Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2015.1030112

57 (2016) 7574–7581
April

Taylor & Francis
Taylor & Francis Group

Effects of aeration on/off times and hydraulic retention times in an intermittently aerated membrane bioreactor

Changkyoo Choi[a], Moonil Kim[b], Euntae Yang[c], In S. Kim[a,c,*]

[a]*Global Desalination Research Center, Gwangju Institute of Science and Technology, 123, Cheomdan-gwagiro, Buk-gu, Gwangju 500-712, Korea, Tel. +82 62 715 2436; Fax: +82 62 715 2584; email: iskim@gist.ac.kr (I.S. Kim)*
[b]*Department of Civil & Environmental Engineering, Hanyang University, 1271, Sa-1 dong, Sangnok-gu, Ansan, Gyeonggi-do 425-791, Korea*
[c]*School of Environmental Science and Engineering, Gwangju Institute of Science and Technology, 123, Cheomdan-gwagiro, Buk-gu, Gwangju 500-712, Korea*

Received 19 November 2014; Accepted 11 December 2014

ABSTRACT

Intermittently aerated membrane bioreactor is a process that combines an intermittently aerated bioreactor with a membrane. A membrane bioreactor can achieve complete separation between solids and liquids, and improve nitrogen removal because the reactor contains bacteria relevant to nitrifying and denitrifying. This paper is an investigation into removal efficiencies on two operation factors (aeration on/off times and hydraulic retention times (HRTs)). Permeate concentrations of T-N and T-P in 60 min-on/60 min-off were 19.6 and 4.41 mg/L, respectively, and permeate concentrations of T-N and T-P in 30 min-on/30 min-off were 22.7 and 4.56 mg/L, respectively. Accordingly, we found that 60 min-on/60 min-off was superior to 30 min-on/30 min-off. This was due to the high mixed liquid suspended solid concentration and the sufficient aerobic/anoxic time for the reaction. In the experiments with HRTs of 6, 9, and 12 h, the removal efficiency of organic matter was above 90% under all conditions. However, the HRT of 6 h was the best condition for removal efficiencies of T-N and T-P, due to high chemical oxygen demand loading rates per unit time of the influent.

Keywords: Intermittently aerated membrane bioreactor; Membrane bioreactor; Nutrient removal; Aeration on/off time; Hydraulic retention time

1. Introduction

Membrane bioreactor (MBR) processes have many advantages such as reducing the process size because they do not require a sedimentation tank and disinfection process. Also, the process operates for long sludge retention times (SRTs) due to the maintenance of whole microbes in the reactor and steady removal of solids regardless of settling ability [1,2]. Intermittently aerated bioreactor (IABR) processes have shown high and stable removal capability of nitrogen and phosphorus in treatments with high loading rates of nutrients (e.g. livestock and night soil) [3,4].

*Corresponding author.

Presented at IDW 2014 — The 7th International Desalination Workshop, November 5–8, 2014, Jeju, Korea

An intermittently aerated membrane bioreactor (IAMBR) is a more advanced process than MBR and IABR in the removal of both organic matter and nutrients [5]. It has been reported that IAMBR successfully achieved nitrification and denitrification without installing an additional tank and reduced surplus biological sludge production due to a shorter aeration time compared to that of MBR [6,7]. Zhang et al. [8] reported that intermittently aerated sequencing batch reactors (IASBRs) have been found to efficiently remove nitrogen through partial nitrification followed by denitrification (PND). Hence, the intermittent aeration process has potential for greater removal, if operation factors are well optimized.

Most studies about IAMBR have been independently accomplished with MBR [9,10], IABR [11], or membrane fouling [12]. Nah et al. [13] researched the nitrogen removal of IAMBR, only for long hydraulic retention times (HRTs) of above 10 h, even though the removal efficiency increases with shorter HRTs. Lim [14] researched nitrification through removal capacity and micro-organism structure analysis according to aeration on/off times in IAMBR. However, the result mainly showed microbial structure and treatment performance with a constant anoxic/oxic time of 60/90 min and the HRT of 8.4 h without considering various conditions of IABR. Pan et al. [15] reported that IASBRs could greatly removenitrogen using slaughterhouse wastewater than sequencing batch reactor (SBR). Guo et al. [16] reported that an airlift intermittent circulation membrane bioreactor enhanced the removal of COD, T-N, and PO_4^{3-}-P. These researches proved that intermittent aeration could improve the removal capability of nitrogen and phosphorus; however, the removal efficiency of IAMBR has not been reported.

Therefore, the current paper attempts to find proper operating conditions of IAMBR by observing various permeate concentrations including nitrogen and phosphorus under different aeration on/off times and HRTs.

