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Effect of driving pressure and recovery rate on the performance of nanofiltration and reverse osmosis membranes for the treatment of the effluent from MBR

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ABSTRACT

This research was carried out to evaluate the suitable operating condition for both nanofiltration (NF) and reverse osmosis (RO) membranes for the reuse of wastewater effluent from membrane bioreactor (MBR). Various parameters such as pH, conductivity, total dissolved solids, UV_{254}, dissolved organic carbon, total nitrogen and total phosphorus were analysed for the permeate from the NF and RO to compare the membrane performance. Batch experiments were conducted using a lab-scale NF and RO systems. Effluent from the MBR system treating synthetic wastewater was used as feed water to NF and RO. Filtration tests were performed at the operating pressure ranging from 0.2 to 1.0 MPa. Flux was measured at every 5 min, and the permeate was collected at the end of each experiment. Although the permeate flux and salt rejection increased in proportion to the operating pressure for NF, the increase in salt rejection was tapered off at a certain range of the operating pressure over 0.6 MPa for RO. As a result, an optimum operating pressure should be considered when using RO for treating the effluent from MBR. On the other hand, a better performance would be expected at higher operating pressure when using NF. The removal rates for various components in the feed slightly decreased by less than 5% as the recovery rate increased from 50 to 80%. Therefore, the optimization of the operating pressure and recovery rate should be considered when NF and RO systems were applied effectively to wastewater reuse purpose.

Keywords: MBR-NF; Nanofiltration; Operating pressure; Reverse osmosis; Wastewater reuse

1. Introduction

Pollution in the environment is rapidly increasing due to urbanization and industrialization. Increase in water demand causes a need for an efficient treatment and supply of water that meets a quality standard for various usage of product water from the limited water resources. Recently, wastewater and the effluent have been gradually reused for the increasing water. Approximately 50% of the water is being used by

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households, and the other 50% is for industrial and agricultural activities [1].

The wastewater can be considered as an alternative water resource which can mitigate the demands for fresh water [2]. In order to attain the environmental standards, membrane technologies provide an important solution in wastewater discharge, reuse and recovery of water and recycling valuable components from the waste stream [3].

Currently, several processes are being used for wastewater reuse such as filtration or disinfection followed by microfiltration (MF) and reverse osmosis (RO). One of the membrane technologies that can be used for advanced wastewater treatment is nanofiltration (NF). NF falls between ultrafiltration and RO and its separation characteristics are based on both sieve and charge effect. Most commercial NF membranes have negative electric charge, so the ion rejection by NF membranes are based on the combination of electrostatic and steric interactions associated with charge shielding, Donnan exclusion and the degree of ion hydration [4,5].

Compared to RO membrane systems, higher flux rates can be obtained from NF membrane systems at low operating pressure. In addition, NF membranes have an ability to remove organic matter, hardness as well as microorganisms. Although the rejection rate of monovalent ions was 70% by NF membranes, higher rejection can be achieved ranging from 85 to 95% for colour, organic carbon, precursor of THM and hardness. Applied operating pressure of NF is usually ranged from 350 to 1,000 kPa, which is lower than RO, is commonly applied from 1,400 to 6,800 kPa.

The purpose of this study is to treat the membrane bioreactor (MBR) permeate, which is increasingly used in wastewater treatment, by NF and RO membranes with operating pressure ranging from 0.2 to 1.0 MPa. Various factors were considered to determine the optimum operating condition such as pressure, recovery rate and membrane type, which can be helpful for designing and operating the wastewater reuse systems configured with NF or RO effectively.

2. Materials and methods

MBR system used in this study consisted 1st anoxic, 2nd anoxic, anaerobic and aerobic reactor which was used in filtration chamber with MF membranes composed of two polyvinylidene fluoride flat-sheet membranes [6]. Synthetic wastewater was used as a feed water for MBR with components based on environmental business establishment of Gapyeong, South Korea. All tested membranes for NF and RO were made of Polyamide (PA) flat-sheet type with an effective area of 60 cm^2. One of the advantages of current PA membranes is considered to be its resistance to various ranges of pH [7]. Four kinds of flat-sheet NF and RO membranes with different salt rejection rates were used in this study. Characteristic of the membranes are shown in Table 1.

