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Case study on pressured microfiltration and reverse osmosis membrane systems for water reuse

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ABSTRACT

According to the announcement by OECD [1], Korea is listed as the most "severe water stress" nation among OECD countries. As competition for restricted water resources is expected in the coming decades, development of technologies for water treatment and reuse becomes urgently needed. The combined microfiltration (MF) and reverse osmosis (RO) process has been one of the mostly employed treatment methods in obtaining recyclable quality for wastewater reclamation and reuse, yet few has reported a pilot-scale investigation with the pressurized MF (without pretreatment) and RO system. The pilot plant operated in Gimcheon City Sewage Treatment Plant consists of a PVDF membrane in pressurized MF (treatment capacity of MF and RO: 30 and 20 m^3/day) and a RO unit of wastewater reclamation. The result of the pilot study indicates that the reclaimed water can conform industrial water reuse standard (i.e., Turbidity (MF): 0.05 NTU, TDS (RO): 4.9 mg/L, TOC (RO): 0.79 mg/L). While the recovery rate run at the MF unit was 90%, the RO system was operated at 67%, to reach an overall system recovery rate of 60%. Herein, we report the performance of a pilot-scale pressurized MF and RO system operated for water reuse and discuss possible applications of the system for a test bed.

Keywords: Pressured microfiltration; Reverse osmosis; Water reuse; Polyvinylidene fluoride (PVDF) membrane modules

1. Introduction

As water scarcity is expected to increase incredibly in the near future, and the shortage of fresh water supplies turns into a barrier to environmental sustainability, demands for water reuse become intense. In fact, reuse is necessary throughout the world for the generation of potable water. Wastewater reclamation could be one of the means to increasing pressures on water supply and the problems of municipal wastewater disposal in terms of satisfying treatment efficiency and economic feasibility [2]. For reuse purposes, treatments of municipal wastewater are essential to an acceptable quality level.

As one of the water treatment technologies used for water reuse and environmental protection, membrane processes have been widely applied over

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the conventional wastewater treatment technologies. Conventional wastewater treatments have a particular difficulty in removing total dissolved solids (TDS) of sewage for most reuse applications. Membrane technology specifically the combined microfiltration (MF) as a pretreatment step and reverse osmosis (RO) seems to be practicable to produce quality waters for reuse purposes. The presence of emerging contaminants (i.e. endocrine disrupting compounds, pharmaceutically active compounds, or other unregulated trace pollutants) is though one of the most concerns in designing such treatment processes [3]. For more technological applications, improvement in membranes led to resist to changes in pH and temperature [4].

There has been research on the evaluation of MF and RO systems for the treatment of wastewater effluents. For instance, membrane processes appear to be mature technologies to traditional biochemical corn starch wastewater treatments, though the effectiveness of MF depends on concentrations of the feed solution and can be further improved by applying RO to the MF filtrate [5]. The performance of a small membrane facility for the production of high-quality waters from secondary effluents was evaluated with hollow fiber MF membranes as a pretreatment followed by RO and NF membranes and showed that combined NF and RO membranes removed total orthophosphorus [6]. Since MF should provide an effective pretreatment to RO, reverse osmosis (RO) or nanofiltration (NF) would be able to produce potable quality permeate.

Costs for treating secondary effluents by MF and RO processes were reported to be \$0.22–0.56/m^3 and \$0.40–0.93/m^3, respectively [7]. While the membrane technology is economically viable treatment, it has several hurdles to overcome, particularly accumulated fouling of contaminants at the membrane surface. Membrane fouling may occur concurrently by several factors such as scaling, organic fouling, colloidal fouling, and biofouling [8].

Some of the key issues for the reclamation of secondary effluents by MF and reverse osmosis (RO) or nanofiltration (NF) membranes include operating conditions, pretreatment, and cleaning. Hydrodynamic factors, including flux and/or applied pressure, pretreatment by coagulation prior to MF, and cleaning by physical backwashing or chemical cleaning, are all possible parameters on the issues [9]. Maintaining a constant flux for MF and cleaning (backwashing) could assist to avoid fouling on the membrane surface in the reclamation of municipal effluents. Of membrane technologies, RO has been commonly used for desalination of sea water and wastewaters. However, RO applications could encounter its limitation due to fouling and the ability of conventional pretreatment technologies [10].