2. Experimental protocols

Three reactors (Fig. 1) were simultaneously operated with an effective volume of 6 L (reactor's volume of 10 L) and a submerged hollow-fiber membrane [16]. Synthetic wastewater flowed in at the aeration off time and the permeate flowed out at the aeration on time. Operations of the inflow/outflow line and blower were automatically controlled by a timer and mixed liquid was removed from the reactor once a day for adjusting SRT. A pressure gage was installed onto the permeate line to measure transmembrane pressure. Stirring speed of mixing the biomass and substrate was 60 rpm.

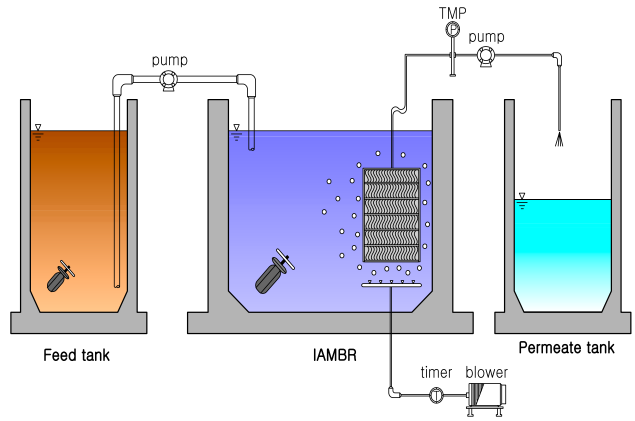

Fig. 1. Schematic diagram of an IAMBR.

Feedwater for IAMBR was based on the results of water quality of the influent for an aeration tank in the domestic wastewater treatment facility [15]. Feedwater was composed of glucose ($C_6H_{12}O_6$) for organic matter, ammonium sulfate ($(NH_4)_2SO_4$) for nitrogen, potassium phosphate (KH_2PO_4) for phosphorus, sodium bicarbonate ($(NH_4)_2SO_4$) for alkalinity, and magnesium sulfate ($MgSO_4{\cdot}7H_2O$), iron chloride ($FeCl_3{\cdot}6H_2O$), calcium chloride ($CaCl_2{\cdot}2H_2O$), and manganese sulfate ($MnSO_4{\cdot}H_2O$) for inorganic matter.

This system used a microfiltration membrane with a pore size of 0.1 μm, surface area of 0.01 m^2, inner diameter of 0.27 mm, and outer diameter of 0.41 mm. The material of the microfiltration membrane was hydrophilic polyethylene hollow fiber [17]. The detailed influent concentrations and experimental conditions in two experimental steps are shown in Table 1.

Samples were collected after MLSS concentrations were constantly maintained. COD was determined by dichromate reflux method, T-N, NH_4^+-N, NO_3^--N, T-P, and PO_4^{3-}-P were measured by DR-4000 spectrometer, and suspended solid (SS) was determined gravimetrically.

3. Results and discussion

3.1. DO profile in a cycle

As shown in Fig. 2, investigating the DO variation in aeration 60 min-on and 60 min-off, DO concentration increased to 3.8 mg/L within 20 min after aeration started and maintained at approximately 4 mg/L up to the end of aeration on time. Also, DO concentration dropped to 0.05 mg/L within 10 min after aeration

Table 1
Concentration of influent and experimental conditions of reactor

	Experiment 1		Experiment 2	
	Run 1	Run 2		
Aeration on/off (min/min)	30/30	60/60	60/60	
HRT (h)	9	6	9	12
OLR (g-COD/d)	3.2	4.8	3.2	2.4
NLR (g-TN/d)	0.72	1.08	0.72	0.54
PLR (g-TP/d)	0.0495	0.132	0.495	0.066
SRT (d)	30			
COD (mg/L)	190–210(200)			
NH_4^+-N (mg/L)	35–45(40)			
NO_3^--N (mg/L)	<4.0			
PO_4^{3-}-P (mg/L)	5–6(5.5)			
C/N ratio (COD/T-N)	4.5			
Flux (L/m^2 h)		20	15	10
pH	7 ± 0.5			
Temperature (℃)	23 ± 2			
DO (mg/L)				
Aeration on	5–6			
Aeration off	<0.05			

stopped and was maintained at approximately 0.01 mg/L. This result showed that DO concentration was appropriate for nitrification and denitrification.

3.2. Effects of aeration on/off time

This paper compared the results between Run 1 (60 min-on/60 min-off) and Run 2 (30 min-on/30 min-off). Aeration on and off times were fixed based on the previous study [18] which presents that the same time interval of aeration on and off times (e.g. 30 min-on/30 min-off and 60 min-on/60 min-off) could be achieved by the improved removal of nutrients in intermittently aerated biological treatment.

