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Biological treatment of reverse osmosis concentrate from low salinity water

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ABSTRACT

With increasing water demand and growing scarcity of potable water, the reuse of water recovered from low salinity water like sewage or surface water is becoming an important issue from both technical and economic points of view. The reverse osmosis (RO) membrane processes widely used for water recovery inevitably produce RO concentrate having very high concentrations of salts and other materials of concern. Disposal to nature or feeding back into the recovery facility can be an option, but may have an impact on environment and raise legal problems. This study deals with the biological treatment of RO concentrate produced during water reclamation processes. The RO concentrate studied had low BOD_5 and T-P, but high T-N and COD concentrations. The sequencing batch reactor (SBR) process and the modified Ludzack-Ettinger (MLE) process were compared in controlled lab-scale experiments. The pilot-scale plant was operated to evaluate the performance of the SBR process under more realistic conditions. Kinetic parameters such as specific substrate utilization rate (SSUR), specific nitrification rate (SNR), and specific denitrification rate (SDNR) were obtained, and empirical equations were derived relating these parameters to the food-to-micro-organism (F/M) ratio. These parameters could prove useful tools for process design, operation, and improvement of anoxic and aeration tanks. Non-biodegradable COD components in the RO concentrate turned out to be hard to remove, which implies some physical or chemical process (e.g. flocculation, precipitation, or adsorption) may be needed in addition to the biological treatment process.

Keywords: Water reuse; Reverse osmosis concentrate; Biological treatment; Kinetic parameters

1. Introduction

According to a report from OECD (Organization for Economic Cooperation and Development) [1], by 2050 over 40% of the global population is projected to be living in river basins under severe water stress, and global water demand is expected to increase by some 55%. In order to meet this challenge, efforts are being made to secure water from unconventional resources.

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They include seawater desalination, rainwater harvesting, and reuse of low salinity water from sources such as sewage, wastewater or river water, among others.

Water reuse through the reclamation of sewage, wastewater, or surface water of poor quality is becoming prevalent globally. Many countries in the Middle East and northern Africa, where water shortage is very serious, have actively adopted water reuse. In countries like Singapore, Australia, Spain, and Italy, which are affected by limited water resources and climate change, water reuse is rapidly increasing. North America is no exception; examples can be found in California and Florida. Global Water Intelligence [2] expects that by 2025, the global water market will grow to reach 865 billion dollars and that water reuse will emerge as a new industry and create a market of 20 billion dollars.

The purpose of the use of reclaimed water varies. In many cases, agriculture and industry are the main users. Environmental use for aquifer and stream enhancement is also common. The treatment goal to be achieved and corresponding technology differ, depending on the purpose of the water reuse. A great deal of effort is being made to advance the technology [3,4]. Currently, treatment may consist of a single, or of combined unit, processes of sand filtration, activated sludge, microfiltration, membrane bioreactor (MBR), reverse osmosis (RO), and chlorination. RO, in particular, is widely used when the reclaimed water must meet high water quality standards, as for groundwater recharge or direct irrigation [5].

However, there are still problems to be solved both economically and technically. In particular, the use of RO membrane technology inevitably incurs the problem of disposing of concentrate having high concentrations of nutritive salts and ions. Generally, the rate of RO concentrate (ROC) production is about 20–30% of sewage influent and 5–20% for surface water. In countries like the United States and Australia, ROC can be discharged into surface waters or fed back to a sanitary sewer system [6,7]. Deep well injection can be an option, and sometimes zero liquid discharge is attempted using techniques including thermal or enhanced evaporation systems [8,9]. In some countries, however, discharging the concentrate to nature without treatment is not allowed due to environmental concerns. In South Korea, for instance, Sewerage Act regulates the quality of effluent water and water quality standards are much lower than the concentration of typical ROC (BOD < 0 mg/L; COD < 40 mg/L; SS < 10 mg/L; T-N < 20 mg/L; T-P < 0.5 mg/L) [10]. And, there could be technical or economic challenges in applying emerging technologies like zero liquid discharge.

Therefore, there exists a need for research to understand the characteristics of ROC of low salinity water and to develop a cost-effective system to treat it; so that the effluent from the system could meet discharge standards. Advanced oxidation processes (AOPs), such as ozonation, Fenton process, photocatalysis and photo-oxidation, sonolysis and electrochemical oxidation, may be the most promising management options, but the high cost may limit their application [11].

This study focuses on biological treatment approaches mainly because of their lower cost, compared to chemical methods. Biological treatment is known as economic and efficient method for the effluent standards. Recent work employing biological treatment of ROC can be found in the literature [12]. Here, we report the results from lab-scale experiments and a pilot-scale plant operation of biological treatment systems for ROC. These were conducted to investigate the effects of various changes in operational conditions (e.g. load fluctuation and water temperature) on the removal efficiencies of nutrients and organics. Based on the experimental results, empirical relations for kinetic parameters are derived that could be applied to the design and operation of real-world systems.