The effluent from MBR was used as feed to NF and RO processes. The characteristics of the effluent were shown in Table 2, and the schematic diagram of MBR-NF(RO) system was shown in Fig. 1.

The feed water to NF and RO systems is introduced by single-phase induction motor and separated into permeate and retentate. For the filtration experiments, the operating pressure was changed for each membrane, then the rejection rate was calculated based on the concentrations of feed water and permeate. The NF and RO systems were operated at various pressures of 0.2, 0.4, 0.6, 0.8 and 1.0 MPa, respectively, for each filtration test. The retentate flow rate was set to 0.07 L/min. For the determination of recovery rate, membrane C was used because it showed the highest rejection among other membranes.

The pressure fixed to 0.6 MPa, recovery operated 50.0, 60.0, 70.0, 80.0% and measured to change of feed water, permeate and retentate. The temperature of feed water was maintained at 20˚C using a water bath. Each experiment was conducted for 2 h. The test equipment was washed with DI water for one hour when finishing each test [8].

Table 1
Characteristics of membranes tested

Parameter	A	B	C	D
Type	NF	Normal grade RO	Normal grade RO	Normal grade RO
Shape	Flat-sheet	Flat-sheet	Flat-sheet	Flat-sheet
Material	Polyamide	Polyamide	Polyamide	Polyamide
Salt rejection	55%*	99.5%*	99.7%*	99.65%*

*Manufacture's data.

Table 2
Characteristics of the MBR effluent

Parameter	Value (min–max)
pH	7.64–8.43
Conductivity (μS/cm)	462–521
TDS (mg/L)	227–256
TOC (mg/L)	3.41–3.78
UV_{254} (abs)	0.02–0.04
T–N (mg/L)	7–30
T–P (mg/L)	3.5–5.9

Various parameters such as pH, Salinity, Conductivity, TDS, TOC, UV_{254}, T–N and T–P were measured for feed water and permeate samples. Methods of analysis for each parameter were described in Table 3.

Equations for rejection, flux, recovery rate and salt passage are as follows:

$R\,(\%) = (1 - C_p/C_0) \times 100$ [2],

Flux (LMH, $\mathrm{L/h/m^2}$)$= (Q/A) \times (\mu_T/\mu_{25}) \times (\Delta P/\mathrm{TMP})$ [9],

Recovery rate $(\%) = (Q_p/Q_f) \times 100\,(\%)$ [10],

Salt passage $(\mathrm{SP}) = \mathrm{SP} = (C_p/C_{fm}) \times 100\,(\%)$ [7],

where C_p is the concentration of the permeate, C_0 is the concentration of the feed, Q is the filtration flow rate, A is the effective area of the membrane, μ_T is the viscosity at actual temperature, μ_{25} is the viscosity at 25℃, ΔP is the operating pressure, Q_p is the quantity of feed water, Q_f is the quantity of permeate and C_{fm} is the mean salt concentration in the feed stream.

3. Results and discussion

The changes in flux at different operating pressures were described in Fig. 2. Flux was proportioned to the operating pressure for the all the membranes tested. Membrane A showed the highest flux or permeability. This result is attributed to the nature of NF membrane which has a larger pore size than RO membrane. Little difference was seen in terms of flux between RO membranes which have similar salt rejection rates. Therefore, the permeability of membranes is thought to directly depend on the salt rejection rate of the membranes. In terms of solute transfer, however, an important factor is not a pressure difference but a concentration difference. Rejection ability of solute by the membrane driving force was influenced by indirect or very weak pressure difference. At elevated pressure, high solute flux was observed, which lowers the total rejection rate [11].

