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Treatment of reverse osmosis concentrate by biological aerated filter

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ABSTRACT

The aim of this study is to employ the biological aerated filter (BAF) in the treatment of reverse osmosis (RO) concentrate received from reuse of wastewater treatment plant. BAF is known as economic and efficient treatment method for the effluent standards. The result of the treatment of RO concentrate by BAF process was found to be efficient for biological oxygen demand (BOD) removal (95.86%). However, it was relatively less efficient in the chemical oxygen demand (COD) (88.95%) and suspended solids (SS) (81.12%) removal. A high BOD removal efficiency is due to the complete oxidation of organic matter which comes from low food to micro-organisms (F/M) ratio (0.049 kg BOD/kg MLSS day) of the influent. The TN (total nitrogen) and NO_3-N removal percent were found to be 81.42% and 76.70%, respectively. However, total phosphorous (TP) and PO_4-P removal percent were obtained low with 67.66 and 61.42%, respectively. It is observed that decreasing the COD/N ratio caused to decrease the TP and PO_4-P removal efficiency. However, the denitrification and nitrification rates were increased from 211.8 to 301.0 mg/L day and 87.7 to 109.4 mg/L day, respectively, for a change in COD/N ratio from 8.19 to 7.64. Therefore, in order to reuse the RO concentrate, BAF process could effectively treat the RO concentrate.

Keywords: Biological aerated filter; COD/N ratio; Nutrients removal; RO-concentrate; Wastewater reuse

1. Introduction

Water resources are under tremendous stress and found scarce in many areas of the world because of its increased and widespread demand. Reverse osmosis (RO) is a membrane-based technology widely applied in water desalination, production of potable water, and more recently in tertiary wastewater treatment process [1]. In recent years, RO is also applied to in the treatment of secondary effluents of wastewater treatment plants (WTPs). The RO concentrates obtained from the WTPs contained with less salinity than the RO concentrates from desalination plants. However, it contained with high content of organic matters along with persistent micro-pollutants [2]. Solley et al. [3] reported that the level of contamination of RO concentrate is 6–7 times higher than the usual wastewater contamination level. Advanced oxidation process (AOP) employed with sorbing resins showed fairly a good treatment process for the treatment of RO concentrate along with the removal persistent micro-pollutants. AOPs, such as ozonation, fenton processes, photocatalysis and photooxidation, sonolysis and electrooxidation, are probably the most promising technologies to degrade and detoxify

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endocrine disrupting compounds [4]. However, high chemical dosage and high energy consumption of these technologies may limit their application [5]. Therefore, specific treatment, such as biological aerated filter (BAF) process was proposed in order to reduce the pollutant load in the treatment of wastewaters.

The BAF process is ideal for reclamation and reuse of wastewater. The BAF is a down/up flow, high rate, fixed film, biological wastewater treatment system. It is an excellent process in the removal of organic matter and suspended solids (SS). Moreover, it is easy to maintain and achieve energy saving and space conservation [6]. The process is operated to obtain high level of denitrification, although this requires lower loading rates and a bigger system for the same flow. Since filtration is performed in the lower portion of the filter, the BAF system eliminates the need of an additional secondary clarifier. Although, a secondary filter is needed in case the effluent is enriched with low SS. This substantially reduces the capital and operating cost of the process. Another advantage of the process is less land requirement since system requires substantially less space than other conventional systems (approximately one-fifth the area for conventional activated sludge systems) [7,8].

The aim of this study is to optimize the treatment of RO concentrate obtained from reuse of WTP using the BAF process. Furthermore, the influence of the COD/N ratio on the nutrient removal is studied as to predict possible pathways of nutrient removal.

2. Materials and methods

2.1 Characteristics of wastewater

The chemical characteristics of the wastewater and RO concentrate used for present investigation are given in Table 1. A pilot scale plant is installed at industrial WTP located in Ulsan city, Korea. This industrial wastewater is contained with more Na, Mg, Cl, Mn, and Ba content but less with nutrients comparing to the municipal wastewater. RO concentrate is contained with more BOD, TN, TP, and PO_4-P content than that of influent wastewaters. The operation period of pilot plant is fixed for 150 days.