2. Materials and methods

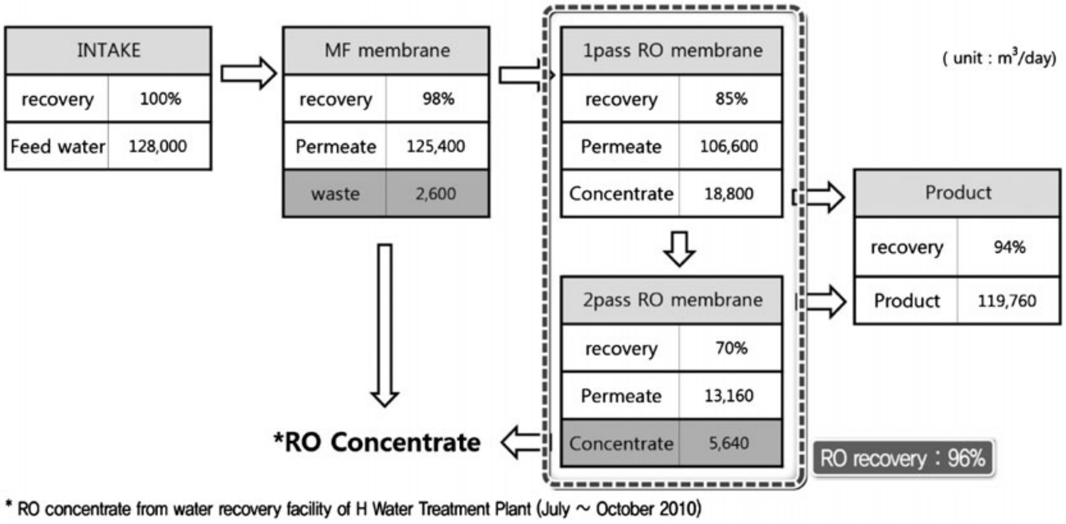
2.1. Preliminary analysis of ROC

H Water Treatment Plant in South Korea supplies water to an industrial complex, using the lake water as a source. ROC is produced as a result of water production and its process is shown in Fig. 1. ROC was collected in June 2010 and general water quality parameters analyzed using Standard Methods [13]. A relatively low carbon to nitrogen (C/N) ratio indicated the need for an extra carbon source to remove nitrogen effectively. The T-P concentration was also low, thus not suitable for ordinary biological treatment. Experiments were planned with a lab-scale setup and details are described below.

2.2. Lab-scale experiment

We considered two specific biological processes for the treatment of ROC: (1) the Sequencing Batch Reactor (SBR) process, known to be adaptable for high load fluctuations, and (2) the Modified Ludzack-Ettinger (MLE) process, which performs well for nitrogen removal.

Water samples were taken over a longer period, including the wet season, and concentrations were



* RO concentrate from water recovery facility of H Water Treatment Plant (July ~ October 2010)

Fig. 1. Water supply and ROC production at H Water Treatment Plant.

generally in ranges lower than those found in the preliminary analysis. The water quality parameters are shown in Table 1. Because of high T-N and relatively low BOD concentrations, it seemed obvious that an external carbon source would be needed for the biological denitrification process. The TCOD/$TBOD_5$ ratio of about 2.0 indicated that approximately 50% of the organics were non-biodegradable.

Table 1
Water quality parameters of RO concentrate used for lab-scale experiment*

	Concentration (mg/L)		
Chemical component	Min.	Max.	Avg.
pH	7.46	8.51	7.94
Alkalinity	390.00	615.91	487.60
$TBOD_5$	48.00	64.00	54.73
$SBOD_5$	38.00	58.00	46.92
TCOD	89.75	132.25	110.03
SCOD	82.25	122.25	100.73
T-N	107.5	150.00	122.27
TKN	48.50	75.20	60.18
NH_3-N	42.00	68.60	55.93
NO_3^--N	43.20	70.00	56.46
T-P	1.74	4.60	2.92
PO_4^{3-}-P	1.24	3.70	2.43
TSS	7.00	15.00	10.09
VSS	4.20	11.40	8.00
EC (μS/㎝)	–	–	13,884

*Sample from water recovery facility of H Water Treatment Plant (July–October 2010).

A series of experiments was conducted in order to see the relationship between hydraulic retention time (HRT) and influent rate. The change in treatment efficiency according to variation of water temperature was also of concern. Details on the experimental conditions are listed in Table 2.

First, SBR and MLE processes (Fig. 2) were compared under the same operating conditions, except for HRT and the recycling ratio. In the SBR process, 12 h of operation constituted one cycle, consisting of five hours of aeration followed by five hours non-aeration, then 30 min of reaeration, one hour of precipitation, 30 min of discharge, then rest. As for the MLE process, the internal and external recycling ratios were fixed at $1Q_{in,}$ and $2Q_{in}$.

Methanol was used as the external carbon source. The methanol injection rate was determined based on Eq. (1) [14]. The design concentrations were used for calculations: 0 mg/L for NO_2^--N and DO, and 120 mg/L for NO_3^--N. As a result, 296 mg/L of methanol was supplied to both SBR and MLE processes under anoxic conditions to meet the standard for nitrogen discharge (20 mg/L).

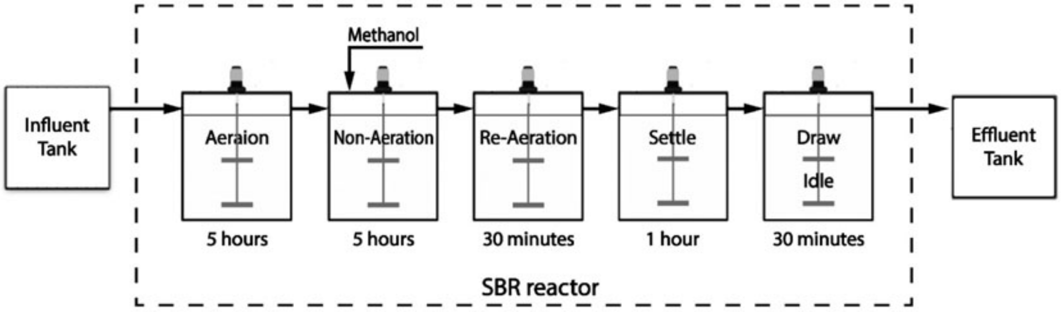
The SBR process, which showed higher nitrogen-removal efficiency, was chosen and the effect of influent change (10–15 L) was investigated (Mode 2). One operation cycle consisted of eight hours operation, consisting of three hours of aeration, followed by three hours of non-aeration, 30 min of reaeration, one hour of precipitation, 30 min of discharge, then rest.

The effect of changes in water temperature (from 20 to 8℃ or less) was observed in Mode 3.

