Halle, P.M. Huck, S. Peldszus, J. Haberkamp, M. Jekel, Assessing the performance of biological filtration as pretreatment to low pressure membrane for drinking water, Environ. Sci. Technol., 43 (2009) 3878–3884.
[29] K. Majamaa, J.E. Johnson, U. Bertheas, Three steps to control biofouling in reverse osmosis systems, Desal. Wat. Treat., 42 (2012) 107–116.
[30] U. Bertheas, K. Majamaa, A. Arzu, R. Pahnke, Use of DBNPA to control biofouling in RO systems, Desal. Wat. Treat., 3 (2009) 175–178.