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Article

Full-Scale Implementation of a Vertical Membrane Bioreactor for Simultaneous Removal of Organic Matter and Nutrients from Municipal Wastewater

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Abstract: In nutrient-sensitive estuaries, wastewater treatment plants (WWTPs) are required to implement more advanced treatment methods in order to meet increasingly stringent effluent guidelines for organic matter and nutrients. To comply with current and anticipated water quality regulations and to reduce the volume of produced sludge, we have successfully developed a vertical membrane bioreactor (VMBR) that is composed of anoxic (lower layer) and oxic (upper layer) zones in one reactor. Since 2009, the VMBR has been commercialized (Q = 1100–16,000 m^3/d) under the trade-name of DMBR^{TM} for recycling of municipal wastewater in South Korea. In this study, we explore the performance and stability of the full-scale systems. As a result, it was found that the DMBR^{TM} systems showed excellent removal efficiencies of organic substances, suspended solids (*SS*) and *Escherichia coli* (*E. coli*). Moreover, average removal efficiencies of total nitrogen (*TN*) and total phosphorus

(*TP*) by the DMBR™ systems were found to be 79% and 90% at 18 °C, 8.3 h HRT and 41 d SRT. Moreover, transmembrane pressure (TMP) was maintained below 40 kPa at a flux of 18 L/m^2/h (LMH) more than 300 days. Average specific energy consumption of the full-scale DMBR™ systems was found to be 0.94 kWh/m^3.

Keywords: nutrients; wastewater treatment plants; vertical membrane bioreactor; DMBR™; specific energy consumption

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1. Introduction

Eutrophication is a key driver causing a number of pressing environmental problems including reductions in light penetration and increases in harmful algal blooms. It is known as that wastewater is an important point source for N and P loading in many aquatic environments [1]. In nutrient-sensitive estuaries, municipal and industrial WWTPs are required to implement more advanced treatment methods in order to meet increasingly stringent effluent guidelines for nutrients. According to literature, biological nutrient removal (BNR) processes that incorporate coupled nitrification/denitrification have the potential to remove *TN* down to about 5–12 mg/L, in selected cases, down to 3 mg/L. The *TN* concentration in effluent is known as less than 10 mg/L at most inland municipal WWTPs [2]. However, it is thought difficult to remove bacteria effectively from the effluent of WWTPs using the conventional activated sludge (CAS) process without a disinfection facility.

One of the possible technologies to meet this need is the membrane bioreactor (MBR) [3–6]. Rejection of bacteria by microfiltration (MF) or ultrafiltration (UF) membranes has been shown to be highly effective [7,8]. Additionally, MBR provides absolute separation of hydraulic retention time (HRT) and sludge retention time (SRT), thus allowing more flexible control of the bioreactor [9]. MBR systems can offer a solution in highly populated areas, or in areas where land used to disperse bioreactor effluents can be better used for other purposes [10]. Large-scale applications of MBR in urban wastewater treatment will require new technological developments saving energy and space, and producing high quality effluents for further applications [11,12].

In these regards, we developed and optimized a novel VMBR to reduce the problems on pollutant removal from wastewater and the volume of produced sludge from a bench-scale to field-scale systems. The effects of various operating factors such as anoxic zone/oxic zone ratio, internal recycle rate, and HRT on nutrient removal were studied using a bench-scale VMBR (working volume = 32 L) fed with synthetic wastewater containing glucose as a sole carbon source [13]. Under the optimum condition (*i.e.*, anoxic zone/oxic zone ratio = 0.6, HRT = 8 h, and internal recycle rate = 400%), the average removal efficiencies of *TN* and *TP* were 75% and 71%, respectively [13]. The effects of water temperature on nutrient removal were evaluated using a pilot-scale VMBR (working volume = 1333 L) treating municipal wastewater. During the continuous operation for one year, average removal efficiencies of *TN* and *TP* by the pilot-scale VMBR were found to be 74% and 78% at 8 h HRT, 60 d SRT and various temperatures (13–25 °C) [14,15].

In 2009, the VMBR was commercialized by Daewoo Engineering and Construction under the trade-name of Daewoo MBR (DMBR™). Currently, six full-scale plants (*Q* = 1100–16,000 m^3/d) are in operation in South Korea. In this study, we report performance and stability of the full-scale plants for the long-term operation (1–5 years).

