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High reuse potential of effluent from an innovative vertical submerged membrane bioreactor treating municipal wastewater

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Abstract

The main objective of this study is to investigate the reuse possibility of effluent from a vertical submerged membrane bioreactor (VSMBR) treating municipal wastewater. The average removal efficiencies of total chemical oxygen demand (COD), total nitrogen (T-N), and total phosphorus (T-P) were 96, 74, and 78%, respectively at 8-h hydraulic retention time (HRT) and 60-day sludge retention time (SRT). Additional removal of organic matter and improved nitrification and denitrification efficiencies were found by the formation of a dynamic membrane. The effluent quality of the vertical submerged membrane bioreactor (VSMBR) could satisfy most items in the current drinking water standards of Korea and the WHO (World Health Organization). Accordingly, the reuse of the effluent from the VSMBR could be possible for various purposes such as toilet flushing, sprinkling, and car washing.

Keywords: VSMBR; Municipal wastewater; Dynamic membrane; Water reuse

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1. Introduction

As nutrients in municipal wastewater have been recognized as major culprits contributing to eutrophication in water environment, biological nutrient removal (BNR) processes are now widely used in wastewater treatment. For the purpose of simultaneous organic and nutrient removal, the BNR process has been designed to provide proprietary combinations of anaerobic, anoxic, and aerobic conditions. Current and impending world legislation on wastewater effluent discharge has led to the need for improved removal of not only organic matter and nutrients but also bacteria [1]. However, it is thought difficult to remove bacteria effectively from the effluent from treatment facilities for BNR. One of the possible means to meet this need could be a membrane bioreactor (MBR). Rejection of bacteria by microfiltration (MF) membrane has been shown significant [2]. MBRs take only half the land area of conventional activated sludge processes, and sludge production is similarly halved [3]. In addition, the MBR maintains high biomass concentration in the reactor, which could reduce HRT permitting a higher rate of organic and nutrient removal [4].

In these regards, the VSMBR composed of anoxic and oxic zones in one reactor has been fabricated, which due to its physical structure, is expected to challenge current problems related to the effective removal of organic matter and nutrients from wastewater [5–7]. Specially, in this study, water reuse possibility of effluent in a pilot-scale VSMBR was evaluated under various operating conditions.

2. Materials and methods

2.1. A pilot-scale VSMBR and influent characteristics

As shown in Fig. 1, a pilot-scale VSMBR with an effective working volume (WV) of 1333 L was separated into an anoxic zone (lower layer, 500 L WV) and an oxic zone (upper layer, 833 L WV). The poly-tetrafluoroethylene (PTFE) membrane having nominal pore size of 0.45 μm was used as described in the previous study [7]. The initial pH and volatile suspended solid to total suspended solid (VSS/TSS) ratio of the seed sludge were 7.2, and 0.73, respectively. Average mixed liquor suspended solid (MLSS) concentrations of the anoxic and the oxic zones were 8.7 and 4.2 g/L, respectively. As listed in Table 1, municipal wastewater (influent) discharged from KAIST (Korea Advanced Institute of Science and Technology) in Korea contained total chemical oxygen demand to total nitrogen (total COD/T-N) ratio of 5.5 indicating a shortage of carbon for effective nutrient removal.

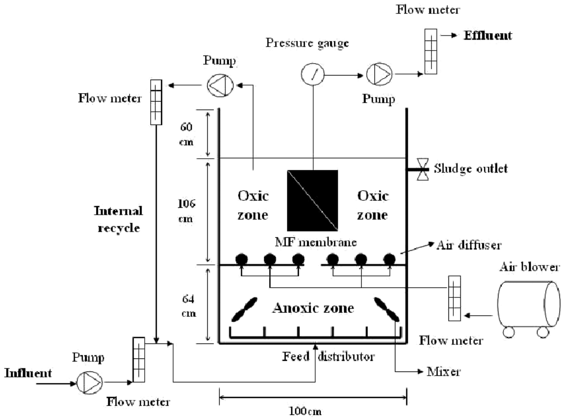

Fig. 1. Schematic diagram of a pilot-scale VSMBR.