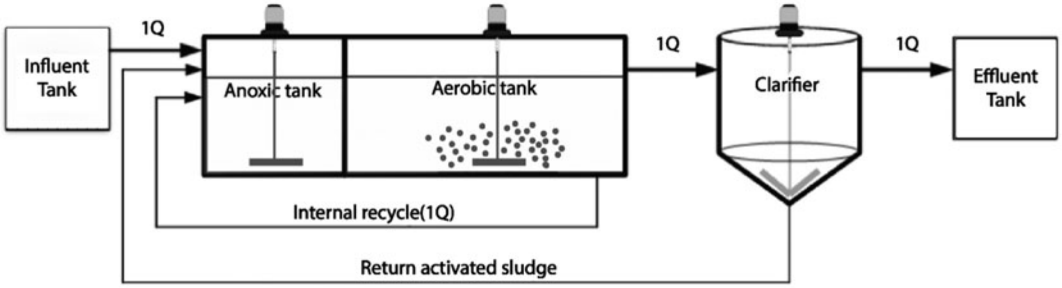
Table 2
Conditions of lab-scale experiments

Mode 1	Process type	Q_{in} (L/d)	Total tank volume (L)	Hydraulic retention time (cycles/d)	Recycle ratio	Solid retention time (d)	Air injection rate (mL/min)	Temp. (℃)
1	SBR	10	10	2	–/–	30	250	20
1	MLE	10	10	24	1Q/2Q	30	250	20
2	SBR	15	10	3	–/–	30	250	20
3	SBR	10	10	2	–/–	30	250	8

Note: The unit of hydraulic retention time for MLE is hour. The same water sample was used for Mode 1 experiment. For Mode 2 and 3, water samples were taken at the time of experiments, respectively.



(a) SBR Process (Mode 1)



(b) MLE Process

Fig. 2. Operation conditions of lab-scale setups.

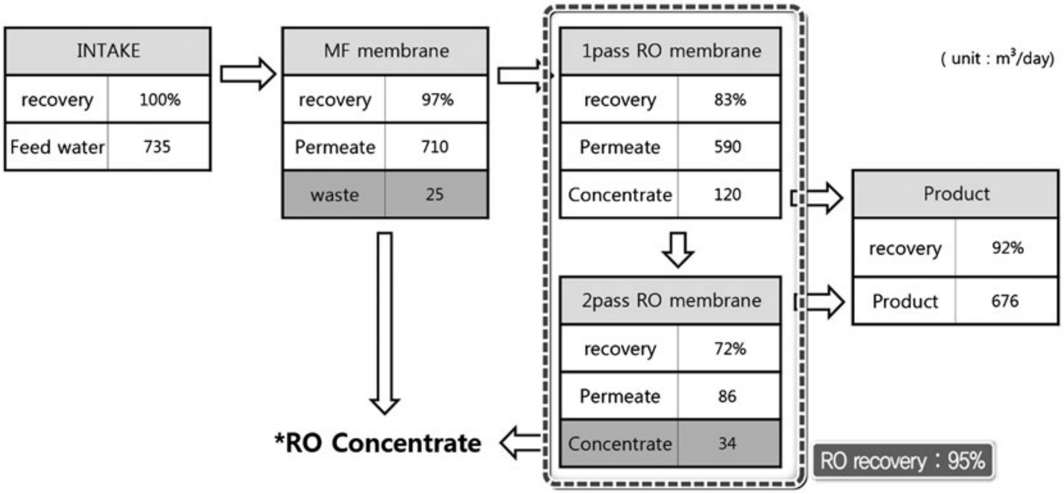
$$CH_3OH\ (mg/L) = 2.47\ NO_3^- \text{-N} + 1.53\ NO_2^- \text{-N} + 0.87\ DO \quad (1)$$

2.3. Pilot-scale plant operation

For pilot-scale plant operation, the RO concentrate from A Water Treatment Plant was used. There, industrial water is supplied using RO equipment (Fig. 3). Processes of two water treatment plants studied (H and A), including the RO recovery, are quite similar. Unlike the lab-scale experiment, however, the pilot plant operation included the winter season when water temperature is low and the source water quality is lower than that of the warmer season due to less precipitation.

Analysis results of the RO concentrate are shown in Table 3. Similar to the case of the lab-scale experiment, the RO concentrate had high T-N and low BOD concentrations, suggesting the need for external carbon. A TCOD/TBOD$_5$ ratio of about 8.6 indicated that the concentrate contained substantial amounts of non-biodegradable organic matter. In addition, unlike ordinary sewage or wastewater, the RO concentrate had large seasonal variations in water temperature: sometimes as low as 2–5℃ during winter.

Fig. 4 shows the configuration of the pilot-scale plant. We adopted the SBR process that had showed



* RO concentrate from water recovery facility of A Water Treatment Plant (August 2011 ~ February 2012)

Fig. 3. Water supply and ROC production at A Water Treatment Plant.

Table 3
Water quality parameters of RO concentrate used for pilot-scale plant experiment*

	Concentration (mg/L)		
Item	Min.	Max.	Avg.
pH	6.83	8.23	7.49
$TBOD_5$	5.40	40.20	19.31
TCOD	32.63	302.25	165.41
SCOD	19.75	267.25	148.33
T-N	17.60	108.50	51.32
NH_3-N	0.36	17.40	8.28
NO_3^--N	1.00	46.00	27.32
T-P	0.24	8.60	1.06
PO_4^{3-}-P	0.03	1.15	0.32
·Cl^-626.81	117.00	1,450.00	626.81
TSS	22.33	115.00	54.56
EC	–	–	21,209

*Sample from A water treatment plant (August 2011–February 2012).

relatively higher nitrogen removal efficiency in the laboratory experiments. The plant was built with a capacity of 62 m^3/d. As for the operation, we took into account the experience from Mode 2 of the laboratory experiment, which showed that better economic feasibility resulted from treating more influent with the same tank volume. Thus, a 12 h operating cycle was selected that included three hours of inflow, three hours of aeration, three hours of non-aeration, 30 min of reaeration, one hour of precipitation, one hour of discharge, and 30 min of rest. The solid retention time (SRT) was maintained at 30 d, and an electric heater was installed to keep the water temperature at 8℃ for stable nitrification. Air was injected sufficiently to ensure nitrification and decomposition of the organic matter. Methanol was injected at a rate of 2.7 mg methanol/mg NO_3^--N.

