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Development of the anaerobic baffled reactor-membrane bioreactor (ABR-MBR) as a biological nutrient removal system for high-rise building wastewater recycling

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ABSTRACT

A novel anaerobic baffled reactor-membrane bioreactor (ABR-MBR) system has been developed as a compact combined biological treatment system and membrane separation unit for wastewater recycling from high-rise buildings. Here, the anaerobic baffled reactor (ABR) compartment had five baffles and served as anaerobic degradation zone, followed by the aerobic membrane bioreactor (MBR) compartment for further aerobic degradation of organic residues. The total operating hydraulic retention time (HRT) of the ABR-MBR system was 3 h (2 h for ABR compartment and 1 h for aerobic MBR compartment). The wastewater used in the study came from Charoen Wisawakam Building, Faculty of Engineering, Chulalongkorn University, located in Bangkok city, Thailand. The results showed that treated effluent quality was quite good and highly promising for water reuse purposes. The average permeate flux of the membrane was kept at 30 L/m^2-h. The ABR-MBR system could remove more than 90% COD, total nitrogen, and total phosphorus from building wastewater at total operating HRT of only 3 h. Specific phosphorus uptake rate obtained in the aerobic MBR compartment is calculated to be 4.82 mgP/gMLSS h. Moreover, a rapid phosphorus uptake phenomenon in the MBR compartment implies that PAOs biomass seems to respond for biological phosphorus removal by the ABR-MBR system. The research suggests that the ABR-MBR system can be a promising system for water reuse and reclamation for high-rise buildings in the near future.

Keywords: Anaerobic baffled reactor (ABR); Membrane bioreactor (MBR); High-rise building; Wastewater recycling; Biological nutrient removal; ABR-MBR (anaerobic baffle reactor-membrane bioreactor)

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1. Introduction

Wastewater from high-rise buildings such as shopping malls or office buildings play important role in generating large volume of wastewater. These buildings have high rate of water consumption, more than typical houses. The composition of organics and nutrients in wastewater such as COD, nitrogen, and phosphorus can have significant impacts on environment together. Up to now, the development of wastewater treatment to remove nutrient at the recent time has focused on decreasing impacts of nitrogen and phosphorus on the eutrophication problem. Recently, membrane bioreactor (MBR) technology has offered many benefits over the traditional activated sludge process such as space-saving, high quality of treated effluent, less sludge wastage, and high potential for biological nutrient removal [1–4]. The necessity of a pretreatment step for the MBR plant was also previously suggested [5–7]. This research work focuses on the removal of carbon, nitrogen, and phosphorus by the developed anaerobic baffled reactor-membrane bioreactor (ABR-MBR) as a compact decentralized wastewater recycling system. The concept of the ABR-MBR system is the incorporation of anaerobic baffled reactor (ABR) compartment to the MBR as a compact treatment unit without the use of sedimentation tank for sludge settling after the ABR system. The proposed ABR-MBR system has many advantages; for example, as a compact system in treating high organic and nutrient loading wastewater and can support shock load condition due to high biomass retention in the MBR unit, the system has a short hydraulic retention time (HRT) and its design and maintenance is easy. Moreover, the series of baffles in the ABR compartment help increased contact time of wastewater with the active biomass accumulated in the system. In MBR, the membrane has a very small pore size that can filtrate bacteria, and also achieve high quality of treated water. Finally, treated effluent can be reused for various purposes as required by buildings. Then, the ABR-MBR system can provide a high potential for treatment and reuse of wastewater from high-rise buildings in a longer period for system operation due to sustainable permeate flux and high MLSS concentration that could be maintained in the system.