2. Materials and Methods

2.1. Operating Conditions of Field-Scale VMBRs

All field-scale DMBR^{TM} systems have been identically designed and operated. The anoxic zone/oxic zone ratio and internal recycle rate were maintained at 0.6 and 4*Q*, respectively as reported in the previous study [13]. As shown in Figure 1, influent and mixed liquor of suspended solid (MLSS) that was recycled from the oxic zone were introduced to the anoxic zone through the flow distributors. The aerobic zone is separated from the anoxic zone by a horizontal plate with a hole in the center. In the aerobic zone, disk-type diffusers were used to provide air bubbles (2800 m^3/h = 0.42 $m^3/m^2/h$) for oxidation of organic and ammonia and to reduce membrane fouling. Final effluent was withdrawn through 0.45 μm poly-tetrafluoroethylene (PTFE) hollow fiber membranes (Sumitomo Electric Fine Polymer, Inc., Tokyo, Japan). A permeate pump was operated for 9 min on and 1 min off in repeating cycles. After 36 cycles, the membranes was backwashed using permeate (flow rate = 1.5*Q*) for 1 min. To improve removal efficiency of phosphorus, $FeCl_3$ (33%) was added into the oxic zone at 1.1 mole Fe/mole P in the feed ratio. Excess sludge was withdrawn from the anoxic zone to maintain SRT. Average HRT of the MBR systems was 8.3 h. MLSS concentration in the bioreactor varied between 8400 and 9600 mg/L depending on SRT (37–45 d) (Table 1).

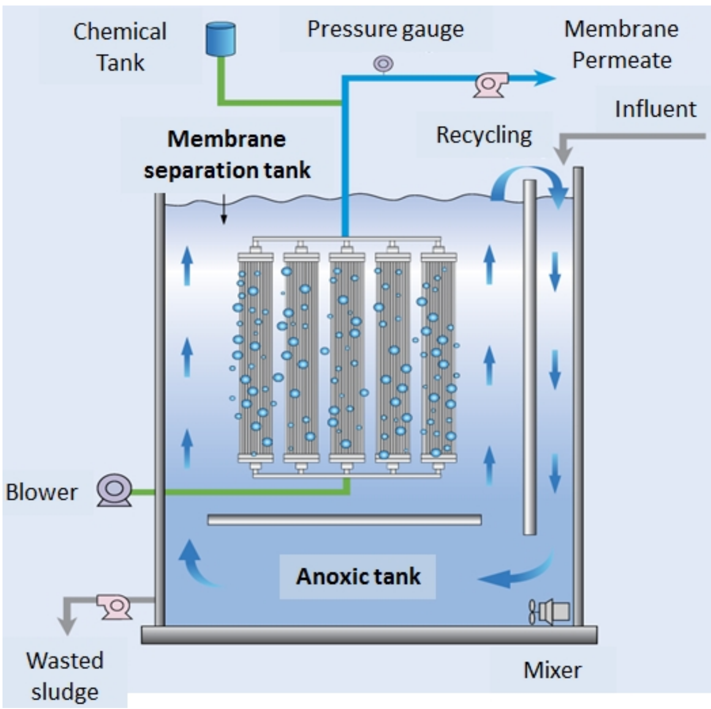

Figure 1. Schematic diagram of a field-scale DMBR^{TM} system.

Table 2 shows characteristics of municipal wastewater used for the field-scale DMBR^{TM} systems. The *COD*/*TN* ratio and the *COD*/*TP* ratio of influent was found to be 1.8–2.6 and 19.0–29.1, respectively indicating a shortage of carbon for effective nutrient removal.

Table 1. Key information of the DMBR™ systems treating municipal wastewater larger than 1000 m^3/d.

Location in South Korea	Capacity (m^3/d)	Commission (year)	Membrane Area (m^2)	Water Temperature (°C)	HRT (h)	SRT (d)	MLSS Concentration (mg/L)
Dangjin-si (A)	3,500	2009	6,720	17.9 ± 4.5	8.3	41	9,100
Dangjin-si (B)	1,500	2009	2,560	18.1 ± 4.2	7.9	45	9,600
Gumi-si	8,000	2011	15,360	19.1 ± 3.4	8.4	40	8,500
Jecheon-si	1,100	2012	1,920	17.1 ± 5.2	9.2	37	8,900
Kwangju-si	16,000	2013	32,400	19.3 ± 3.9	8.5	38	8,500

Table 2. Characteristics of wastewater for the field-scale DMBR™ systems.