3. Results and discussion

3.1. Treatment characteristics

First, the performance of SBR and MLE processes was compared. The removal efficiency of organic matter based on $TBOD_5$ did not show a big difference between the two processes (SBR 87.59% and MLE 87.15%). The effluent from both processes had relatively high COD compared to BOD_5, indicating that the effluent contained a good deal of non-biodegradable matter. This implied that another system, in addition to a biological treatment system, would be needed to remove the non-biodegradable COD. The BOD:T-P ratio was at a level similar to that of ordinary sewage, and it was considered that no extra process would be needed to remove phosphorus.

As for the removal of nitrogen, the SBR and MLE processes showed different characteristics. Both processes showed nitrification efficiency greater than 98% from NH_3-N to NO_3^--N due to an adequate SRT. For denitrification, however, the SBR effluent had a lower T-N concentration (6.52 mg/L compared to 30.28 mg/L for the MLE). This is because dissolved oxygen that fed back into the anoxic tank from the aerobic tank during MLE, decreased the denitrification efficiency.

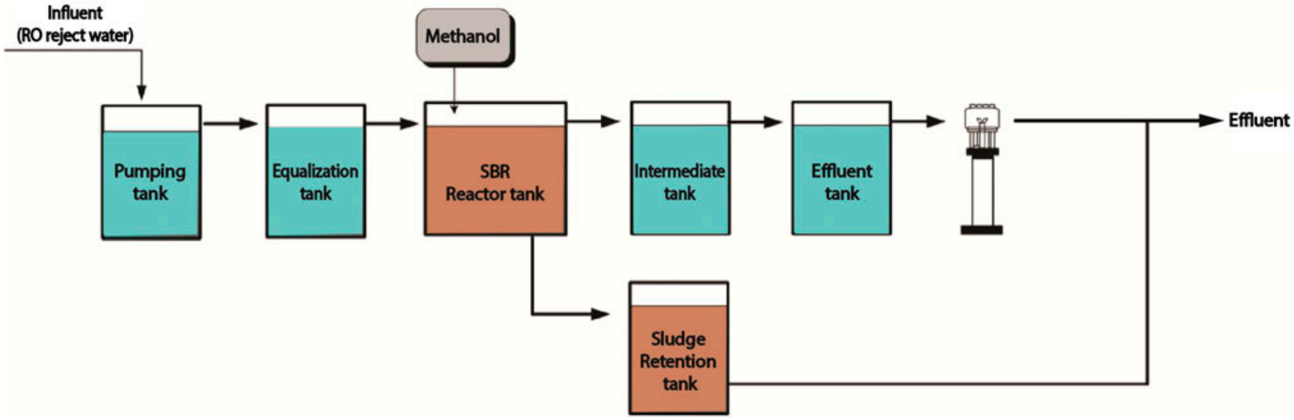


Fig. 4. Pilot-scale plant.

Given the same influent rate and reactor capacity, the overall performance of the SBR process turned out to be better than that of MLE. Of course, a simplistic comparison must be avoided. For instance, the denitrification efficiency will increase if the sludge return rate is raised, but this will in turn increase the operating cost. Overall, we concluded that the SBR process was more competitive than MLE from an economic point of view, even though SBR processes are somewhat more difficult to operate than continuous flow processes like MLE.

In the lab-scale Mode 1 experiment, we examined the treatment characteristics of the SBR process with different operation cycles and inflow rate (from 10 to 15 L/d). The $TBOD_5$-based removal efficiency when operating with 2 cycles/d (87.59%) was slightly higher than that of operation with 3 cycles/d (84.80%), while the total N-based removal efficiency dropped from 94.93% (2 cycles/d) to 86.89% (3 cycles/d). The decrease in reaction time is considered to be the cause of these results. However, since operation with 3 cycles/d still meets the effluent water quality standards, three cycles/d could be used for emergencies, like a sudden increase in the influent rate.

Mode 2 was designed to observe the effect of water temperature change (from 20 to 8℃). A slight decrease in the $TBOD_5$-based removal efficiency was observed (87.59 to 84.83%), but the water temperature did not seem to affect the overall removal efficiency of organic matter.

As for the T-N removal, the efficiency decreased from 94.93% at 20℃ to 87.26% at 8℃. This is believed to be due to the reduced activity of the micro-organisms. Note that the nitrification reaction occurs in the temperature range of 8–30℃ [15]. Detailed results of the lab-scale experiment are given in Table 4.

As stated earlier, the SBR process was chosen for the pilot plant operation since it showed better performance in the removal of nitrogen in particular. Compared to lab-scale, the influent concentration for the pilot plant was generally lower, with the exception of COD (Table 3). Therefore, the removal efficiency based on $TBOD_5$ was relatively low for both summer (48.06%) and winter (40.31%) seasons. The effluent concentration during the winter (12.98 mg/L) did not meet the discharge standard of 10 mg/L [10]. The decrease in the amount of external carbon consumed during denitrification in the winter may be the cause of the low efficiency.