MLSS concentrations of Run 1 and Run 2 were fixed around 2,600–3,400 mg/L and 2,200–2,600 mg/L, respectively, at 18 d after the start-up. MLVSS concentrations were around 2,100–2,500 mg/L and 1,600–2,000 mg/L at Run 1 and Run 2, respectively. Accordingly, the F/M ratio of 0.18 (g COD/g MLVSS d)

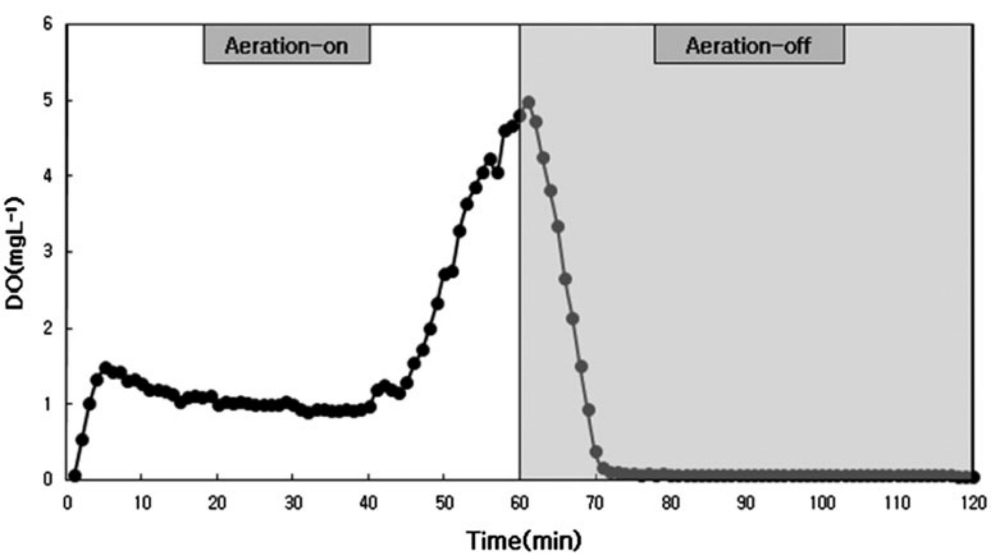

Fig. 2. DO profile in a cycle.

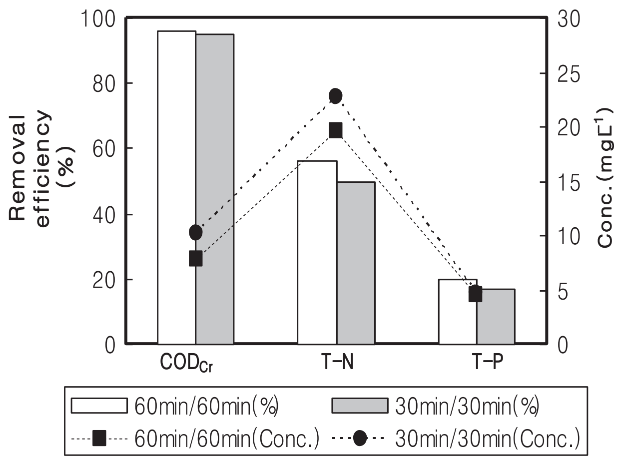

Fig. 3. Permeate concentrations and removal efficiencies of COD, T-N, and T-P. *% is efficiency and conc. is concentration, and so forth.

at Run 1 was lower than that of 0.22 (g COD/g MLVSS d) at Run 2, in spite of the same COD loading rate of the influent. Fig. 3 shows the permeate concentrations and removal efficiencies of Runs 1 and 2. The removal of Run 1 was greater than that of Run 2. T-N and T-P concentrations (average removal efficiency) of permeate were 17.1–22.2 mg/L (56.4%) and 3.31–5.33 mg/L (19.8%) in Run 1, respectively, and 20.3–24.9 mg/L (49.6%) and 3.66–5.44 mg/L (17.1%) in Run 2, respectively. The reason for these results is that the lower F/M ratio was maintained at higher MLSS concentrations in the reactor, and the anoxic condition (<0.1 mg DO/L) of Run 1 carried on well at aeration off time, 50 min for Run 1 and 20 min for Run 2 during the anaerobic state. Also, COD concentrations of the permeate showed stable removal efficiencies under the two conditions, 96.1% for Run 1 and 94.9% for Run 2.