Item	Dangjin-si (A)	Dangjin-si (B)	Gumi-si	Jecheon-si	Kwangju-si
pH	7.5	7.4	7.2	7.1	7.1
BOD_5 (mg/L)	91.6	151.5	128.3	165.4	177.0
COD_{Mn} (mg/L)	90.4	97.1	96.0	53.2	89.6
SS (mg/L)	73.6	144.0	168.8	161.0	179.8
TN (mg/L)	35.3	38.5	36.3	32.0	36.6
TP (mg/L)	4.3	4.9	3.3	2.8	3.6
E. coli (cfu/100 mL)	88,660	86,443	109,747	44,101	247,795

2.2. Chemical Cleaning of the Membranes

Two different chemical cleaning schemes were applied for mitigation of membrane fouling in the bioreactor. Firstly, an *in-line* cleaning is applied once a week for 30 min at 4.96 mL/min/m^2 using a mixture solution of NaOCl (1000 mg/L) and NaOH (100 mg/L). Secondly, an *off-line* cleaning was conducted if TMP reaches to 60 kPa. For this purpose, the membrane modules was removed from the bioreactor and immersed into a mixture solution of NaOCl (1000 mg/L) and NaOH (2%) for 8 h, and followed by H_2SO_4 (1%) for 8 h.

2.3. Characterization of Wastewater and Membrane Permeate

SS and ML*SS* concentrations were determined by vacuum filtration of 100 mL of activated sludge through a pre-dried GF/C filter (Whatman–GE Healthcare, Pittsburgh, PA, USA) and then dried at 105 °C for 2 h. Chemical oxygen demand (COD_{Mn}), biochemical oxygen demand (BOD_5), total Kjeldahl nitrogen (TKN), NH_4–N, and *TP* concentrations were analyzed as described in the previous study [14]. Concentrations of various ions such as NO_2–N, NO_3–N, and ortho-P were analyzed using ion chromatography (IC) (Dionex DX-120, Sunnyvale, CA, USA) after filtering with a 0.45 μm membrane filter (ADVANTEC MFS Inc., Dublin, CA, USA). Temperature and pH were measured by temperature and pH electrodes connected with a pH meter (Orion Model 420A, Orion Research Inc., Beverly, MS, USA). Average removal efficiency of *SS*, organic compounds, and nutrients by the DMBR™ systems as calculated as:

$$\text{Removal efficiency (\%)} = (1 - C_f/C_i) \times 100 \quad (1)$$

where C_f is the final concentration in the membrane permeate and C_i is the initial concentration in the influent.

Tryptone-broth was used to enumerate *E. coli*, which was incubated at 37 °C for 24 h. Removal rejection efficiency of *E. coli* by the membrane was calculated by the following equation:

$$\text{Removal efficiency (\%)} = (1 - N_P/N_f)\times 100 \quad (2)$$

where N_p is colony forming units (cfu) of *E. coli* per 100 mL in the membrane permeate and N_f is the cfu of *E. coli* per 100 mL in the influent.

3. Results and Discussion

3.1. Performance and Fouling Characteristics of the Full-Scale DMBR™ Systems

During the long-term operation of the field-scale DMBR™ systems treating municipal wastewater, it was found that organic matter (BOD_5 > 99%), particles (*SS* removal efficiency > 99%), and *E. coli* (>99.9%) have been effectively removed (data not shown).

Average removal efficiencies of *TN* and *TP* by the DMBR™ system were found to be 79% and 90% at 18 °C, 8.3 h HRT and 41 d SRT. Interestingly, there is no big change in removal efficiency of nutrients (*TN* = 78%–82% and *TP* = 89%–97%) regardless of the system size (Q = 1100–16,000 m^3/d) (Figure 2). Moreover, the TMP was maintained below 40 kPa with membrane permeate flux at 18 LMH more than 300 days (Figure 3).

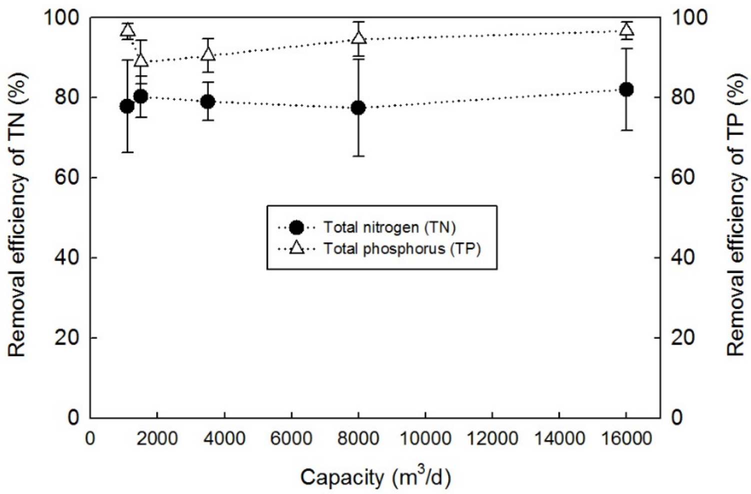

Figure 2. Average removal efficiencies of total nitrogen (*TN*) and total phosphorus (*TP*) by the full-scale DMBR™ systems (Data obtained from the full-scale DMBR™ systems for 1–5 years depending on operation period of each system).