The ratio of COD/N/P ratio is found to be 100/20/2 for the wastewater samples and is recommended for its nutrient removal. The BOD/TP and BOD/PO_4 ratios for influent wastewater (10.34 and 12.34) are also found to be reasonably high comparing to the RO concentrate (8.00 and 9.27). However, the PO_4/TP ratio is having almost identical values for influent wastewater and RO concentrate, i.e. 0.84 and 0.86, respectively.

2.2. Process of UF/RO

The industrial wastewater plant is operated with 92 m^3/day wastewaters and is generating a RO concentrate of 20.5 m^3/day. The operating conditions of chemical pretreatment, UF (ultra filtration), and RO process are represented in Table 2. The backwash of the UF process is conducted four times using NaOCl (200 ppm) and 3 times using citric acid (1,000 ppm) once in a week. Each backwash was 45 min with aeration.

Table 1
Characteristics of the influent wastewater

Parameter	Influent (wastewater) (mg/L)	RO concentrate (mg/L)
Na	568.60 (468.60–676.70)	2,707 (2,078–3,157)
Mg	61.14 (50.34–79.74)	317.81 (240.12–357.46)
Cl	1486.00 (1120.31–1697.00)	6743.52 (5935.93–7147.24)
Ca	428.80 (404.70–462.38)	1,656 (1,611–1,695)
TDS	3,400 (3,050–3,700)	8,470 (7,000–13,280)
Mn	0.104 (0.08–0.19)	0.404 (0.29–0.58)
Ba	0.62 (0.61–0.64)	2.60 (2.51–2.64)
COD (Cr)	227.73 (90.52–500.45)	364.55 (130.78–740.54)
BOD	22.34 (10.91–40.54)	48.30 (11.14–127.16)
SS	38.42 (23.62–56.45)	98.95 (28.57–210.23)
TN	12.15 (2.57–20.32)	44.50 (17.34–58.61)
NO_3-N	9.82 (4.25–17.25)	27.12 (21.33–31.45)
NH_4-N	1.49 (0.98–2.15)	16.19 (12.47–20.54)
TP	2.16 (0.84–3.17)	6.03 (3.14–7.51)
PO_4-P	1.81 (0.41–2.26)	5.21 (2.73–5.92)

Table 2
Operating conditions of chemical pretreatment, UF, and RO

	Operating conditions
Pre-treatment	• $KMnO_4$: None–2 ppm • NaOCl: 2–5 ppm • PACl: None–3.5 ppm • NH_4Cl: As needed • HCl: pH: 6.7–7.2
UF	• Recovery: 90–95% • Flux: 34–38 LMH • Max. TMP: <0.84 kg/cm^2 • Backwash process: 45 min
RO	• HCl: pH: −6.5 • MDC: 5–9 ppm • Product flow (avg.): 2.56 m^3/h • Recovery: 70–75% • Max. TMP: <0.4 kg/cm^2 • Restoration cleaning: acid: 30–60 days, base: 30–60 days

The operating parameters of UF–RO are represented in Table 3. The UF consist of three-membrane system a ZeeWeed-1000 (ZW-1000) supplied by Zenon Environmental Inc., outside/in ultrafiltration hollow fiber membrane. A maximum operational pressure of RO is maintained at 600 psi (4,137 kPa). Similarly, a constant operating pressure i.e. 200 psi (1,379 kPa) is kept in the batch single-pass mode.

2.3. BAF process

A schematic diagram of the BAF process and BAF media to treat the RO concentrate are shown in Fig. 1. The BAF process possesses several advantages which confer its benefit in adaptation of this technology [9,10].

The attached growth on an inert granular media in BAF allows for a much higher concentration of active biomass than a suspended growth-activated sludge system so that the size of reactor is reduced. In addition, SS in the influent are captured physically by the media; this eliminates the requirement of separate secondary clarification. Overall, this is space-saving layout that consumes only one-third the footprint space of an activated sludge process [11].

In this experiment, the BAF is an upflow and biological wastewater treatment system with floating media. The process is capable of removing nutrients from the wastewater. The BAF technology relies on the suspension (fluidization) of small particles flowing upward in the wastewater. The BAF process operated at 4 m^3/day of flux and is prepared with a total volume of 0.4 m^3 (media 2.5 m) and 0.2 m^3 (media 1.5 m) for denitrification (DN) phase and nitrification (N) phase, respectively (Fig. 1). The operating parameters of BAF plant are represented in Table 4. Experiments are performed in two steps, DN phase and N phase, at different linear velocity (LV) and empty bed contact time (EBCT).