Salt passage was calculated from the feed and permeate salinities. Salt passage through a membrane is generally affected by feed salinity. Effect of salinity is known to be directly related to the charge of

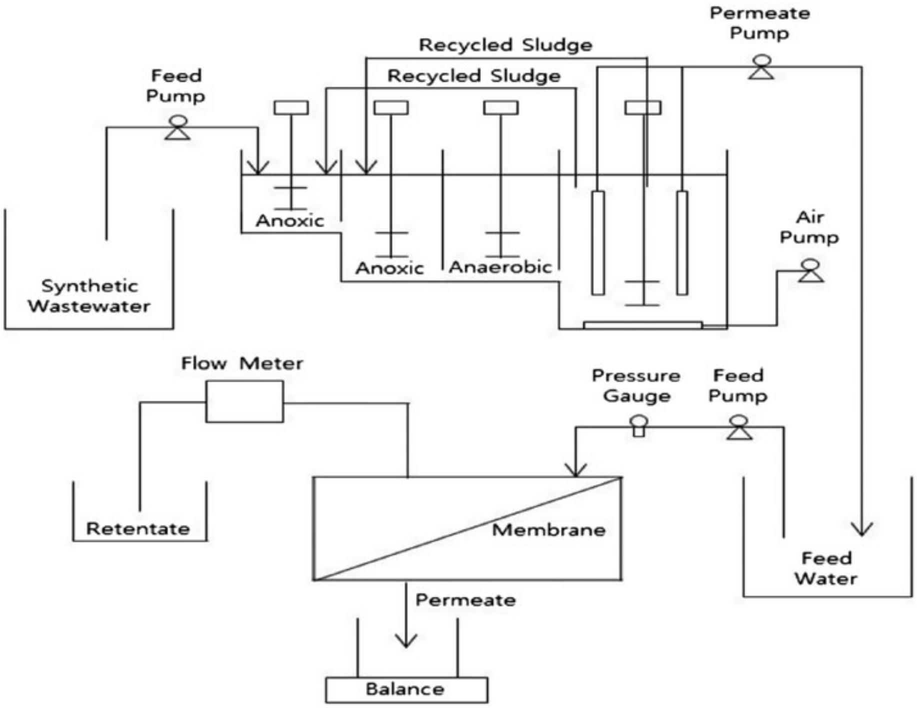

Fig. 1. Schematic diagram of lab scale MBR-NF(RO) system.

Table 3
Methods of analysis for each parameter

Parameter	Method	Equipment
pH	pH meter	Thermo, orion 3star
Conductivity	Conductivity meter	Thermo, orion star A series
TDS	Conductivity meter	Thermo, orion star A series
TOC	Infrared spectrophotometer	SHIMAZU, TOC analyzer
UV_{254}	Ultra violation spectrophotometer	SHIMAZU, UV 1800
T–N	Chromotropic acid method	HACH, DR 2800
T–P	Molybdovanadate method	HACH, DR 2800

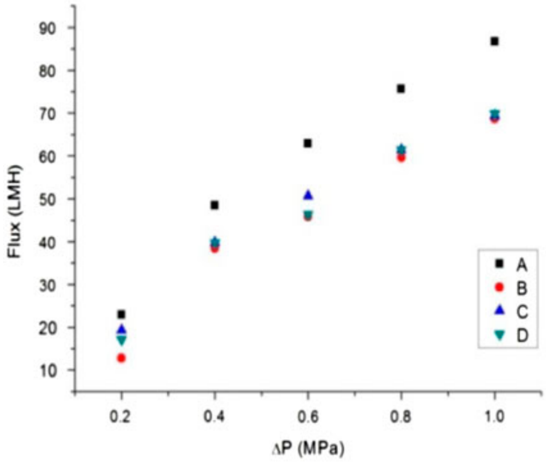

Fig. 2. Relationship between the permeate flux and the applied pressure (ΔP).