Most problems in RO operation are reported to stem from inadequate feed pretreatment step. While traditional pretreatments such as sand filters, cartridge filters, chlorination, and flocculation do not effectively remove contaminants, causing RO membrane fouling, MF pretreatment appears to produce the most satisfying degree of water quality to RO [11].

Drewes et al. [12] compared MF followed by RO membrane systems with soil-aquifer treatment (SAT) for the effectiveness of producing potable reuse of wastewater. According to the report by the authors, removal of TOC by MF/RO and SAT was 0.3 and 1.0 mg/L, respectively. While the MF/RO process entirely removed the contaminants (EDTA and APECs) to below the detection limit, in the SAT treated effluent, EDTA and APECs were removed to approximately 4.3 and 0.54 mg/l, respectively. The removal of contaminants by SAT is mainly due to adsorption and biodegradation, while physical separation is the removal mechanism by membrane technologies [12].

Gabelich et al. [13] investigated both MF and ozonate/biofiltered (O_3/BF) processes as the best RO pretreatment technology. Conventional treatments left the RO system susceptible to organic and biological fouling and required more frequent cleanings than either MF or ozonation/biofiltration (O_3/BF). On the other hand, both microfiltered and ozonate/biofiltered waters provided steady RO performance. However, MF offered the best RO pretreatment technology [13].

Environmental protection, treatment efficiency and economical process costs with stringent environmental regulations and growing market preference have impinged on many industries [14]. Influenced by such factors, we performed a case study to investigate the feasibility of treating wastewater effluents (tertiary effluents) using a pilot-scale pressured MF followed by RO membrane system. We evaluated the combination of MF and RO units to explore the possibility of reducing wastewater pollution, producing quality waters for reuse purposes. A pilot-scale test program was run to demonstrate the ability of pressured MF and RO technologies in treating wastewater effluents from Gimcheon City Sewage Treatment Plant.

The objectives of the pilot system operated as a case study are (1) to validate that the pressured MF and RO systems can constantly produce high-purity waters for water reuse purposes; (2) to estimate the operational performance of the MF and RO systems without any pretreatment; (3) to collect analytical and process data to develop parameters for future test bed applications; (4) to offer operational experience with the treatment technique for water reuse commercialization.

2. Materials and methods

2.1. Source water

Tertiary effluents from standard activated sludge method were pilot tested to assess the capability of combined MF and RO membrane systems to produce high-quality permeate. The water quality of the source water collected during the pilot operation is revealed in Table 1.

2.2. Microfiltration pilot-scale system

MF pilot-scale system was provided by Korea Data Company. The MF using a 0.04 μm PVDF membrane of 38 m^2 was carried out in a tertiary wastewater treatment plant without any pretreatment step. The MF consisted of a hollow fiber, polyvinylidene fluoride (PVDF) membrane module with the dimensions of 194 mm diameter and 1,500 mm long. Details on the membrane module are provided in Table 2. Raw water was collected in a feed tank from which it was pumped and allocated to the MF unit. Filtration takes place from outside to inside and the MF unit was operated in a dead-end flow mode, which means that during filtration all the fluid in the feed passed through the membrane, while all of the rejected particles (larger than the pore sizes of the membrane) were stopped at its surface and accumulated within the module. A constant filtrate flow rate was maintained by the system operated in a manner that raw water was pumped to the membrane. Once the MF produce filtrate, it was stored in the RO feed tank and was then pumped to the RO system. The MF auto-monitoring screen and a process flow diagram of the pilot-scale system are provided as Figs. 1 and 3. During the operation, a membrane cleaning-in-place (CIP) was not conducted. The times for filtrate, backwashing, aeration, drain, and water supply in the MF system were 1050, 60, 30, 140, and 40 s, respectively.