As BAF technology is applied to RO concentrate treatment, the selection of granular media plays an important role in maintaining a high amount of active biomass and variety of microbial populations. The used floating media in the experiment is 2–3 mm in diameter, 0.07–0.08 media g/cm^3 density, 1,000–1,350 m^2/m^3 specific surface area, and 2.5 kg/cm^2 compressive strength, which is made by poly-propylene (Fig. 2). Using the media with adsorption capacity, an approach

Table 3
Operating parameters of UF and RO

	Unit	UF	RO	Remarks
Model		ZW1000	AG8040	
Configuration		Outside-in hollow fiber	Thin film membrane	
Pore size	m	0.02	–	Nominal
Specific membrane surface area	m^2	41.8	32.5	per module
Number of membrane	ea	3	18	
Material		PVDF	Polyamide	
Max. operating temperature	℃	40	50	

Table 4
Operating parameters of the BAF plant

	DN phase	N phase
Flux	4 m^3/day	4 m^3/day
Size	0.35 m (D) × 4.5 m (H) (floating media 2.5 m)	0.25 m (D) × 3.5 m (H) (floating media 1.5 m)
LV	1.8 m/h	3.40 m/h
EBCT	1.5 h	0.5 h

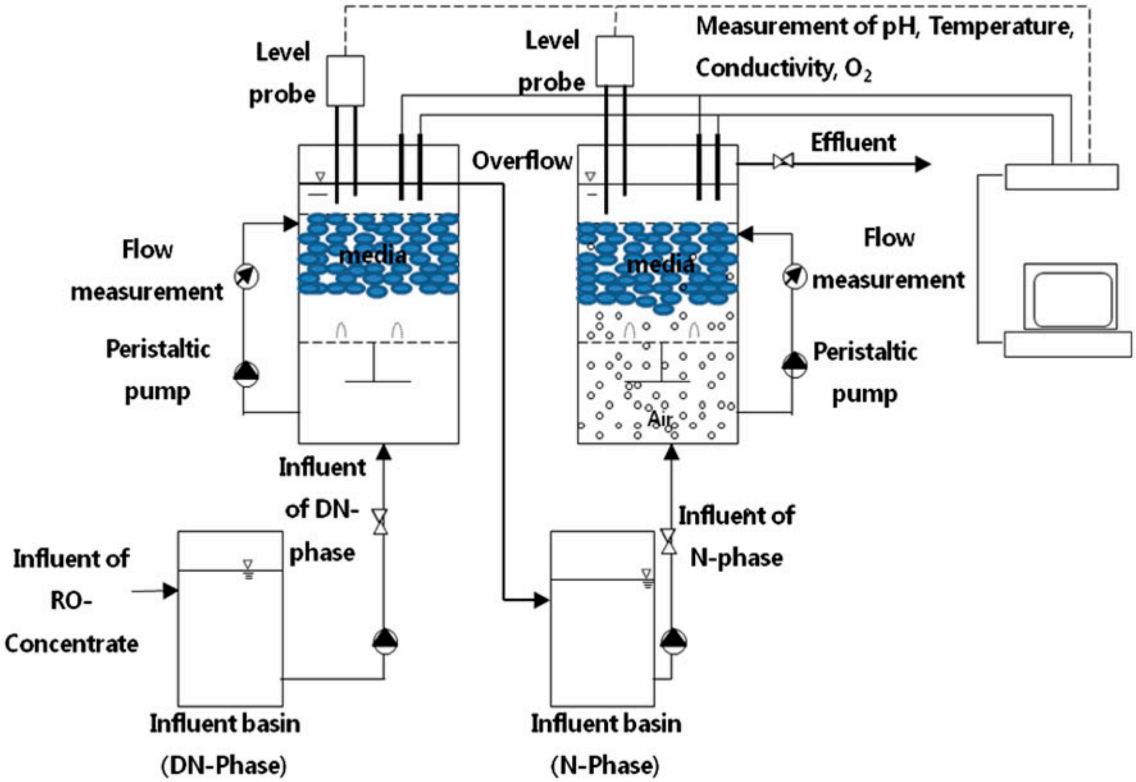

Fig. 1. Schematic diagram of BAF process.

for the integration of biological removal and adsorption is possible.