2.2. Experimental conditions

As shown in Table 2, to study the reuse possibility of effluent from the pilot-scale VSMBR, four different HRTs were tested for the period of 600 days. The internal recycle rate from oxic to anoxic zone and SRT were adjusted to 400% of the influent flow rate and 60 days, respectively. The permeate flux through the membrane was adjusted to 6.2 $L/m^2/h$ (=0.15 m/day).

Table 1
Influent characteristics

Constituents		Concentration
COD (mg/L)	Total	232 ± 41
	Soluble	161 ± 25
SS (mg/L)	Total	220 ± 52
	Volatile	110 ± 30
Nitrogen (mg/L)	Total	42 ± 5
	NH_3-N	27 ± 3
	NO_3-N	<0.1
Phosphorus (mg/L)	Total	3.2 ± 0.4
	Soluble	1.9 ± 0.4
Volatile fatty acids (mg/L)		<1.0
Initial pH		7.3 ± 0.1
Alkalinity as $CaCO_3$(mg/L)		125 ± 47

Table 2
Experimental conditions for the pilot-scale VSMBR

Phase	HRT	Operation period
1	10 h	29–68 days
2	8 h	69–360 days
3	6 h	361–480 days
4	4 h	481–600 days

2.3. Analytical methods

One liter of samples from the anoxic and the oxic zones in the reactors, and effluent was analysed for the following items every other day. TSS was determined by vacuum filtration of 10 mL of activated sludge through a pre-ignited GF/C filter (Whatman, USA) and then dried at 105°C for 2 h. VSS were determined after igniting the sample of SS at 550°C for 20 min. COD, TKN (total kjeldahl nitrogen), NH_3-N, and T-P concentrations were measured according to Standard Methods [8]. Concentrations of various ions such as nitrite-N, nitrate-N, and ortho-P were analysed using ion chromatography (Dionex DX-120, IonPac AS4A-SC column).

3. Results and discussion

3.1. Performance of the pilot-scale VSMBR

As shown in Fig. 2, the average removal efficiencies of suspended solid (SS) and total COD were 100% and as high as 94% during the whole experimental periods. As a result, it was concluded that the pilot-scale VSMBR had great potential in removing organic matter, and its stability was maintained for the long-term operation. The effluent NH_3-N remained generally as low as 5 mg/L from Phase 1 to 3 as HRT decreased from 10 to 6 h (Fig. 3A). However,

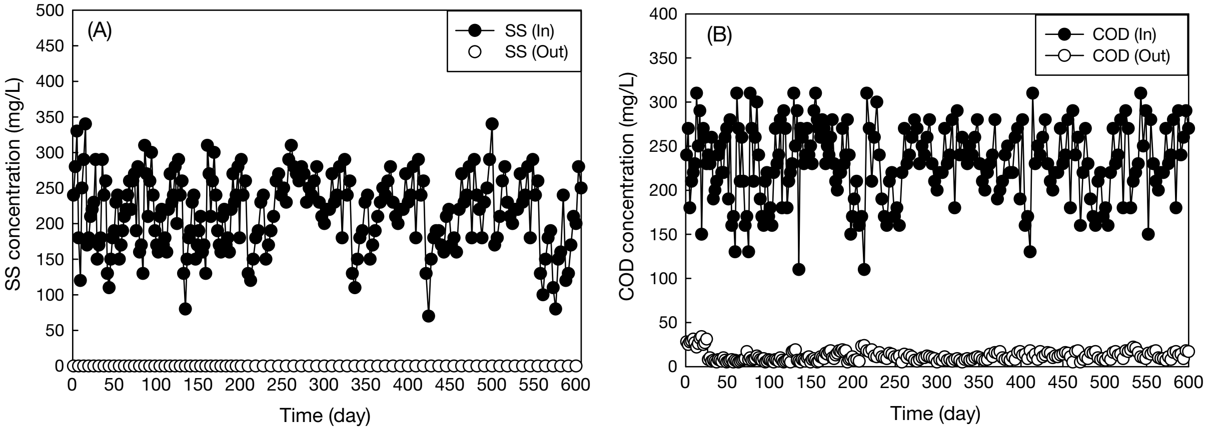

Fig. 2. Influent and effluent concentrations of SS and COD in the VSMBR.