Table 1
Water quality of the source water

Item	Unit	3/8/2012	3/11/2012	Average
TOC	mg/L	7.242	7.428	7.335
COD_{Mn}	mg/L	8.6	9.8	9.2
SS	mg/L	0	0	0
pH	–	7.6	7.4	7.5
T-N	mg/L	7.1	7.4	7.25
NH_3-N	mg/L	3.71	2.3	3.005
NO_3-N	mg/L	3	4.6	3.8
T-P	mg/L	0.36	0.17	0.265
TDS	mg/L	238	237	237.5
Conductivity	μm/cm	476	474	475
Ca	mg/L	30.65	29.28	29.965
Na	mg/L	40.51	45.68	43.095
Mg	mg/L	5.43	5.45	5.44
Mn	mg/L	0	0	0
Al	mg/L	0.03	0	0.015
Fe	mg/L	0	0	0
Ba	mg/L	0.017	0.021	0.019
Cl^-	mg/L	42.7	43.4	43.05
SO_4^{2-}	mg/L	28	28	28

Table 2
MF membrane specifications

Membrane property	Characteristic
Dimensions of modules	194 mm diameter × 1,500 mm long
Number of modules	1
Active membrane area per module	38 m^2 based on outside diameter
Membrane pore size	0.04 m
Membrane material	PVDF
Membrane configuration	Hollow fiber, Outside-in flow
Allowable operating pH range	1–10

2.3. RO pilot-scale system

The RO pilot-scale system contained two pressure vessels, which have two elements per vessel (Table 3). The pressure vessel housed 102 mm diameter RO membrane elements (Table 3). The RO membrane elements were provided by Woongjin Chemical Co. Ltd. (Model Number: RE4040-Fen) and are further described in Table 3. The feed pH to the RO unit was approximately 7.7, and the RO membrane was cleaned according to the manufacturer's guidelines. Anti-scalant chemicals for minimizing and preventing inorganic scaling on the membrane surface, and acid chemicals were not added to the RO feed water due to the short time of operation. During the pilot-scale testing, a CIP for the RO membranes was not performed. Unlike the MF system which operates in a dead-end flow mode, the RO system operates in a cross-flow mode. The RO system has a recovery rate of 67 percent at which the RO system could be