Fig. 4 shows the variation of NH_4^+-N and NO_3^--N in a cycle (Fig. 3(a) and (b)) and the removed concentration of nitrogen compounds every 10 min in a cycle (Fig. 3(c) and (d)) for Runs 1 and 2. NH_4^+-N concentrations decreased by nitrification during the aerobic state and increased by the supply of influent in the anoxic state. For Run 1, nitrification was completed at approximately 50 min after aeration was started, then NO_3^--N continued to increase up to 60 min. However, NO_3^--N was suddenly removed by denitrification up to 100 min, and it showed little removal of NO_3^--N from 100 min up to the end of the anoxic state. For Run 2, there was a lower nitrification rate than that in Run 1 during the aerobic state, due to the feeding time of 30 min, and nitrate-nitrogen was less removed than in the Run 1 anoxic state. These results showed that the reaction times for both nitrification and denitrification were insufficient because the residue of DO affected the next condition.

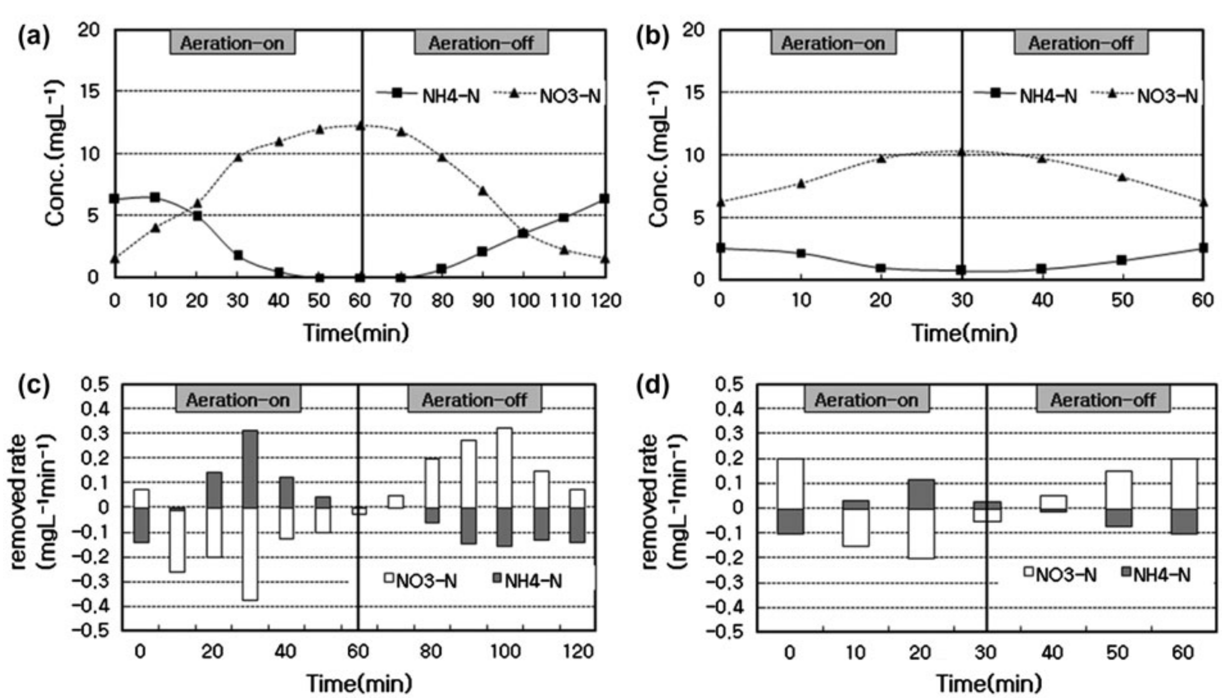

Fig. 4. Track study and removal rate of nitrogen compounds in a cycle: (a) and (c) for 60 min-on/60 min-off, (b) and (d) for 30 min-on/30 min-off.