Table 3 represents performance of full-scale submerged MBR systems treating municipal wastewater. System configuration of the MBR systems are similar to the Modified Ludzack-Ettinger (MLE) process (*i.e.*, pre-denitrification followed by aerobic thank with submerged membranes). At the relatively higher *COD*/*TN* ratio (*i.e.*, 8.5 and 17.2), the MLE-type MBRs showed good performance for both N and P removal. However, when the *COD*/*TN* ratio is low (*i.e.*, 3.9), P removal efficiency was limited.

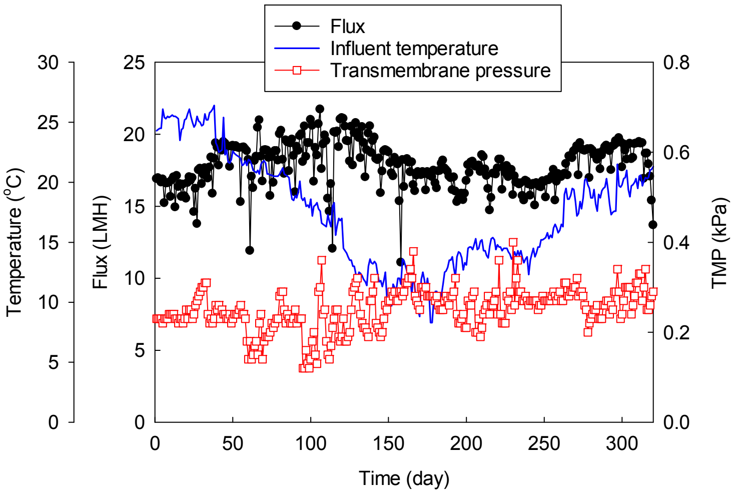

Figure 3. Progress of membrane fouling in a field-scale DMBR™ system (Dangjin-si (A), South Korea).

Table 3. Performance of various submerged membrane bioreactor (MBR) systems treating municipal wastewater.

MBR Type	Capacity (m^3/d)	Operating Conditions	Influent Characteristics (mg/L)	*TN* Removal (%)	*TP* Removal (%)	Influent *COD*/*TN* Ratio	Reference
MLE	1,375	HRT = 33 h SRT = n.a.	*BOD* = 114 *TN* = 29 *TP* = 3.4	78	50	3.9 [a]	[11]
MLE	2,400	HRT = 16.6 h SRT = 40 d	*COD* = 447 NH_4-N = 26 *TP* = 7.3	99	91	17.2 [b]	[16]
MLE	6,520	HRT = 3.5–5 h SRT = 14–21 d	*COD* = 220 *TN* = 26 *TP* = 3.9	70	92	8.5	[17]
Verical MLE	1,100–16,000	HRT = 7.9–9.2 h SRT = 37–45 d	*COD* = 53–97 *TN* = 32–39 *TP* = 2.8–4.9	78–82	89–97 [c]	1.7–2.6	This study

Notes: [a] *BOD*/*TN* ratio; [b] *COD*/NH_4-N ratio; [c] The chemical precipitation was employed using $FeCl_3$; n.a.: data was not available.

As shown in Table 3, the DMBR™ system showed competitive performance for nitrogen removal compared to other MBR systems even at the relatively low influent *COD*/*TN* ratio (<3). However, P removal efficiency of the DMBR™ was below 50% (data not shown) at the low *COD*/*TN* ratio. To enhance the removal efficiency of P, $FeCl_3$ (1.1 mole Fe/mole P in the feed) was introduced into the aerobic tank resulting in 89%–97% removal of phosphorus.

3.2. Chemical Dosage and Excess Sludge Production

Because of the unique feature of MBRs and particularly the significant decrease in membrane price, MBRs have been increasingly and widely used for wastewater treatments in the last decade [12,16,17].

However, despite these developments and applications of MBRs, energy demand together with frequent membrane cleaning remain a challenge in terms of energy consumption and optimization of MBRs [9].