2.4. Analyzed methods

COD, BOD, SS, TP, PO_4-P, TN, NO_3-N, and NH_4-N are measured according to the standard methods given elsewhere [12]. Sulfate is measured by Ion Chromatography (IC). Potentiometric titrimetry or IC is used for chloride estimation. ICP-AES is used to analyze total calcium, sodium, and potassium.

Fig. 2. Schematic description of floating media.

3. Results and discussion

3.1. Removal of nutrients in BAF process

The results obtained in the removal of various nutrients in the RO concentrate were represented in Table 5. The results clearly demonstrated that BAF treatment for RO concentrate significantly reduces the BOD content and the percent removal is as high as 95.86%. However, the removal percent of COD

Table 5
Summary of the removal efficiency of nutrient in the RO concentrate

Parameter	DN phase (RO concentrate) (mg/L)	N phase (mg/L)	Effluent (mg/L)	Average removal (%)
COD (Cr)	364.55	178.18	40.27	88.95
BOD	48.30	25.62	2.00	95.86
SS	98.95	88.73	18.68	81.12
TN	44.50	23.32	8.27	81.42
NO_3-N	27.12	14.09	6.12	76.70
NH_4-N	16.19	7.42	1.95	87.96
TP	6.03	3.09	1.95	67.66
PO_4-P	5.21	3.01	2.01	61.42

(88.95%) and SS (81.12%) was relatively low compared to that of BOD. The high BOD removal efficiency is due to the complete oxidation of organic matter which often comes from food to micro-organisms (F/M) ratio (0.48 kg BOD/kg MLSS day) of the influent. Despite the fluctuations of influent COD concentration ranging from 130.78 mg/L to 740.58 mg/L, the effluent COD concentrations were always lower than 58.32 mg/L. It is worth to notice that most of the COD was removed in the N phase. These data inferred that the BAF system could provide a consistent high removal efficiency of COD removal. Chang et al. [9] reported 99% BOD, 86% COD, and 74% SS removal efficiency while treating the textile wastewater in a BAF with zeolite media. A relatively low efficiency of COD removal was obtained, i.e. in the range of 61.52–69.2%, while the domestic wastewater was treated using BAF process as reported by Wang et al. [11]. The COD and SS removal efficiencies achieved in this study were found to be slightly higher compared to the studies demonstrated elsewhere for different systems.

It was observed that throughout the operation, the removal efficiencies of TN and NH_4-N were not as high as that of COD. The TN and NH_4-N removal efficiencies were found to be 81.42 and 87.96%, respectively, with the average effluent concentrations of 8.27 and 1.95 mg/L, respectively. These data indicated that about 6.32 mg/L NO_3-N remained with the treated samples, which implied that the denitrification was not accomplished fully.

Similarly, results suggested that the removal efficiencies of TP and PO_4-P were not as good as TN and NH_4-N. It was assumed that organic matter in influent was consumed to remove nitrogen by denitrification rather than the PO_4-P removal. TP and PO_4-P removal efficiencies were relatively low with 67.66 and 61.42%, respectively. Fu et al. [13] found relatively higher the PO_4-P removal (90.5%) having the COD/N ratio of 9.3 in a modified membrane bioreactor treating high strength wastewater.

3.2. *Effect of COD/N ratio on nitrification and denitrification*

The COD/N ratio of influent is one of the most critical parameters for wastewater nitrogen removal process, because it directly affects the functional micro-organism populations, including autotrophic ammonium (NH_4-N) oxidized bacteria, NO_2–N oxidized bacteria, and heterotrophic denitrifies. In a nitrogen removal system, different micro-organism populations compete for substrate which caused fluctuation in effectiveness of organic and nitrogen removal [14,15]. Theoretically, the stoichiometric requirement for denitrification was 2.86 g COD/g N, considering the electron transmitting balance between organic substrate and NO_3-N [16,17]. However, it was reported that in a combined nitrification/denitrification process, COD/N requirement in practice was higher than 2.86 g COD/g N [18,19]. Nitrogen was removed by both assimilation into biomass and biological nitrification–denitrification processes. However, Tan and Ng [20] observed that cell assimilation was estimated to remove about 15–20% of the influent TN concentration in a pre-denitrification MBR. This result demonstrated that TN removal efficiency operated at long SRT was not due to cell assimilation, rather contributed more significantly by the nitrification–denitrification process. Therefore, nitrogen removal contributed by assimilation was ignored in discussion.