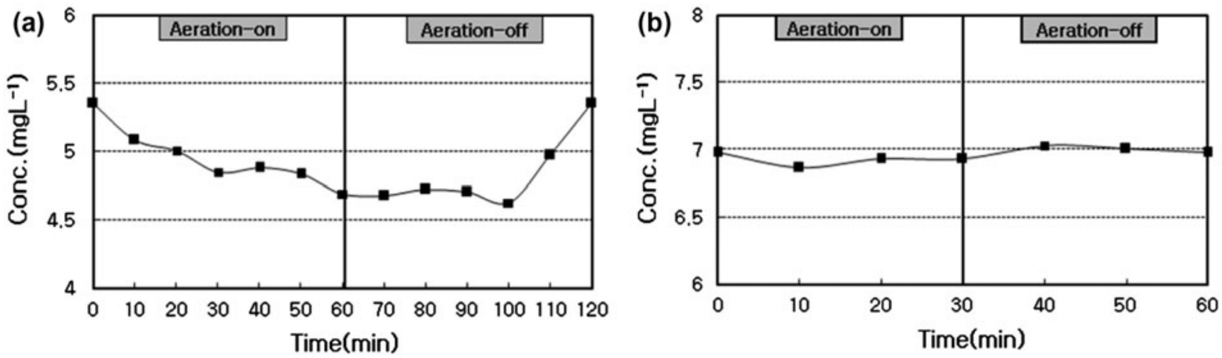

Fig. 5. Track study of ortho-P concentration in a cycle: (a) 60 min-on/60 min-off and (b) 30 min-on/30 min-off.

In conclusion, nitrogen removal for Run 1 was higher than that for Run 2 and denitrification rates showed significant differences between the two conditions.

As shown in Fig. 5, phosphorus release and uptake were not properly achieved during the anoxic and aerobic states. However, the PO_4^{3-}-P concentration at Run 1 (Fig. 5(a)) is lower than that at Run 2 (Fig. 5(b)), due to the sufficient reaction time and the lower NO_3^--N concentration despite a long SRT for Run 1. PO_4^{3-}-P removal rate was low between 100 and 120 min for Run 1, but for Run 2 it remained constant during the cycle. The reason that the PO_4^{3-}-P concentration in the reactor was higher than influent condition for Run 2 was ortho-P accumulation during the operation.

The nitrogen mass balance was estimated to prove removal pathways and quantities with respect to aeration on and off times from the reactor. Nitrogen loading was 0.72 g/d. The permeate accounted for 38%, sludge wasting for 9%, and denitrification for 53% in nitrogen removal for Run 1. For Run 2, the permeate accounted for 43%, sludge wasting for 7%, and denitrification for 47% at the same loading. The results indicated that Run 1 presented a better condition for denitrification. According to the results, sufficient retention time for the reaction in Run 1 is a conceivable driving force of stable denitrification and P-release.

3.3. *Effects of hydraulic retention time*

HRTs of 6, 9, and 12 h were investigated to estimate the daily treatment volume and stability according to the high loading rate of influent. HRT was fixed at the longer or shorter time than 9 h, which was an ordinary operational condition of real plant.

MLSS at HRTs of 6, 9, and 12 h decreased to 3,500–3,900 mg/L, 2,800–3,200 mg/L, and 2,100–2,400 mg/L, respectively. F/M ratios were 0.31 (g COD/g MLVSS d) for the HRT of 6 h, 0.23 (g COD/g MLVSS d) for the HRT of 9 h, and 0.24 (g COD/g MLVSS d) for the HRT of 12 h, and COD loading rates per day were 4.8, 3.2, and 2.4 g/d for the HRT of 6, 9, and 12 h, respectively.

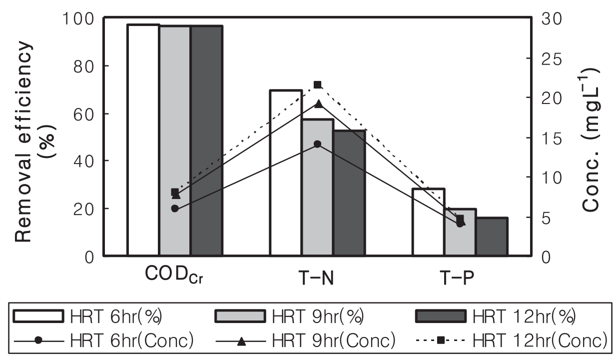

Fig. 6. Removal efficiency and permeate concentrations of COD, T-N, and T-P.

Removal efficiencies and permeate concentrations of pollutants are shown in Fig. 6 for the three HRTs. Removal efficiency of COD was above 96% and the permeate concentration was below 8 mg/L. Hence, the removal of organic matters was high under all conditions. However, removal efficiencies of T-N and T-P were the highest at the HRT of 6 h, which indicated that removal efficiencies increased as HRT decreased. Also, even though the loading rates of T-N and T-P in the influent were the highest, the permeate concentrations of nutrients were the lowest at the HRT of 6 h. These results showed a trend contrary to the general outcomes of the biological nutrient removal (BNR) process because the higher loading rate of the influent organic matters at the anoxic state enhanced the nitrogen removal capability and the entire phosphorus assimilation. In addition, phosphorus removal was