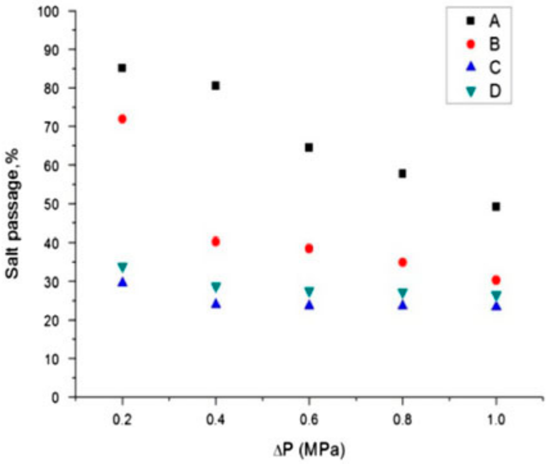

Fig. 3. Salt passage for the membranes according to the applied pressure (ΔP).

membrane surface, membrane chemistry and feed water composition. The increase in salt passage is most pronounced at high salinities when treating a sodium chloride solution with a strong negatively charged membrane. This phenomenon can be explained by Donnan potential [12]. However, the decrease in salt passage was observed as the pressure increases in Fig. 3. This can be thought that the increase in water passage was greater than the increase in salt passage through the membrane due to the higher flux by the higher pressure applied.

For conductivity, the lowest salt passage (or the highest rejection) was obtained by membrane C with 94.0% as shown in Fig. 4(a), although the salt rejection rate provided by manufacturer was somewhat higher. The results of salt passages attained from the test showed that the provided salt rejection rates of membranes were well reflected on the real conditions. Although there was a small difference in salt rejection between the RO membranes, the test results was clearly seen in order.

Membrane C also showed the highest rejection for the other parameters; 92.7% for TDS, 72.8% for TOC, 89.2% for UV_{254}, 98.9% for T–N and 100% for T–P (Fig. 4(b)–(f)). The results show that TOC rejection is not only related with sieving mechanism but also with other mechanisms such as charge effect, which can intervene in its rejection [2]. The reason for the lower rejection of T–N than that of T–P can be explained by molecular weight cut-off for the parameters. The molecular weight of phosphorus is higher than nitrogen, and thus phosphorous species can be easily rejected by membranes, compared to nitrogen species. In spite of low molecular weight of nitrogen species including nitrite and nitrate, such high rejection is possibly thought to be attributed to the electrostatic repulsion between membrane surface and ions of nitrogen species.

Behaviour of increasing trends in rejection rate for the parameters was quite different between NF and RO, although higher rejection was observed at higher pressure. NF showed a proportional correlation between the rejection and the applied pressure. On the other hand, little increase in the rejection was found at the applied pressure over 0.6 MPa while the