As in the case of organic matter, the nitrogen concentration of the effluent (26.70 mg/L) did not satisfy the standard (20 mg/L) during the winter [10]. It was believed that lowered microbial activity at low water temperature slowed the speed of the nitrification and denitrification processes. This confirmed the necessity to maintain the water temperature at 8℃ or higher [15]. Keeping the level of mixed liquor suspended solids (MLSS) in a reaction tank steady and increasing the aeration time could also promote microbial activity and lead to better nitrogen removal. When the water temperature was below 8℃, a combination of such measures was temporarily applied for experimental purposes, and the effluent concentration of T-N (3.82–9.20 mg/L) meeting the water quality standards for discharge was resulted. Detailed results from analysis of the pilot plant operation are given in Table 5.

Table 4
Analysis results of lab-scale experiment

	Mode 1						Mode 2			Mode 3		
	SBR (20℃, 2 cycles/d)			MLE (20℃)			SBR (20℃, 3 cycles/d)			SBR (8℃, 2 cycles/d)		
Parameters	Inf. (mg/L)	Eff. (mg/L)	R.E. (%)	Inf. (mg/L)	Eff. (mg/L)	R.E. (%)	Inf. (mg/L)	Eff. (mg/L)	R.E. (%)	Inf. (mg/L)	Eff. (mg/L)	R.E. (%)
pH	8.19	8.20	–	8.19	7.79	–	7.83	8.10	–	7.83	7.84	–
$TBOD_5$	55.29	6.86	87.59	55.29	7.10	87.15	54.32	8.26	84.80	54.64	8.29	84.83
$SBOD_5$	49.79	5.33	89.30	49.79	5.69	88.58	45.20	6.58	85.43	46.00	6.5	85.88
TCOD	111.57	77.97	30.11	111.57	83.71	24.97	107.89	77.45	28.21	110.75	80.15	27.63
SCOD	101.95	70.14	31.20	101.95	76.19	25.26	99.49	68.65	31.00	100.85	74.95	25.68
TSS	10.42	6.92	33.56	10.42	6.14	79.85	9.63	7.79	19.04	10.26	7.22	29.55
VSS	8.02	5.06	36.87	8.02	4.37	76.26	7.80	5.82	23.24	8.52	6.08	26.52
T-N	128.68	6.52	94.93	128.68	30.28	76.88	119.46	15.66	86.89	119.18	15.18	87.26
TKN	63.99	1.28	98.00	63.99	1.39	97.87	58.85	6.21	89.42	57.99	5.51	90.34
NH_3-N	57.23	0.85	98.51	57.23	1.06	98.21	54.90	5.59	89.81	55.76	4.81	91.38
NO_3^--N	57.99	3.68	93.66	57.99	25.20	60.74	54.21	8.78	83.80	57.30	7.61	86.72
T-P	2.99	1.93	35.53	2.99	1.59	46.93	2.93	1.69	41.25	2.86	1.84	33.42
PO_4^{3-}-P	2.48	1.53	38.21	2.48	1.25	39.72	2.45	1.39	42.03	2.36	1.13	49.74

Note: Mode 1 is for process comparison. Values are averaged.

Table 5
Analysis results of pilot plant operation

	Average			Summer season			Winter season		
Item	Inf. (mg/L)	Eff. (mg/L)	R.E. (%)	Inf. (mg/L)	Eff. (mg/L)	R.E. (%)	Inf. (mg/L)	Eff. (mg/L)	R.E. (%)
$TBOD_5$	19.31	10.61	44.22	16.52	8.28	48.06	22.16	12.98	40.31
TCOD	165.41	131.41	21.19	140.85	106.02	25.12	190.49	157.32	17.18
SCOD	148.33	119.29	20.70	123.62	94.70	24.49	173.56	144.39	16.82
TSS	54.56	33.63	37.56	47.59	27.53	40.84	61.83	39.99	34.15
T-N	51.32	19.79	60.91	36.64	13.03	62.54	66.29	26.70	59.25
NH_3-N	8.28	4.00	56.59	3.80	1.09	66.61	12.85	6.98	46.36
NO_3^--N	27.32	9.22	66.81	21.09	5.14	72.69	33.68	13.39	60.82

Note: Values are averaged.