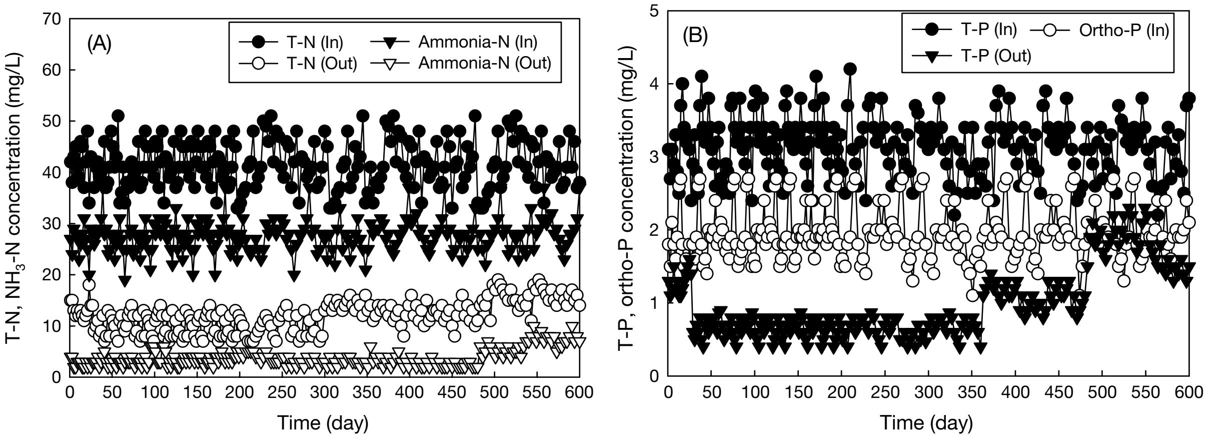

Fig. 3. Influent and effluent concentrations of nitrogen and phosphorus in the VSMBR.

nitrification efficiency was deteriorated when HRT decreased to 4 h. As summarized in Table 3, the removal efficiency of T-N decreased from 76 to 62% as HRT decreased from 10 to 4 h, respectively. On the other hand, denitrification was a limiting step for the removal of phosphorus because organic matter in the influent was insufficient for effective nutrient removal from Phase 1 to 4. T-P removal efficiency was affected by both nitrate-N and organic concentrations (Fig. 3B).

3.2. The role of a secondary dynamic membrane in pollutant removal

Membrane fouling in MBRs takes place mostly on the outside of the membrane, resulting in a dynamic biofilm layer on the membrane surface. In this study, a distinct difference in removal efficiency was observed after formation of the dynamic biofilm on the membrane surface. Table 4 shows the increased removal of organic matter and nutrients by the dynamic membrane in the pilot-scale VSMBR. The increase in the removal efficiency of organic matter was found to be about 4% under various operating conditions. Nitrification and denitrification efficiencies also improved about 5 and 4%, respectively by aerobic and anaerobic biofilms. For denitrification, the stored organic matter or the remaining organic matter in the treatment stream could be used. On the other hand, soluble phosphorus concentration