Energy demand of full-scale CAS processes for municipal wastewater treatment, expressed per volume of treated wastewater was reported to be in the range of 0.1–0.6 kWh/m^3 [18]. However, energy consumption of MBRs was generally higher due to intensive membrane aeration rates required to mitigate membrane fouling and clogging than that of CAS systems. Typical energy demand values for full-scale MBR systems are reported to be in the range of 0.4–2.0 kWh/m^3 [11,18].

The energy requirement of the DMBR^{TM} systems was in the range of 0.8–1.0 kWh/m^3 (data not shown). The specific energy consumption of the full-scale DMBR^{TM} systems was averaged at 0.94 kWh/m^3. This is slightly higher than that of the CAS systems and some MBRs mainly due to addition of $FeCl_3$ for enhanced phosphorus removal.

On the other hand, waste activated sludge (WAS) from CAS processes is one of the most serious problems in wastewater treatment [19]. It has been known that extremely low sludge production (0.05–0.25 kg mixed liquor of volatile suspended solid (MLVSS)/kg *COD*) is possible for low food-to-microorganism (F/M) ratios and long SRT in MBRs [20]. In this study, $FeCl_3$ was introduced to improve P removal efficiency. However, as $FeCl_3$ dosage increased from 8 to 63 kg/d, the observed sludge yield of the full-scale DMBR^{TM} systems was also increased from 7.2 to 54.8 kg MLSS/m^3 (or from 0.92 to 6.3 kg MLVSS/kg *COD*) (Figure 4).

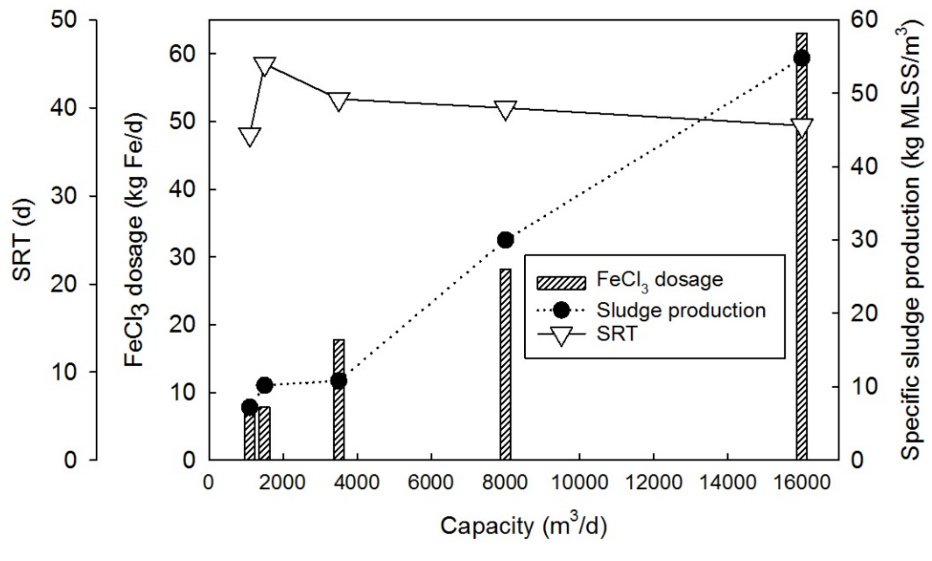

Figure 4. $FeCl_3$ dosage and sludge production from the full-scale DMBR^{TM} systems.

4. Conclusions

Since 2009, five full-scale vertical MBR plants (Q = 1100–16,000 m^3/d) have been successfully in operation to reduce the problems concerning effective removal of nitrogen and phosphorus from municipal wastewater for water recycling. Particles (*i.e.*, *SS*), organic substances (*i.e.*, BOD_5 and COD_{Mn}), and bacteria (*i.e.*, *E. coli*) were effectively removed (>99%) by the MBR systems. *TN* and *TP* removal efficiencies of the MBR plants were found to be 78%–82% and 89%–97%, respectively at 7.6–9.2 h HRT and 37–45 d SRT. However, the introduction of $FeCl_3$ for improvement of phosphorus removal efficiency resulted in relatively high sludge production compared to the conventional MBRs without chemical precipitation.

A stable operation was possible by applying the weekly *in-line* cleaning using a mixture of NaOCl and NaOH without significant increase in TMP (<40 kPa) for approximately one year with the average energy consumption of 0.94 kWh/m^3. Recycling and reuse of P removed by $FeCl_3$ will be beneficial to the MBR operation.

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Author Contributions

So-Ryong Chae, Jin-Ho Chung, Yong-Rok Heo, Seok-Tae Kang, and Sang-Min Lee carried out the experiments and wrote the paper; Hang-Sik Shin contributed to the analysis of the experiment data and edited of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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