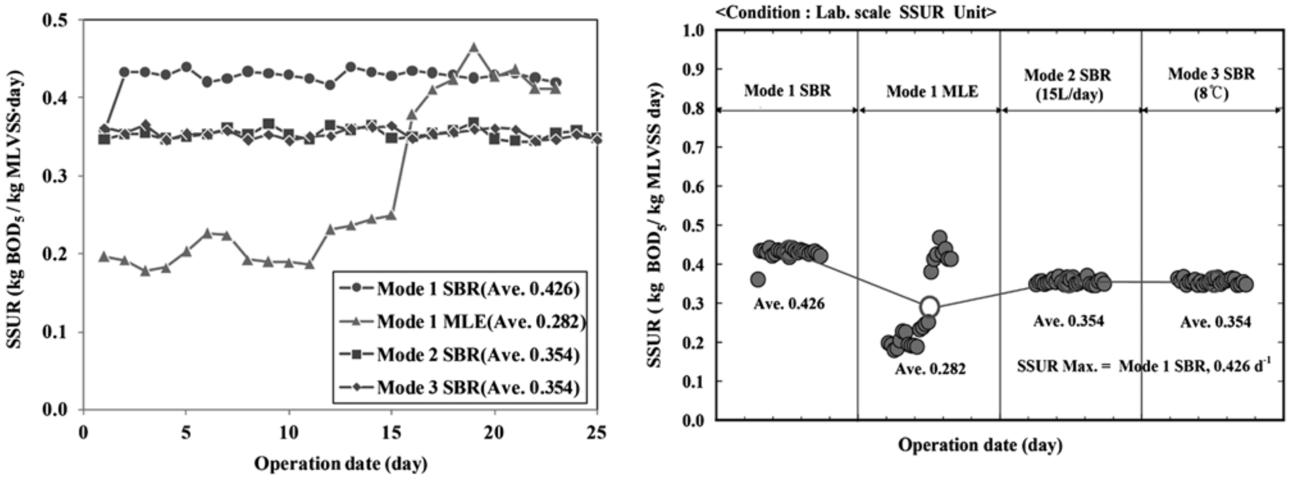
3.2. Kinetic parameters

3.2.1. Data analysis

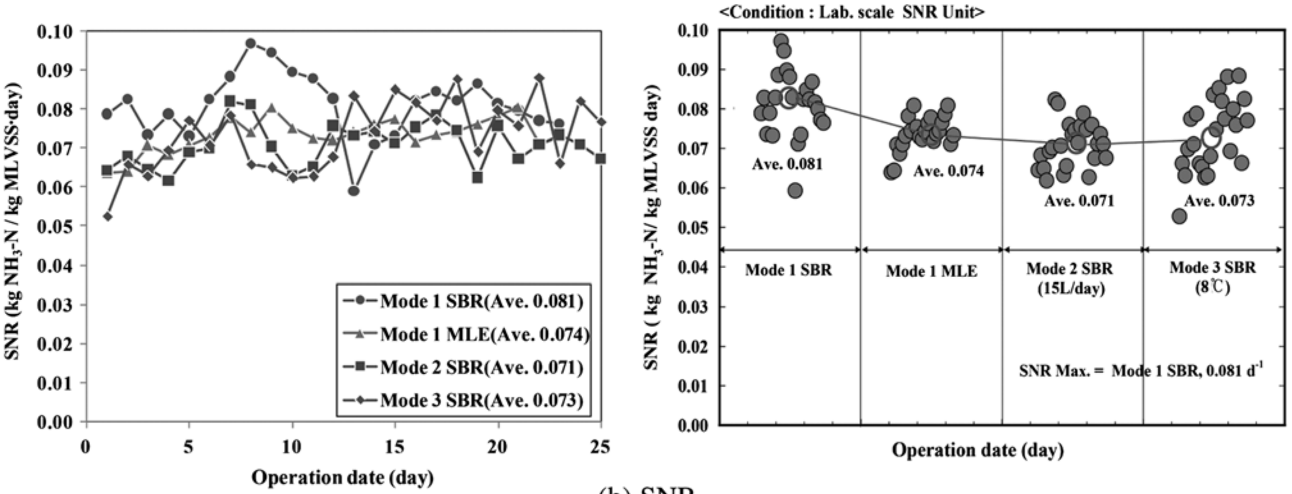
The specific substrate utilization rate (SSUR) is a useful parameter for the determination of aeration tank capacity in biological treatment process design. The SSUR for the lab-scale experiment is shown in Fig. 5(a). The SBR process of Mode 1 showed consistently higher SSUR values than MLE did, in which SSUR increased as the operation continued. The SSUR values in Modes 2 and 3 remained almost the same.

The specific nitrification rate (SNR) is also an important design parameter for an aeration tank. The SNR values of the lab-scale experiment are shown in Fig. 5(b). It was found that the SBR process of Mode 1 resulted in the highest SNR (0.081 kg TKN/kg MLVSS d). The lowest SNR (0.071 kg TKN/kg MLVSS d) was obtained for Mode 2. The SNR values of the lab-scale experiment were larger (Table 6) than results from the literature [14,16–18]. The relatively high water temperature in the laboratory is considered the cause of the high SNR.

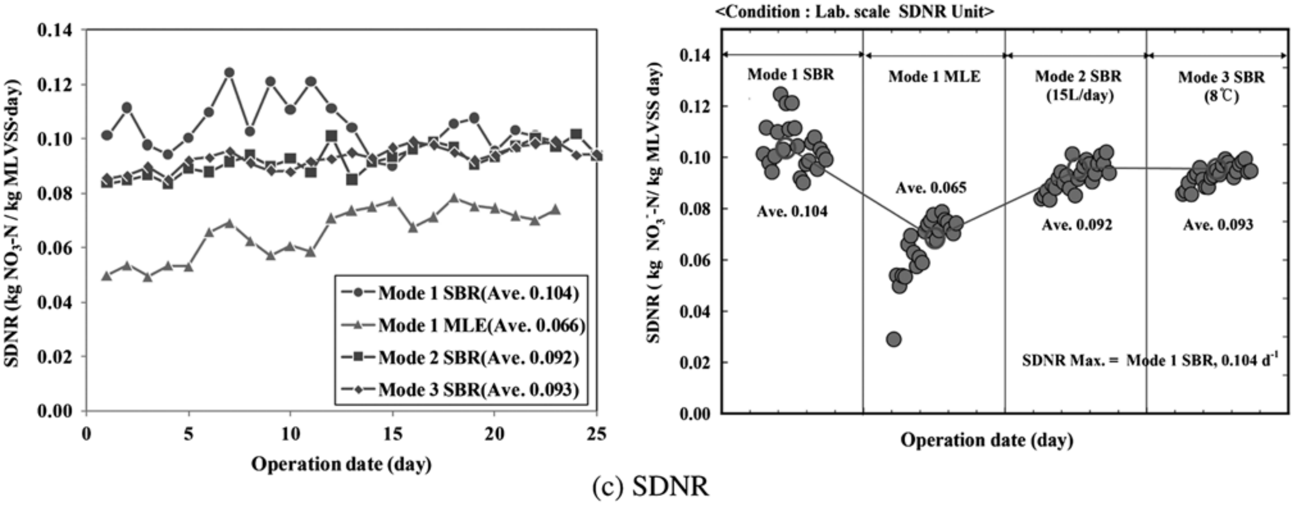
The specific denitrification rate (SDNR) is useful in the capacity design of an anoxic tank, and serves as an indirect indicator of the denitrification capability of a process. SDNR values of the lab-scale experiment are given in Fig. 5(c). The MLE operation resulted in the lowest SDNR. As for the SBR process, the SDNR of Mode 1 was higher than that of Mode 2 and 3. Similar to SNR, the SDNR of the lab-scale study



(a) SSUR



(b) SNR



(c) SDNR

Fig. 5. SSUR, SNR, and SDNR for lab-scale modes.