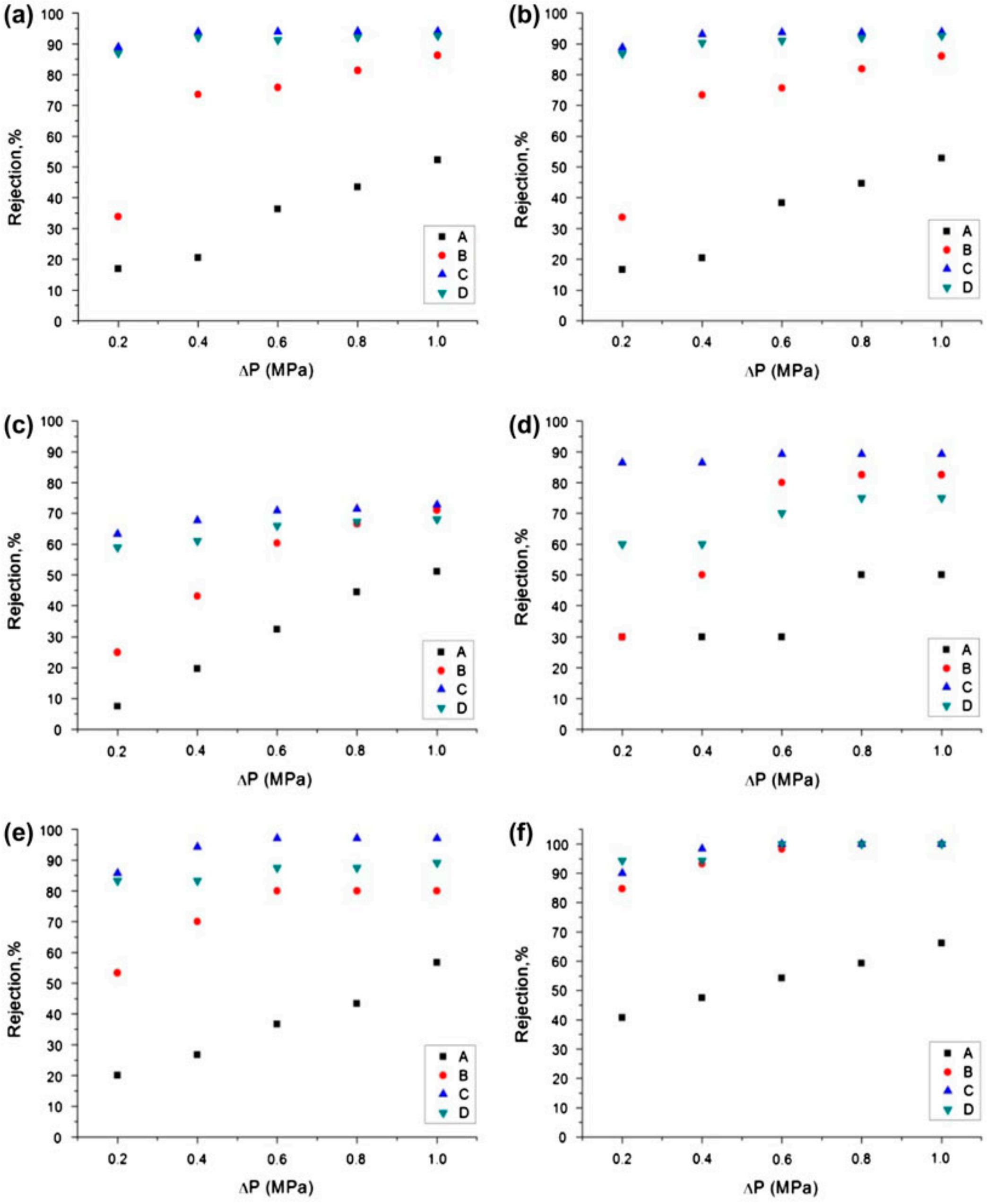

Fig. 4. Rejection for various parameters according to the applied pressure (Δ*P*). (a) Conductivity rejection; (b) TDS rejection; (c) TOC rejection; (d) UV_{254} rejection; (e) T–N rejection; and (f) T–P rejection.

rejection increased linearly with the applied pressure below 0.6 MPa. In case of TOC rejection in Fig. 4(c), higher rejection was found in NF at high operating pressure range from 0.8 to 1.0 MPa than RO at low operating pressure below 0.4 Mpa. This result means that NF could be effectively applied for treating the wastewater effluent for the purpose of organic removal.

Of the all membranes tested, membrane C has the highest rejection for all water quality parameters. Characteristics of the feed and permeate for all membranes were summarized with irrigation water standard in Table 4.

The effect of recovery rate on the rejection rate was also evaluated. The range of recovery was ranged from 50 to 80%. The variation of rejection rate

Table 4
Comparison of feed and permeate characteristics of different membranes

Membrane		A	B	C	D	
Parameter	Feed average	Average permeate of 1.0 MPa	Average permeate of 1.0 MPa	Average permeate of 1.0 MPa	Average permeate of 1.0 MPa	Irrigation water standards
pH	8.04	7.19	7.13	7.14	7.16	5.8–8.50[a]
Conductivity (μS/cm)	491.5	229	65.8	31.2	34.1	0–3,000[b]
TDS (mg/L)	241.5	111	32.8	15.9	16.6	0–2,000[b]
TOC (mg/L)	3.60	1.84	1.09	1.03	1.09	NS[c]
UV$_{254}$ (abs)	0.03	0.02	0.01	0.004	0.005	NS[c]
T–N (mg/L)	18.5	13	6	0.2	1.3	0–10[a]
T–P (mg/L)	4.7	2	0	0	0	0–1[a]

[a] [14].
[b] [15].
[c] No standards.