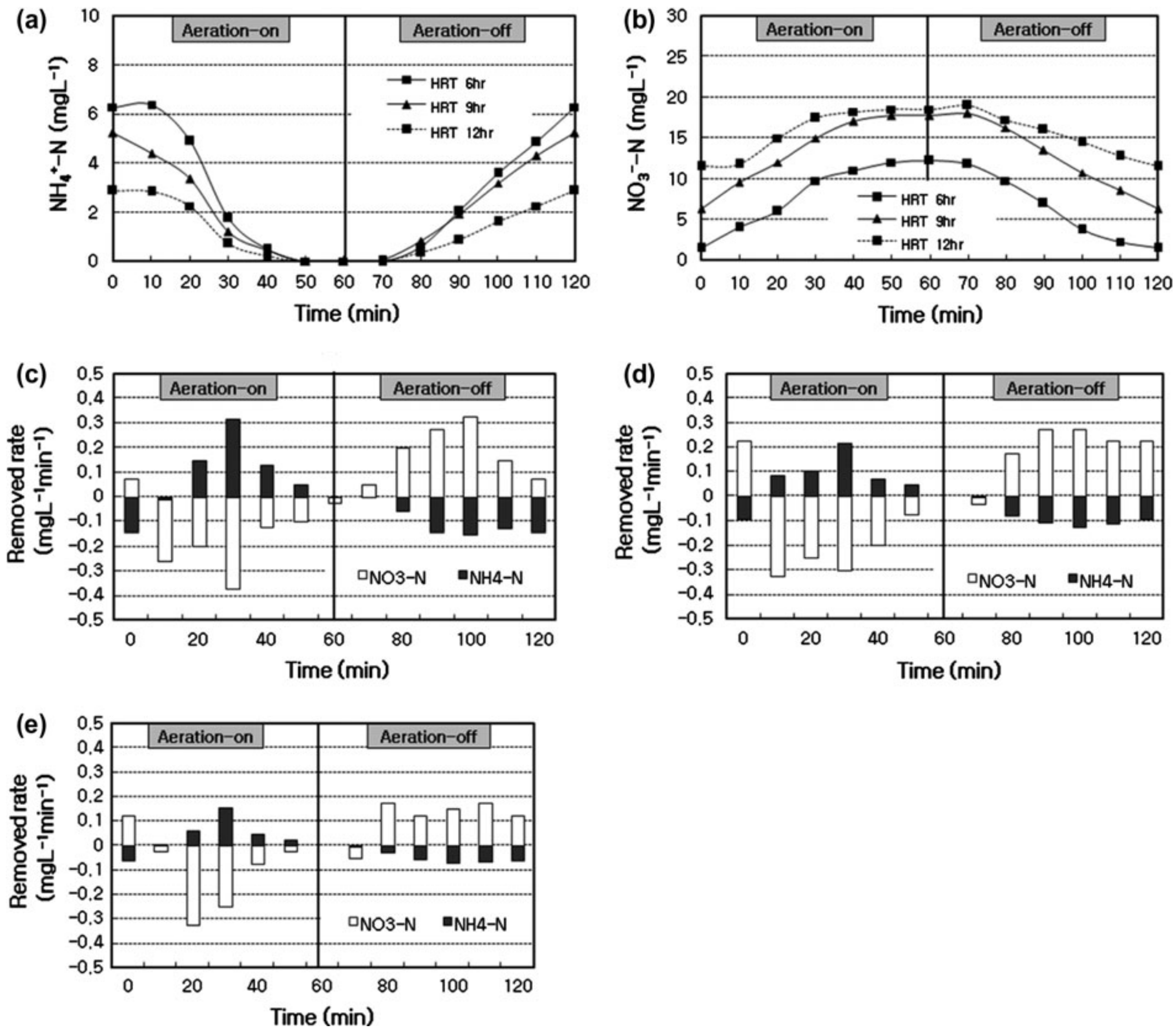

Fig. 7. Track study and removal rate of ammonium and nitrate-nitrogen in a cycle: (a) NH_4^+-N, (b) NO_3^--N, (c) HRT 6 h, (d) HRT 9 h, and (e) HRT 12 h.

lower than nitrogen removal because organic matter in feedwater was preferentially exhausted to convert nitrate-nitrogen into N_2 gas. Thus, IAMBR appears to be able to compact the existing process compared to other MBR or BNR for treatment of the same wastewater volume because it can be operated at low HRTs.