The dependence of nitrification rates and denitrification rates on the COD/N ratio was examined with the data from NH_4-N removal and TN removal, respectively. The nitrification rate and denitrification rate were calculated according to Eqs. (1) and (2), respectively:

$$\Gamma_{\text{nitrification}} = \frac{Q_{\text{in}}(\text{NH}_4 - \text{N}_{\text{influent}} - \text{NH}_4 - \text{N}_{\text{effluent}})}{V_{\text{reactor}}} \quad (1)$$

$$\Gamma_{\text{denitrification}} = \frac{Q_{\text{in}}(\text{TN}_{\text{influent}} - \text{TN}_{\text{effluent}})}{V_{\text{reactor}}} \quad (2)$$

where Q_{in} is the influent flux (L/day) and $V_{reactor}$ is the volume of reactor (L). The calculated data are given in Table 6. The nitrification capacity was influenced by influent COD/N ratio. It was increased from 87.7 to 109.4 mg/L day, when COD/N ratios were decreased from 8.19 to 7.64, respectively. Some researchers reported that the oxygen saturation coefficients of Monod kinetics for nitrifying bacteria were higher than that of heterotrophic bacteria [21,22]. Hence, dissolved oxygen would be utilized primarily by heterotrophic bacteria, rather than nitrifying bacteria. With the decrease of COD/N level, substrate concentration for NH_4-N oxidation bacteria increased,

Table 6
Nitrification and denitrification rates with different COD/N rates

COD/N (mg/L day)	8.19	7.64
$\Gamma_{\text{nitrification}}$	87.7	109.4
$\Gamma_{\text{denitrification}}$	211.8	301.0

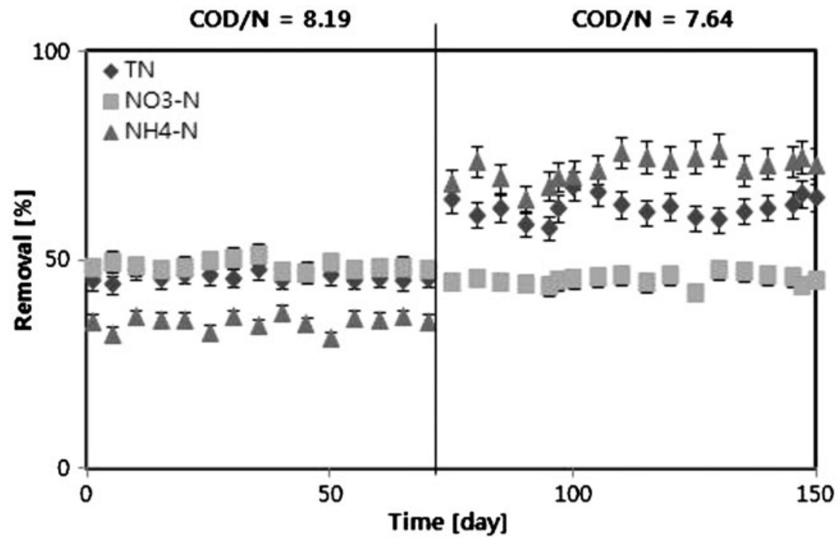

Fig. 3. Removal efficiency of TN, NO_3–N, and NH_4-N by different COD/N ratio.

which stimulated the growth of biomass [13]. Therefore, the nitrification capacity was enhanced.

Denitrification rate was calculated according to the Eq. (2). The denitrification rate was increased from 211.8 to 301.0 mg/L day, when COD/N ratio was changed from 8.19 to 7.64, respectively. Results showed that the denitrification rate was significantly increased. However, the TN removal efficiency was not increased due to the increase of NH_4-N-volume loading. Furthermore, the nitrification and denitrification rates were increased from 2.42 times to 2.75 times, respectively implying that more oxidized nitrogen remained in the reactor. Results further showed that denitrification was the rate limiting step in the total process of TN removal. It was speculated that the denitrification inefficiency was due to insufficient availability of electron donor substances, since it was composed with the anoxic removal of influent organic materials.