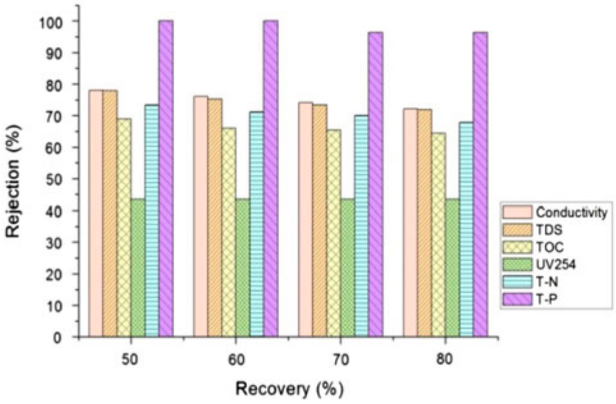

Fig. 5. Rejection rate according to the recovery rate.

according to the recovery was given in Fig. 5, and the permeate quality for membrane C was summarized in Table 5.

For membrane C, Permeate quality at different recovery rates is shown in Table 5.

Different recovery rates caused different permeate qualities.

The results showed that the rejection rate slightly decreased with the increase of recovery rate. Higher recovery rate leads to larger flow stream to permeate side perpendicular to the membrane surface and less flow stream to concentrate parallel with membrane, resulting in the accumulation of rejected component on the membrane surface. Such accumulation causes the increase in the surface concentration on the membrane and the mass transfer through the membrane. As a result, the concentration polarization increases with recovery rate and deteriorates the permeate quality [13]. This means that optimum recovery rate should be considered for the efficient operation of NF and RO systems in respect of permeate quality and membrane fouling.

Table 5
Water quality at different recovery rates

Recovery (%)		50		60		70		80	
Parameter	F[a]	P[b]	R[c]	P[b]	R[c]	P[b]	R[c]	P[b]	R[c]
pH	8.04	7.85	8.73	7.85	8.75	7.86	8.76	7.83	8.76
Conductivity (μS/cm)	654	143.8	792	156.5	1,002	169.2	1,216	182.6	1,422
TDS (mg/L)	321	71	388	79.8	492	85.4	598	90.2	697
TOC (mg/L)	4.21	1.31	5.1	1.43	6.4	1.46	7.7	1.5	8.8
UV$_{254}$ (abs)	0.053	0.03	0.09	0.03	0.12	0.03	0.16	0.03	0.19
T–N (mg/L)	9	2.4	14	2.6	16	2.7	18	2.9	20
T–P (mg/L)	2.7	0	2.9	0	4.3	0.1	5.5	0.1	6.6

[a] Feed water.
[b] Permeate.
[c] Retentate.

4. Conclusions

In this study, operating pressure and recovery rate were evaluated as the operating conditions for using NF and RO membrane in the treatment of wastewater effluent from MBR. Normal grade RO membranes showed higher rejection rate compared to NF membrane which has lower salt rejection than RO. No further increase in rejection rate was found at a certain range of pressure. Recovery rate also affected on the permeate quality. All tested RO membranes satisfied the water quality standard for irrigation use. Although the NF showed insufficient rejection for T–P and T–N, it was obvious that the organic rejection was comparable to the RO membranes. Therefore, NF can be a useful method when the purpose of the process is mainly to remove organic matter. And NF membranes with higher salt rejection or tighter NF would be better performance in rejection of various water quality parameters with relatively low applied pressure.

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