Fig. 7 shows the results of NH_4^+-N and NO_3^--N variation (Fig. 7(a) and (b)) and removed concentration rates in a cycle (Fig. 7c–e). NH_4^+-N concentrations at the beginning of the aerobic state for the HRT of 6 h were the highest because of the higher nitrogen loading rate. However, nitrification was completed at 50 min as under other conditions, indicating that nitrification occurred successfully even if the HRT was only 6 h. For NO_3^--N variation, denitrification was not

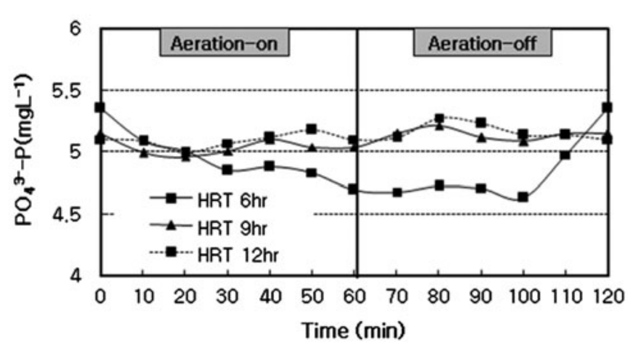

Fig. 8. Track study of ortho-P in a cycle.

completely achieved during the anoxic states under all conditions. However, NO_3^--N concentrations at 120 min of the anoxic state were 0.9–2.1 mg/L, 5.85–6.64 mg/L, and 9.65–13.76 mg/L for HRTs of 6, 9, and 12 h, respectively, showing the lowest nitrate concentrations and the almost complete denitrification at the HRT of 6 h due to the highest COD loading rate despite the high conversion of ammonium nitrogen to NO_3^--N.

Fig. 8 shows the variation of PO_4^{3-}-P concentrations in a cycle. P uptake and release at aerobic and anoxic states were not almost achieved for HRTs of 9 and 12 h. However, much phosphorus was removed at the HRT of 6 h, showing the low concentration in a reactor, even though the P loading rate was the highest because the high COD loading rate led to the increase of assimilation for phosphorus removal. Also, a rise in the P concentration between 100 and 120 min mainly occurred at the HRT of 6 h as the NO_3^--N concentration dropped below 5 mg/L (approximately 2 mg/L) and NO_3^--N did not disturb P-release. However, for HRTs of 9 and 12 h, little variation of the P concentration occurred because of the relatively high NO_3^--N concentration above 5 mg/L, and consequently, NO_3^--N disturbed P release and uptake.

Nitrogen loading for the HRT of 6 h was 1.08 g/d. This was much greater than 0.72 g/d for HRT of 9 h and 0.54 g/d for the HRT of 12 h. However, removed nitrogen from the reactor was 0.299 g/d (27.7%) in the permeate, 0.054 g/d (5.0%) in wasted sludge, and 0.680 g/d (63.0%) in denitrification. For the HRT of 9 h, removed nitrogen was 0.271 g/d (37.7%) in the permeate, 0.048 g/d (6.6%) in sludge waste and 0.382 g/d (53.0%) in denitrification. For the HRT of 12 h, removed nitrogen was 0.228 g/d (42.3%) in permeate, 0.035 g/d (6.5%) in sludge waste, and 0.261 g/d (48.4%) in denitrification. The operation of IAMBR at the HRT of 6 h showed the best performance for T-N and T-P removal in spite of the highest T-N and T-P loading rates. Overall, the results in this study indicated that high COD loading and MLSS led to effective nitrogen and phosphorus removal even at high loadings of influent according to the short HRT.

4. Conclusions

The overall conclusions from the results presented in this study can be summarized as:

On two conditions of aeration on and off times, Run 1 (60 min-on and 60 min-off) was a better condition than Run 2 (30 min-on and 30 min-off) for stable removal of nutrients because it operated in a lower F/M ratio due to higher MLSS concentration in the reactor. In addition, nitrification and denitrification rates for Run 1 were higher, implying that the aerobic and anoxic times were sufficient according to the DO profile as well as low F/M ratio. Also, PO_4^{3-}-P concentrations in a reactor at Run 1 were lower in the reactor due to the same reason with nitrogen removal.

From the results for HRTs of 6, 9, and 12 h, even though the loading rates of T-N and T-P were the highest at the HRT of 6 h, the permeate concentrations of nutrients were the lowest. Nitrification in a track study successfully occurred in all HRTs despite the high initial loading of ammonium nitrogen at the HRT of 6 h. In the terms of denitrification, the HRT of 6 h also showed the almost complete denitrification compared to other conditions. Moreover, much phosphorus was removed at the HRT of 6 h, showing the lower concentration in a reactor, even though the P loading rate was the highest. These results showed a trend contrary to the general results that removal efficiency is better as HRT is longer. It is because the higher loading rate of organic matters at the anoxic state increased nutrient removal. Also, P-release was most successfully achieved since 100 min at the HRT of 6 h among the three conditions because NO_3^--N concentration in a reactor was low enough (approximately 2 mg/L) not to disturb P-release.