Table 6
Comparison of SNR

	Author	System		Source	SNR (g N/g VSS•d)
Literature	Randall et al. [14]	BNR		Municipal wastewater	0.043–0.048
	Randall et al. [14]	Conventional		Municipal wastewater	0.032–0.048
	Baeza et al. [16]	A^2/O		Synthetic wastewater	0.030–0.050
	Chiu et al. [17]	SBR		Synthetic wastewater	0.012–0.046
	Barnes et al. [18]	Activated sludge		Synthetic wastewater	0.024–0.072
This study	Lab-scale	SBR	Mode 1	RO Concentrate + Methanol	0.059–0.097
			Mode 2	RO Concentrate + Methanol	0.062–0.082
			Mode 3	RO Concentrate + Methanol	0.053–0.088
		MLE	Mode 1	RO Concentrate + Methanol	0.064–0.081
	Pilot-scale	SBR	8–18℃	RO Concentrate + Methanol	0.001–0.028
			18–30℃	RO Concentrate + Methanol	0.001–0.018

Table 7
Comparison of SDNR

	Author	System		SDNR (kg NO_3-N/kg MLVSS d)
Literature	Henze [19]	–		0.036–0.401
	Henze [20]	–		0.060–0.144
	Henze and Harremoës [21]	–		0.014–0.072
	Henze [22]	–		0.024–0.120
	Kujawa and Klapwijk [23]	–		0.024–0.144
This study	Lab-scale	SBR	Mode 1	0.090–0.124
			Mode 2	0.083–0.102
			Mode 3	0.085–0.099
		MLE	Mode 1	0.050–0.078
	Pilot-scale	SBR	8–18℃	0.012–0.092
			18–30℃	0.014–0.075

(Table 7) was higher than reported in the literature [19–23]. We believe that it is because of the added methanol, which is more degradable than ordinary sewage.

In Tables 6 and 7, SNR and SDNR from the pilot plant operation are also given. Unlike the lab-scale experiment, the SNR of the pilot plant was low and the range was quite large, compared to the values of other researchers. It is believed that keeping the optimal operating conditions steady would not be easy in practice, and the seasonal change of water temperature affects the nitrogen removal characteristics. Regarding SDNR, the high concentration of nitrogen and the reduced microbial activity might have contributed to relatively low values.

3.2.2. *Empirical equations*

Mathematical expressions for kinetic parameters to be used for process design were derived from the pilot plant operation data. First, SSUR can be expressed [24] as:

$$\mathrm{SSUR} = f\left(\frac{S_0 - S}{X}\right) \tag{2}$$

where SSUR = specific substrate utilization rate (kg BOD_5/kg MLVSS d); S_0 = design concentration of influent (mg BOD/L); S = design concentration of effluent (mg BOD/L); X = design microbial concentration (mg MLVSS/L).

Data from the pilot plant operation are displayed in Fig. 6 and were fitted to linear Eq. (3).

$$\mathrm{SSUR} = 3.5495\left(\frac{S_0 - S}{X}\right) + 0.0097 \tag{3}$$

Once SSUR is obtained, the HRT of an aeration tank can also be calculated [20] using the following relationship.

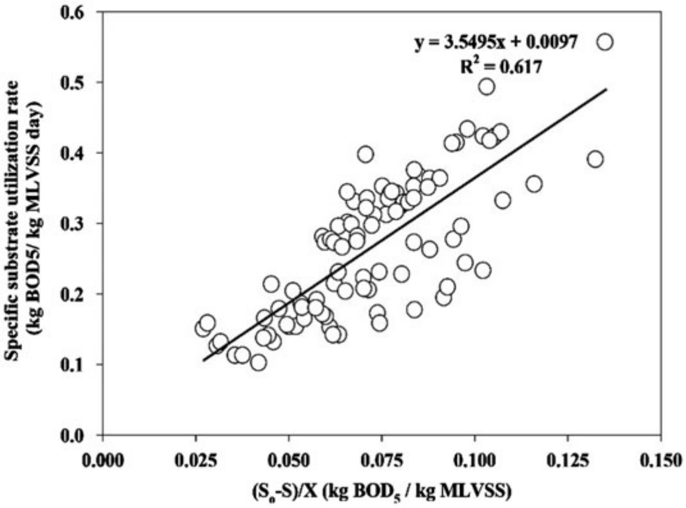


Fig. 6. SSUR vs. $(S_0 - S)/X$.

$$\theta_1 = \frac{S_0 - S}{\mathrm{SSUR} \cdot X} \tag{4}$$

The mathematical expression for SNR can be derived from the mass balance for NH_3-N:

$$N_0 \cdot Q \cdot \Delta t = \mathrm{SNR_N} \cdot f_N \cdot X \cdot V \cdot \Delta t + N \cdot Q \cdot \Delta t \tag{5}$$

where N_0 = NH_3-N concentration of influent (mg/L); N = NH_3-N concentration of effluent (mg/L); Q = flow rate (m^3/d); Δt = time (d); $\mathrm{SNR_N}$ = SNR by nitrifying micro-organism (kg NH_3-N/kg MLVSS d); f_N = fraction of nitrifying micro-organism; X = MLVSS concentration in aeration tank (mg/L); V = volume of aeration tank (m^3).