Fig. 3 shows removal efficiency of TN, NO_3-N and NH_4-N for different COD/N ratios. The removal efficiency of TN and NH_4-N was increased from 47.60 to 64.54% and 54.17% and 73.72% with decreasing the COD/N ratio from 8.19 to 7.64, respectively. The nitrification activity was increased gradually and attained a constant value between 75 day and 150 day, with the average NH_4-N removal efficiency of 73.72%. The

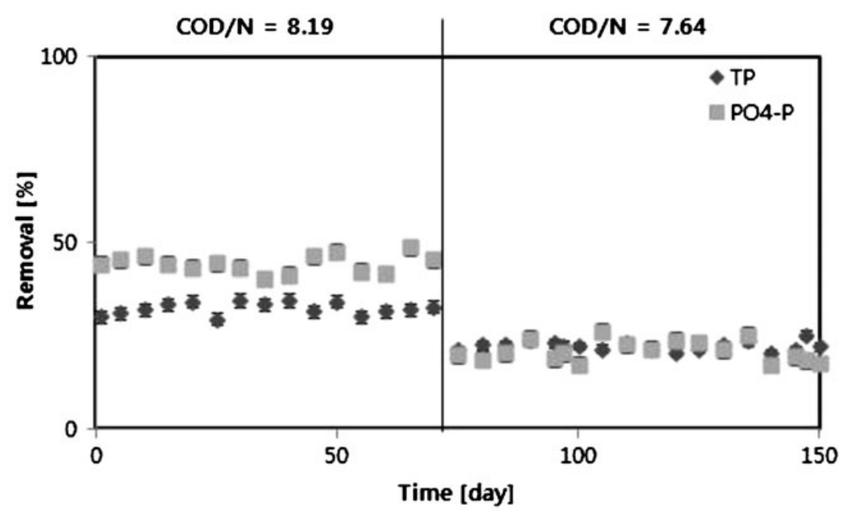

Fig. 4. Removal efficiency of TP and PO_4-P by different COD/N ratio.

average effluent concentrations of NH_4-N and TN were 1.95 mg/L and 8.27 mg/L, respectively. These data clearly demonstrated that about 6.32 mg/L NOx-N remained, which implied that the denitrification did not occurred completely.

3.3. Effect of COD/N ratio on TP and PO_4-P removal

The COD/N ratio was decreased from 8.19 to 7.64 to decrease the removal efficiency of PO_4-P and TP from 42.23% to 33.22%, and from 48.76% to 36.89%, respectively. Moreover, the NO_3-N/PO_4-P ratio was decreased from 5.21 to 4.68 for the similar increase in COD/N ratio from 8.19 to 7.64. It was speculated that reduced NO_3-N/PO_4-P ratio in the reactor had induced a sufficient available substrate for biological PO_4-P removal, which resulted in perfect PO_4-P removal. Fig. 4 presents TP and PO_4-P removal efficiency during whole operation period. Having the COD/N ratio of 7.64 the PO_4-P, the TP concentrations were decreased insignificantly and average TP and PO_4-P removal efficiency were lower than that with COD/N ratio of 8.19. The phenomena showed that the PO_4-P and TP removal process might undergo rapid conversion which was speculated due to the decrease of PAOs. Choi et al. [15] reported that a logical selection would be a classic N, P process. For each gram of COD consumed 0.05 and 0.01 mg of N and P was assimilated in the biomass. With decreasing the COD/N ratio, the excess of N was increased in the reactor. This excess N basically interrupted the TP and PO_4-P removal. Jena et al. [23] reported PO_4-P removal rate was more or less impervious to varying concentration of nitrate and carbon loading in the BAF system.

4. Conclusions

This study inferred to assess the BAF process in the treatment of RO concentrate obtained from reuse of wastewater treatment. Significantly high BOD (95.86%) removal efficiency was obtained compared to the COD (88.95%) and SS (81.12%) removal. This was due to the fact that a major portion of organic matter occurred from F/M ratio (0.48 kg BOD/kg MLSS day) in the influent was oxidized. The TP (67.66%) and PO_4-P (61.42%) removal efficiencies were relatively lower than those of TN (81.42%) and NO_3-N (76.70%). This is due to a low TBOD/TP ratio value (8.01). A decrease in the COD/N ratios caused a decrease in the TP and PO_4-P removal efficiency. However, the removal efficiency of TN and NH_4-N was increased from 47.60 to 64.54% and 54.17 and 73.72% with decreasing the COD/N ratio from 8.19 to 7.64, respectively. In addition, the denitrification rate and nitrification rate were increased from 211.8 to 301.0 mg/L day and 87.7 to 109.4 mg/L day, respectively, when COD/N ratios were decreased from 8.19 to 7.64.

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