Acknowledgment

This research was supported by a grant (13IFIP-C071144-01) from Plant Research Program funded by the Ministry of Land, Infrastructure, and Transport.

References

[1] W. Ghyoot, S. Vandaele, W. Verstraete, Nitrogen removal from sludge reject water with a membrane-assisted bioreactor, Water Res. 33(1) (1999) 23–32.

[2] C. Choi, M. Kim, K. Lee, H. Park, Oxidation reduction potential automatic control potential of intermittently aerated membrane bioreactor for nitrification and denitrification, Water Sci. Technol. 60(1) (2009) 167–173.

[3] H. Yoo, K. Ahn, H. Lee, K. Lee, Y. Kwak, K. Song, Nitrogen removal from synthetic wastewater by simultaneous nitrification and denitrification (SND) via nitrite in an intermittently-aerated reactor, Water Res. 33(1) (1999) 145–154.

[4] J. Campos, J. Garrido-Fernández, R. Méndez, J. Lema, Nitrification at high ammonia loading rates in an activated sludge unit, Bioresour. Technol. 68 (1999) 141–148.

[5] C. Choi, J. Lee, K. Lee, M. Kim, The effects on operation conditions of sludge retention time and carbon/nitrogen ratio in an intermittently aerated membrane bioreactor (IAMBR), Bioresour. Technol. 99(13) (2008) 5397–5401.

[6] S. Jung, K. Miyanaga, Y. Tanji, H. Unno, Effect of intermittent aeration on the decrease of biological sludge amount, Biochem. Eng. J. 27 (2006) 246–251.

[7] H. Hasar, C. Kinaci, A. Unlu, U. Ipek, Role of intermittent aeration in domestic wastewater treatment by submerged membrane activated sludge system, Desalination 142 (2001) 287–293.
[8] M. Zhang, P.G. Lawlor, J. Li, X. Zhan, Characteristics of nitrous oxide (N_2O) emissions from intermittently aerated sequencing batch reactors treating the separated liquid fraction of anaerobically digested pig manure, Water Air Soil Pollut. 223 (2011) 1973–1981.
[9] K. Yeon, J. Park, C. Lee, S. Kim, Membrane coupled high-performance compact reactor: A new MBR system for advanced wastewater treatment, Water Res. 39 (10) (2005) 1954–1961.
[10] M. Vocks, C. Adam, B. Lesjean, R. Gnirss, M. Kraume, Enhanced post-denitrification without addition of an external carbon source in membrane bioreactors, Water Res. 39(14) (2005) 3360–3368.
[11] A. Klapwijk, H. Brouwer, E. Vrolijk, K. Kujawa, Control of intermittently aerated nitrogen removal plants by detection endpoints of nitrification and denitrification using respirometry only, Water Res. 32(5) (1998) 1700–1703.
[12] D. Anja, V. Martin, I. Vera, L. Boris, K. Matthias, Influence of unsteady membrane bioreactor operation on EPS formation and filtration resistance, Int. Congr. Membr. Membr. Processes, Desalin. 192 (2006) 1–9.
[13] Y. Nah, K. Ahn, I. Yeom, Nitrogen removal from household wastewater treatment using an intermittently aerated membrane bioreactor, Environmental Tech. 21(1) (2000) 107–114.
[14] B. Lim, Microbial community structure in an intermittently aerated submerged membrane bioreactor treating domestic wastewater, Desalination 161(2) (2004) 145–153.
[15] M. Pan, X. Wen, G. Wu, M. Zhang, X. Zhan, Characteristics of nitrous oxide (N_2O) emission from intermittently aerated sequencing batch reactors (IASBRs) treating slaughterhouse wastewater at low temperature, Biochem. Eng. J. 86 (2014) 62–68.
[16] H. Guo, J. Chen, Y. Li, T. Feng, S. Zhang, Nitrogen and phosphorus removal in an airlift intermittent circulation membrane bioreactor, J. Environ. Sci. 25 (2013) S146–S150.
[17] Mitsubishi Rayon Engineering Co. Ltd., Introduction of Membrane. Available from: <http://www.mrc.co.jp/mre/english/sterapore/index.html>.
[18] C. Choi, Biological Nutrients Removal by Using Intermittently Aerated 1-Tank Activated Sludge Process, Master's Thesis, Graduated school of Engineering, Chungbuk National University, Cheongju, Republic of Korea, 1999.