Table 3
Average removal efficiencies of organics and nutrients at various HRTs

Phase	SS		Total COD					T-N					T-P				
	In (mg/L)		In (mg/L)		Out (mg/L)		Re. (%)	In (mg/L)		Out (mg/L)		Re. (%)	In (mg/L)		Out (mg/L)		Re. (%)
	Avg	Std	Avg	Std	Avg	Std		Avg	Std	Avg	Std		Avg	Std	Avg	Std	
1	197	52	227	45	6.8	2.9	97	40.7	4.4	9.8	1.8	76	3.1	0.4	0.7	0.1	77
2	216	51	231	43	9.0	3.6	96	41.4	4.4	10.6	2.6	74	3.2	0.4	0.7	0.2	78
3	217	47	232	39	12.3	3.6	95	42.4	4.8	12.3	1.8	71	3.2	0.5	1.1	0.2	66
4	205	62	230	43	13.4	4.2	94	41.6	4.9	15.7	1.8	62	3.1	0.4	1.8	0.3	42

Avg: average; Std: standard deviation; Re.: removal efficiency.

Table 4
The effect of the dynamic membrane on the removal of organics and nutrients

HRT	Total COD			NH_3-N			NO_3-N			Ortho-P		
	Ox (mg/L)	Eff (mg/L)	Re. (%)	Ox (mg/L)	Eff (mg/L)	Re. (%)	Ox (mg/L)	Eff (mg/L)	Re. (%)	Ox (mg/L)	Eff (mg/L)	Re. (%)
10 h	7.0	6.8	3	3.4	3.1	8	4.9	4.7	4	0.70	0.73	–4
8 h	9.5	9.0	5	3.2	3.0	6	6.1	5.8	5	0.71	0.74	–4
6 h	12.7	12.3	3	2.8	2.7	4	7.5	7.3	3	1.17	1.14	–3
4 h	14.2	13.4	5	6.5	6.3	3	9.3	9.0	3	1.88	1.83	–3

Ox = oxic zone; Eff = effluent; Re. = removal efficiency.

increased while overall removal efficiency of phosphorus decreased by about 4% because the secondary release of phosphorus occurred in the anaerobic biofilm formed on the membrane surface where oxygen transfer was limited.

3.3. Reuse potential of the effluent from the VSMBR

The average effluent quality from the pilot-scale MBR of 8-h HRT is summarized in Table 5. It can be seen that all the listed items except for microorganisms and NH_3-N met the current drinking water standards of Korea and the WHO. In these regards, the VSMBR effluent could be suitable for potable use after disinfection. However, a concern whether drinking water standards were adequate to ensure the safety of all waters is still under dispute as there is a limit to complete filtration by MF membrane of pathogens that can cause health problems. Despite of technological advances and high quality of treated effluents, public reactions to direct potable reuse are unfavorable. Comparatively, reuse of the effluent for municipal purposes including toilet flushing, sprinkling, car washing, and cleaning were more prone to public acceptance considering its quality [9]. In addition, the MBR effluent could be used for irrigation purposes. After simple treatment, the effluent may also be applied to cooling tower, stack gas scrubbing and metal processing [1]. By reverse osmosis (RO) or ion exchange, the VSMBR effluent could be ultrapure of which the reuse potential might be upgraded.

4. Conclusions

In this study, the pilot-scale VSMBR was operated at various HRTs in order to remove organic matters and nutrients from municipal wastewater. As a result, it was found that average removal efficiencies of T-N and T-P were 74 and 78%, respectively at 8-h HRT. Accordingly, additional removal efficiency of organic matter by the formation of a dynamic membrane was found to be about 4% under various HRTs. Nitrification and denitrification efficiencies also improved about 5 and 4%, respectively by aerobic and anaerobic biofilms. The effluent quality of the VSMBR of 8-h HRT could satisfy most items in the current drinking water standards of Korea and drinking water guidelines issued by the WHO. Finally, the VSMBR was regarded as an effective and compact process as it showed high removal efficiencies of not only SS and organics but also nutrients. Especially, this process can be strongly recommended for the advanced wastewater treatment and water reuse purposes in urban and rural area.