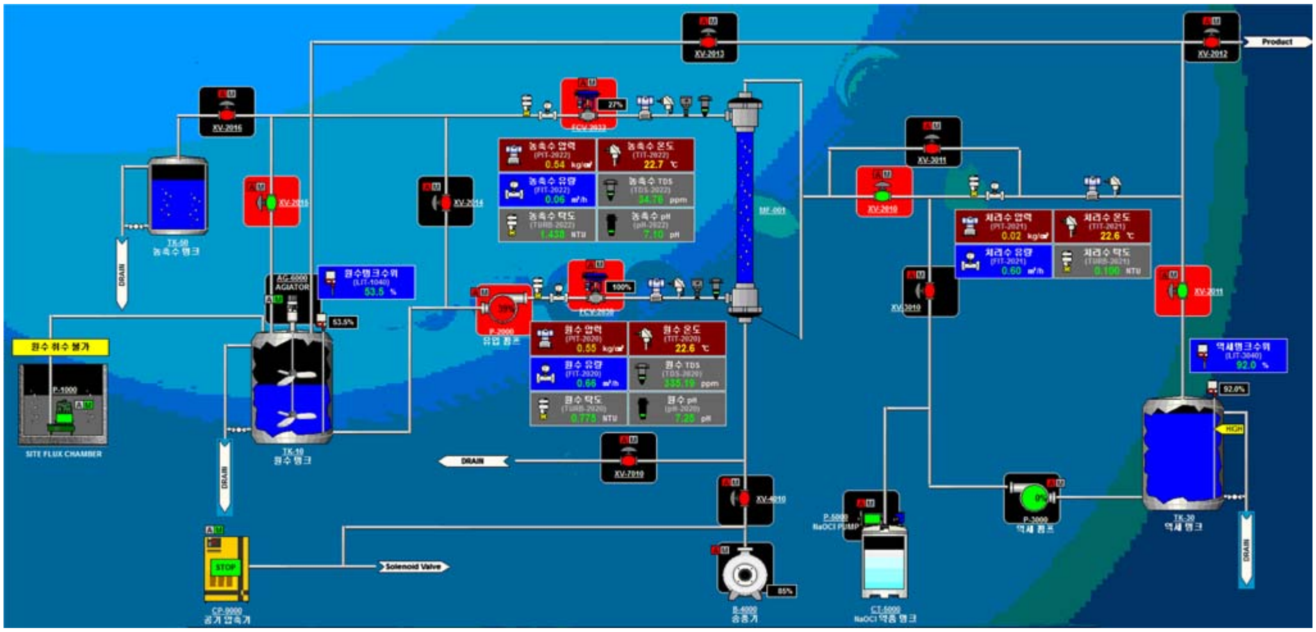

Fig. 1. MF monitoring screen.

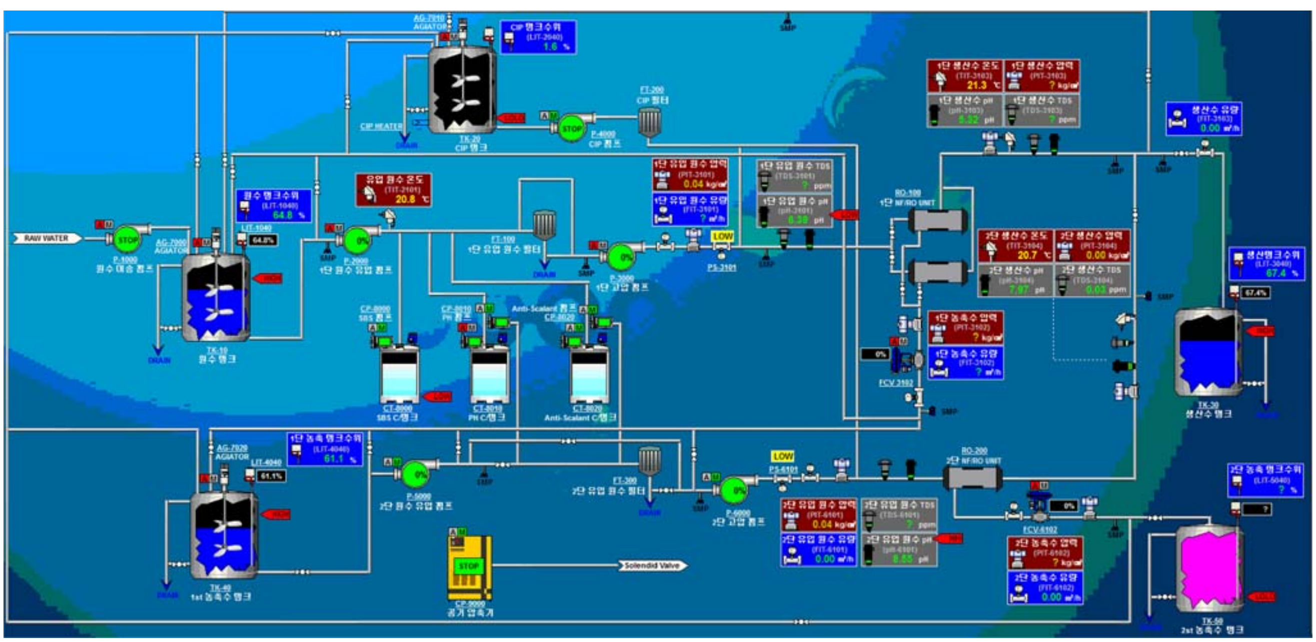

Fig. 2. RO monitoring screen.

operated without the use of anti-scaling agent within the short time period (Fig. 2).

2.4. Pilot-scale system operations

The pilot-scale test systems comprised of a pressured MF and a RO pilot-unit system. The MF and RO pilot equipments were assembled and moved to the site in December 2011, beginning the operation in March 2012 (Photo 1). The data collected used the wastewater treatment plant (WWTP) tertiary effluents as the source water, and it took place in March 2012.