Eq. (5) can be rearranged for SNR of an activated sludge system [14]:

$$\frac{N_0 Q}{X \cdot V} - \frac{NQ}{X \cdot V} = \mathrm{SNR_N} \cdot f_N = \mathrm{SNR} \tag{6}$$

The left side of Eq. (6) can be interpreted as the ratio between F_N and M_{oxic}. The SNR and F_N/M_{oxic} from the pilot plant operation are plotted in Fig. 7, and the following empirical relation was obtained:

$$\mathrm{SNR} = 1.8103\,(F_N/M_{\mathrm{oxic}}) + 0.0016 \tag{7}$$

It might be noteworthy that Eq. (7) is valid for the following conditions: 15 < SRT (d) < 40, 8 < water temperature (℃)< 30, 0.0006 < F_N/M_{oxic} (kg NH_3-N/kg MLVSS d) < 0.0083.

Again, the HRT of an aeration tank can be calculated [14] from Eq. (8):

$$\theta_2 = \frac{N_0 - N}{\mathrm{SNR} \cdot X} \tag{8}$$

When the capacity of an aeration tank is to be determined, one usually compares θ_1 and θ_2, then chooses the larger value. Under operating conditions like those of the pilot plant of this study; however, $TBOD_5$ used for SSUR is indebted more to the external carbon source than to the oxidation of organic matter. Thus, we believe that SNR-based HRT, θ_2, is more appropriate than θ_1.

Similarly, an expression for SDNR was obtained as a linear function of $F_N/M_{\mathrm{anoxic.}}$

$$\mathrm{SDNR} = 0.251(F_N/M_{\mathrm{anoxic}}) + 0.022 \tag{9}$$

The above empirical formula is valid for the range of F_N/M_{anoxic} (kg BOD_5/kg MLVSS d) 0.016–0.126. The temperature effect can be considered as in Eq. (10); then the HRT of an anoxic tank can be obtained using Eq. (11).

$$\mathrm{SDNR}' = \mathrm{SDNR} \times 1.09^{T-20} \tag{10}$$

$$\theta_3 = \frac{(N_0 - N)'}{\mathrm{SDNR}' \cdot X} \tag{11}$$

Here $(N_0 - N)'$ required denitrification (mg NO_3^--N/L), and SDNR′ = overall specific denitrification rate (kg NO_3^--N/kg MLVSS d).

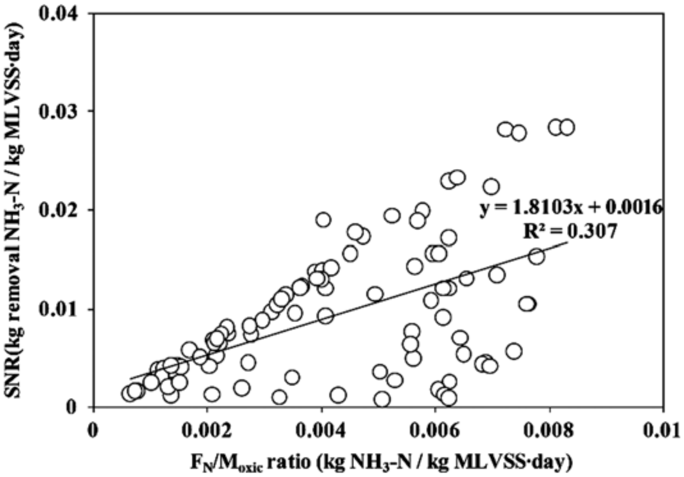


Fig. 7. SNR vs. F_N/M_{oxic}.

4. Conclusions

This work deals with the biological treatment of RO concentrate from treatment of low salinity water such as sewage or surface water of poor quality. The characteristics of this type of RO concentrate were quite different from those of ordinary sewage or wastewater. The concentrate typically had low BOD_5 and T-P concentrations, while it showed high levels of T-N and COD. The portion of NO_3^--N was about 50% of T-N.

Lab-scale experiments were conducted to determine whether the SBR or MLE process was the most appropriate biological treatment for RO concentrate from a water recovery facility. The SBR process was chosen based on its better performance in the removal of nitrogen and organic matter. Then, experimental conditions were varied to find the best setup for a larger scale facility. A pilot plant operation was created to understand the performance of the preferred treatment system under more realistic conditions.

Data were obtained from the pilot plant operation during the period encompassing the summer and winter seasons. Kinetic parameters needed for the design of the aeration and anoxic tanks were obtained (i.e. SSUR, SNR, and SDNR). Further, an empirical equation was derived relating SNR and F_N/M_{oxic}, which could be useful in determining the aeration tank capacity. Also derived was an empirical formula for SDNR as a function of F_N/M_{anoxic}, which could be used for anoxic tank design. HRT for a reactor can be calculated more reasonably using these empirical formulae.

Due to non-biodegradable COD components in the RO concentrate, the biological treatment system showed low COD removal efficiency. This may call for some physical or chemical process in addition to the biological treatment process. Flocculation and precipitation before or after biological treatment could be considered. Adsorption using granular activated carbon may be applicable as well.

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Symbols

F/M — food to micro-organism ratio
f_N — fraction of nitrifying micro-organism
N — NH_3-N concentration of effluent (mg/L)
N_o — NH_3-N concentration of influent (mg/L)
Q — flow rate (m^3/d)
S — design concentration of effluent (mg BOD/L)
S_o — design concentration of influent (mg BOD/L)
Δt — time (h)
T — temperature (℃)
SDNR — specific denitrification rate (kg NO_3^--N/kg MLVSS d)
SDNR′ — overall specific denitrification rate (kg NO_3^--N/kg MLVSS d)
SSUR — specific substrate utilization rate (kg BOD_5/kg MLVSS d)
SNR — specific nitrification rate (kg TKN/kg MLVSS d)
SNR_N — SNR by nitrifying micro-organism (kg NH_3-N/kg MLVSS d)
V — volume of aeration tank (m^3)

X — design microbial concentration (mg MLVSS/L)
θ_1 — HRT of an aeration tank based on SSUR (d)
θ_2 — HRT of an aeration tank based on SNR (d)
θ_3 — HRT of an anoxic tank (d)

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