Table 5
Comparison between drinking water standards and the average effluent quality from the pilot-scale VSMBR

Category		Item (Unit)	Drinking water standards of Korea [9]	Selected values in the WHO guidelines [10]	This study
Microorganisms (4)		Total colony counts (CFU/mL)	100	–	24
		Total coliforms (Count/100 mL)	0	0	11
		Fecal coliforms (Count/100 mL)	0	0	5
		E. coli (Count/100 mL)	0	0	2
Health-related inorganic matters (11)		Lead (mg/L)	0.05	0.01	<0.05
		Fluoride (mg/L)	1.5	1.5	<0.3
		Arsenic (mg/L)	0.05	0.01	<0.01
		Selenium (mg/L)	0.01	0.01	<0.01
		Mercury (mg/L)	0.001	0.001	<0.001
		Cyanide (mg/L)	0.01	0.07	<0.001
		Hexachromium (mg/L)	0.05	0.05	<0.01
		Ammonium-N (mg/L)	0.5	1.5	3.0
		Nitrate-N (mg/L)	10	50	5.9
		Cadmium (mg/L)	0.005	0.003	<0.001
		Boron (mg/L)	0.3	0.5	<0.01
Health-related organic matters (24)	Volatile organic carbons	Phenol (mg/L)	0.005	–	<0.001
		Trichloroethane (mg/L)	0.1	0.07	<0.01
		Tetrachloroethylene (mg/L)	0.01	0.04	<0.001
		Trichloroethylene (mg/L)	0.03	0.07	<0.001
		Dichloromethane (mg/L)	0.02	0.02	<0.001
		Benzene (mg/L)	0.01	0.01	<0.001
		Toluene (mg/L)	0.7	0.7	<0.01
		Ethyle Benzene (mg/L)	0.3	0.3	<0.01
		Xylene (mg/L)	0.5	0.5	<0.01
		1,1 Dichloroethylene (mg/L)	0.03	0.03	<0.001
		Carbon tetrachloride (mg/L)	0.002	0.004	<0.001
	Pesticides	Diazinon (mg/L)	0.02	–	<0.01
		Parathion (mg/L)	0.06	–	<0.01
		Fenitrothion (mg/L)	0.04	–	<0.01
		Carbaryl (mg/L)	0.07	–	<0.01
		1,2-Dibromo-3-Chloropropan (mg/L)	0.003	0.001	<0.001
	Disinfection by products	Free residual chloride (mg/L)	4.0	–	0.5
		Trihalomethans (mg/L)	0.1	1	<0.01
		Chloroform (mg/L)	0.08	0.2	<0.01
		Chloral hydrate (mg/L)	0.03	0.01	<0.01
		Dibromoacetonitrile (mg/L)	0.1	0.07	<0.01
		Dichloroacetonitrile (mg/L)	0.09	0.02	<0.01
		Trichloroacetonitrile (mg/L)	0.004	–	<0.001
		Haloacetic acid (mg/L)	0.1	–	<0.01

Table 5 (*Continued*)

Aesthetic-related Components (16)	Hardness (mg/L)	300	–	78
	Consumption of $KMnO_4$ (mg/L)	10	–	3.5
	Odor	Odorless	–	Odorless
	Taste	Tasteless	–	Not available
	Copper (mg/L)	1	2	0.07
	Color (color unit)	5	15	2
	Alkyl benzene sulfate (mg/L)	0.5	–	<0.01
	pH	5.8–8.5	<8	7.3
				0.04
	Zinc (mg/L)	1	3	0.04
	Chloride (mg/L)	250	250	18
	Total solids (mg/L)	500	–	267
	Iron (mg/L)	0.3	0.3	0.05
	Manganese (mg/L)	0.3	0.4	0.065
	Turbidity (NTU)	0.5	–	0.18
	Sulfate (mg/L)	200	250	16
	Aluminium (mg/L)	0.2	0.2	0.02

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