2.5. Sample collection and analysis

During the operation, samples were collected from the MF feed water, MF filtrate, RO feed water, RO permeate and RO concentrate at the locations

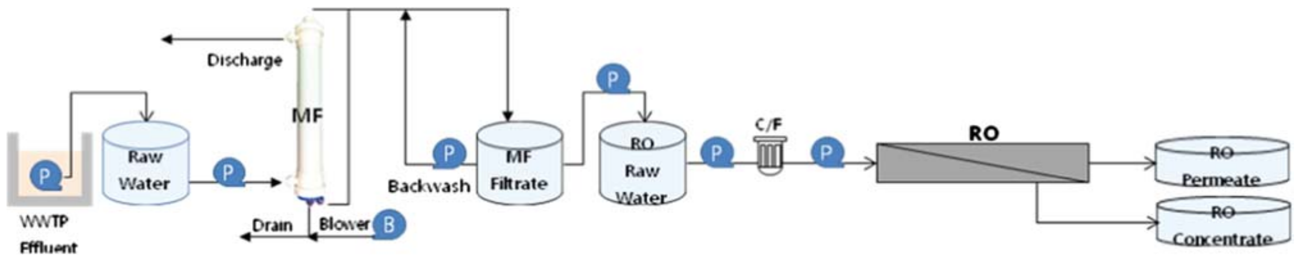

Fig. 3. Pilot-scale system process flow diagram.

Table 3
RO membrane specifications

Membrane property	Membrane characteristics
Membrane type	Spiral wound
Element model number	RE4040-Fen
Dimensions of elements	102 mm diameter × 1016 mm long
Number of elements	4 Array 2 (2 elements/vessel), 2 vessels
Active membrane area per module	7.9 m^2
Nominal rejection rate	99.7% for sodium and chlorine at standard test conditions
Free chlorine tolerance	<0.1 mg/L

specified in Photo 1. All samples were analyzed at a certified laboratory institution. With field measurement equipments, TDS, temperature, pressure, turbidity, and pH were also monitored at the spot.

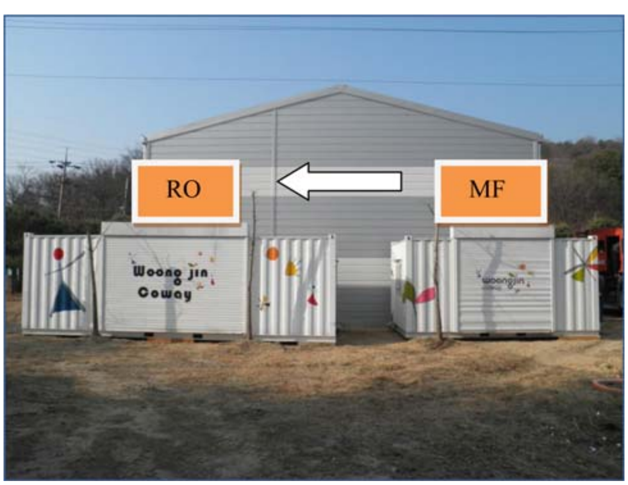

Photo 1. The deployment of MF (30 m^3/d) and RO (20 m^3/d) membrane systems of pilot plant.

3. Results and discussion

3.1. Microfiltration operating performance

The MF operating considerations and process data are given in Table 4. The pressured MF process was operated without any pretreatment. The MF system was operated at a flux of 1.0 m^3/m^2/d over approximately 8 h in a dead-end flow mode. Overall, the TMP stabilized with an average 0.46 kgf/cm^2 at 20˚C. The average filtrate flow rate was 1.56 m^3/h (Fig. 4). In the pilot operation, the MF system operated consistently, and there were no operational problems. TMP for this MF test was approximately 0.7 kg f/cm^2, and the temperature (both feed water and filtrate temperatures) was between 2˚C and 11˚C. The MF itself was found to be ineffective for removing most contaminants except SS, T-P, TOC, COD, while in RO permeate, most compounds are removed to the extent of supplying high-quality water (Table 5). At the process, neither the performance of a CIP nor establishing the cleaning frequency of MF membranes was done as tertiary effluent was used as the source water with the short-time operation. The average MF recovery was estimated by dividing the collective filtrate generated for the runtime by the cumulative raw water fed to the system during the operation time. The MF system recovery was 90 percent.

Samples for the MF feed water and the MF filtrate were collected and analyzed. The total suspended solids concentration of the filtrate was not detected, and the filtrate concentrations of TOC and COD were decreased by 24 and 26%, respectively (Table 5).

During the operation time, the average pH and turbidity of raw water were 7.17 and 1.24 nephelometric units (NTU), and the overall filtrate turbidity was around 0.05 NTU (Fig. 5).

Although there was some variation in feed turbidity, a low turbidity filtrate was obtained consistently.

Evidenced by the above results, MF is likely to be a source of high-quality treated water, since the system produces substantially better than that of traditional pretreatment systems and it improves the

Table 4
Operation considerations and process data (MF)

	Operation conditions		Process data			
MF	Flux	1.0 m3/m^2/d (area: 38 m^2)	Temperature	10.2℃	TMP (25℃)	0.65 kgf/cm^2, 0.53 kgf/cm^2
	Recovery	90%	Water treatment capacity	30 m^3/d	Turbidity	0.05 NTU
	Flow mode	Dead-end				

*Control system: PLC automatic control for the MF and RO sections of the plant.

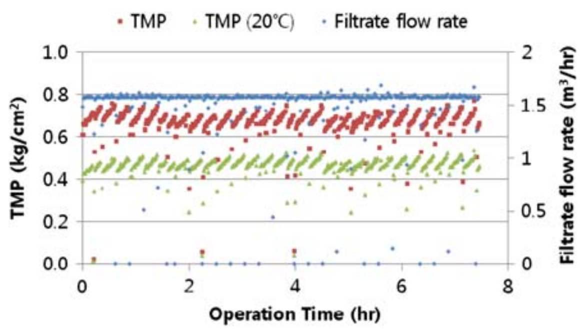

Fig. 4. MF operation—TMP and filtrate flow rate vs. time.

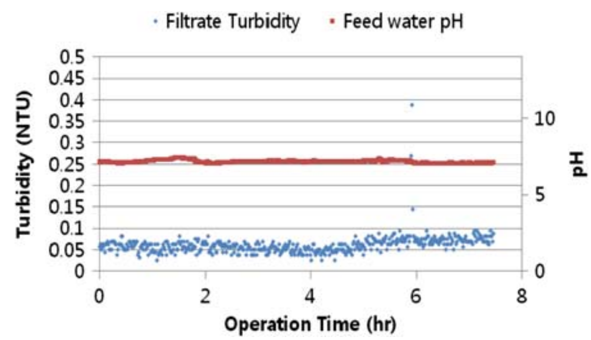

Fig. 5. MF operation—turbidity and pH vs. time.

Table 5
MF water quality data from the pilot plant operation

Parameter		MF	
–	Unit	Raw water	Filtrate
TOC	mg/L	7.335	5.564
COD_{Mn}	mg/L	9.2	6.8
SS	mg/L	6.0	0
pH	–	7.5	7.4
T-N	mg/L	7.25	6.7
T-P	mg/L	0.265	0.04
TDS	mg/L	238	239
Ion			
Ca	mg/L	29.97	29.42
Na	mg/L	43.10	45.88
Mg	mg/L	5.44	5.47
Mn	mg/L	0	0.005
Al	mg/L	0.02	0
Fe	mg/L	0	0
Ba	mg/L	0.02	0.019
Cl^-	mg/L	43.05	44.3
SO_4^{2-}	mg/L	28	28

performance of RO systems [11]. Based on the pore size (0.04 μm) of MF membrane used in the systems, it appears to have superior RO membrane performance. Actually, it was reported to give the highest bacteria removal with a 0.2 m nominal pore size of MF [13].

3.2. Reverse osmosis (RO) operating performance

The RO membrane assessed in this work was used to improve a tertiary effluent feed which was pre-treated by MF. Reverse osmosis (RO) is the process that ensures the highest water quality. In the RO process, no chemicals were added to the system due to the short-time operation. As with the MF system, a CIP was not necessary in the RO membrane.

The use of an RO system for treating the MF filtrate was done at a flow of approximately 0.82 m^3/h (Table 6), and the RO system was operated at an average recovery rate of 67% (Table 6; Fig. 6).

The average flow rate for feed water, permeate, discharge water (concentrate) was 1.21, 0.82, and 0.4 m^3/h correspondingly with an average recovery rate of 67.3% (Fig. 6). The pressures from feed water and concentrate in the RO pilot operation were around 13∼14 kgf/cm^2 with an average pressure drop (DP) of 0.51 kg f/cm^2, indicating a stable operation (Fig. 7). The inflow pressure, pressure drop (DP), flow rate, TDS, salt rejection rate, and recovery rate during the operation are shown in Figs. 6–8.

Water produced from the RO operation was of high quality with an average TDS 7.57 mg/L, salt rejection 99.4%, and TOC 0.79 mg/L, which secured the constant water quality and reached the water quality objectives (Fig. 8). While TDS concentration from the MF filtrate was 239 mg/L, the concentration of TDS from raw water to RO unit was higher as

Table 6
Operation considerations and process data (RO)

	Operation conditions		Process data			
RO	Water capacity (permeate)	0.82 m^3/h	Water treatment capacity	20 m^3/d	Inflow-pressure	13.5 kg f/cm^2
	Recovery	67%	Inflow-TDS	1279 mg/L	Concentrate pressure	13.0 kg f/cm^2
	Flow mode	Cross-flow	Outflow-TDS	7.6 mg/L	TOC	0.79 g/L

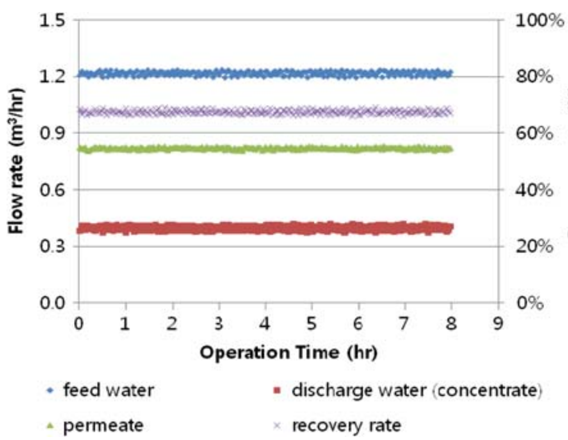

Fig. 6. RO operation—flow rate (m^3/h) and recovery rate (%) vs. time.

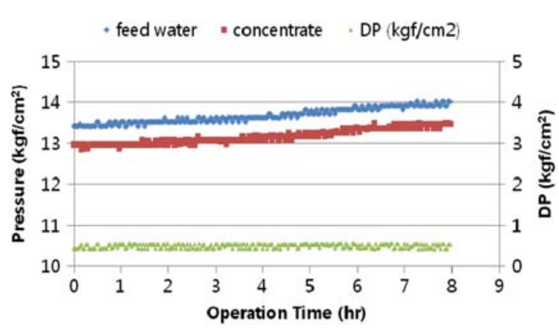

Fig. 7. RO operation—Inflow pressure and pressure drop (DP) vs. time.

643 mg/L due to the recycled RO concentrate (Table 5 vs. Table 7).

Samples were collected of raw water, permeate, and concentrate and analyzed as shown in Table 7. The RO membrane allows only water to pass through, thereby salts and organics are rejected. As expected, the RO membrane showed efficient TOC rejection of more than 94% (Table 7). As seen in Table 7, most contaminants of RO permeate were non-detected and significant removal of TDS (⩾99%) from the RO permeate was observed as revealed in the water quality

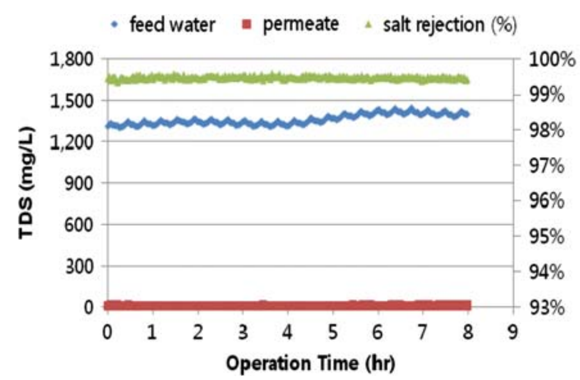

Fig. 8. RO operation—TDS (mg/L) and salt rejection (%) vs. time.

Table 7
RO water quality data from the pilot plant operation

Parameter		RO		
–	Unit	Raw water	Permeate	Concentrate
TOC	mg/L	13.458	0.789	18.576
COD_{Mn}	mg/L	15.8	0	17.8
SS	mg/L	0	0	0
pH	–	7.7	6.3	7.9
T-N	mg/L	21	0	34
T-P	mg/L	1.1	0	1.0
TDS	mg/L	643	4.94	775
Ion				
Ca	mg/L	83.24	0.38	118.1
Na	mg/L	136.3	1.13	171
Mg	mg/L	15.45	0.06	19.2
Mn	mg/L	0.015	0	0.021
Al	mg/L	0.04	0	0.04
Fe	mg/L	0.11	0	0.13
Ba	mg/L	0.055	0	0.067
Cl^-	mg/L	139	0.2	175.4
SO_4^{2-}	mg/L	91	0	115

data (Table 7). The treated water has a very low TDS. In general, the RO system produced permeate that met the established water quality objectives (i.e. overall MF/RO system recovery rate of 60%; TOC ⩽ 1.5 mg/L). With the recovery rate set for the project goal and the permeate flux, steady operation was completed.

4. Conclusions

Considering the overall plant performance presented in this case study, the efficiency of the MF pretreatment is proven by the stable performance of the RO membranes. The treated water (permeate) from the RO plant has TDS of <5 mg/L when treating tertiary wastewater of 643 mg/L TDS. The total system is fully automatic, has data logging, and operated through the remote desktop system. The coupled MF (without any pretreatment) and RO membrane technologies seem to be practicable to produce high-quality water for water reuse purposes. The MF/RO system recovery rate of 60% and TOC 0.8 mg/L from RO permeate were achieved and met the project goals.

Derived from the pilot operational data, the following conclusions can be made:

First, the results indicate that MF process is capable of producing a filtrate suitable for RO treatment, achieving a turbidity of 0.05 NTU. The water quality of RO effluent is superior with average concentrations of TDS 7.57 mg/L (TDS rejection: ⩾99%), TOC 0.8 mg/L (TOC rejection: >94%), and salt rejection of 99.4%.

Second, the MF and RO membranes are capable of consistently producing high-purity water (i.e. mostly non-detectable contaminants) that meets the established water quality goals treating tertiary effluent as source water when operating at an overall recovery rate of 90 and 67 percent, respectively.

Third, overall, the TMP maintained constant at an average 0.46 kg f/cm^2 (20℃) with the average filtrate flow rate of 1.56 m^3/h. The MF is effective as a pretreatment to RO, and the treatment was further improved by applying RO to the MF permeate. When treating tertiary wastewater effluents, the MF/RO systems were operated at the goal of 60% recovery rate.

Lastly, with the recovery rate set for the project goal and the permeate flux, steady operation was completed.

The membrane inventory of an RO plant is reduced by up to 30–40% on account of MF, and the capital and operating costs of RO continue to reduce [10]. In an economic point of view, treating secondary sewage for reuse with the MF and RO technologies could be another alternative [10]. Continuous MF, which allows RO technology to treat impractical source waters, offers RO feed water quality to be easily controlled and consistent [10]. With MF pretreatment prior to RO, there are several benefits such as stable operation, extended membrane life, significant operator labor savings, and start-up times [11].

Based on the present results, membrane processes appear to be an effective alternative to traditional wastewater treatments for reducing the environmental impact and improving the efficiency. From the pilot operation results, designs for a large-scale test bed are being considered, and in long-term operation, minimization of contaminants fouling in MF-RO systems by procedures such as cleaning or disinfection would be valuable both from membrane lifespan and operational aspects.

Acknowledgment

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