2. Materials and methods

The wastewater used in this study came from Charoen Wisawakam Building, Faculty of Engineering, Chulalongkorn University, Thailand. Here, the raw wastewater was mainly from toilet and bathroom. The building has 20 floors and wastewater was pumped from equalization tank at the feed flow rate of 9 L/h to the ABR (5 baffles) with working volume of 18 L, wastewater was passed into the MBR with a fine-bubble aerator using activated sludge aeration. The wastewater characteristic of Charoen Wisawakam Building is illustrated in Table 1. The reactor volume of MBR compartment was approximately 9 L. The seed sludge for the ABR-MBR system was obtained from the return sludge sump of the full-scale activated sludge system at Si Phraya Sewage Treatment Plant, located in Bangkok city, Thailand. The sludge was recirculated from MBR to the ABR at compartment 1 (point A) at 5 L/h rate and SRT was controlled at 20 d with total HRT of 3 h (2 h for ABR and 1 h for MBR). A Polyethylene hollow fiber microfiltration membrane module having surface area of 0.3 m^2 and pore size of 0.4 μm was installed inside the aerobic compartment. The permeate obtained from the membrane was further kept in reclamation storage tank. At present, the system has been operated for more than 3 months (acclimatization phase for 1 month and experimental run for 67 d). Furthermore, the schematic diagram of ABR-MBR system is shown in Fig. 1. The sampling for water quality analysis will be done at points A, B, and C in the ABR compartments 1, 3, and 5, respectively.

Table 1
High-rise building wastewater characteristics used in the study

Wastewater parameter	Range
pH	6.8–7.0
Suspended solid (mg/L)	35–80
COD (mg/L)	197–225
TKN (mgN/L)	22–60
Total phosphorus (mgP/L)	4.5–5.5

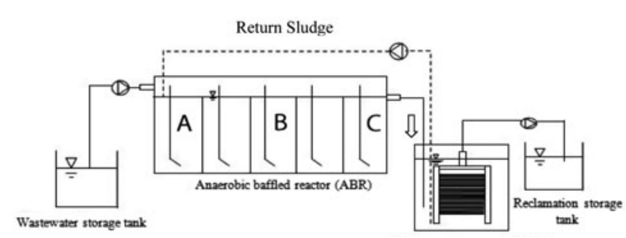

Fig. 1. The schematic diagram of the pilot-scale experimental setup.
Note: A: compartment 1, B: compartment 3, and C: compartment 5.

2.1. Analytical methods

During the whole experimental runs influent and effluent were measured in terms of temperature, pH, COD, suspended solid (SS), total kjeldahl nitrogen (TKN), nitrite nitrogen (NO_2^--N), nitrate nitrogen (NO_3^--N), and total phosphorus (TP). All these parameters were analyzed in accordance with the standard method [8].

3. Results and discussion

3.1. Dissolved oxygen profile in the ABR-MBR system

The variation of Dissolved oxygen (DO) concentration inside each compartment of the ABR-MBR system during a long-run operation is shown in Fig. 2. DO inside the aerobic membrane compartment of the ABR-MBR was maintained higher than 2.0 mg/L, resulting in sufficient nitrification potential. Therefore, DO concentration was not a limiting factor to cause any problem on nitrification and organic removal efficiencies by the ABR-MBR system. Also, nitrifying micro-organisms could be highly maintained in the system due to sufficient DO (up to 5 mg/L) and optimum temperature condition (28–30˚C) within the mesophilic temperature range. The sludge recirculation rate from the aerobic MBR compartment to the first compartment of ABR caused rising of DO content to 1 mg/L at point A. However, DO concentration could be reduced to completely zero in compartment 5 (point C) of the ABR that could realize anaerobic condition inside the ABR compartment. This can promote denitrification activity and also phosphorus release phenomena in the anaerobic baffle compartment.

3.2. Performance of COD removal

Variation of influent COD concentration from 197 to 225 mg/L did not affect the performance of the ABR-MBR system in treating organic carbon from wastewater as illustrated in Fig. 3. Since the COD concentrations in the effluent were always lower than 10 mg/L for the whole period of system operation, together with the COD removal efficiencies which were above 95%, it suggested that stable treatment performance of the system could be achieved. These data indicated that the system could provide a consistent high efficiency of COD removal. The high treatment performance of the ABR-MBR system in treating organic pollutants is due to the combination of a membrane separation unit and biochemical activity of the suspended growth biomass in the same unit. The building wastewater had average COD of 211 mg/L. From Table 2, it was found that the average COD removal efficiency was 96.4% and the average COD in the effluent was 7.63 mg/L. Also, the influent characteristics show that the wastewater sometimes contained high amounts of SS which can deteriorate treatment performance of a conventional activated sludge process. Nevertheless, this can be considered to cause less problems for stable treatment performance using the ABR-MBR system.

The important aspect concerning the operation concept regarding the anaerobic baffle compartment

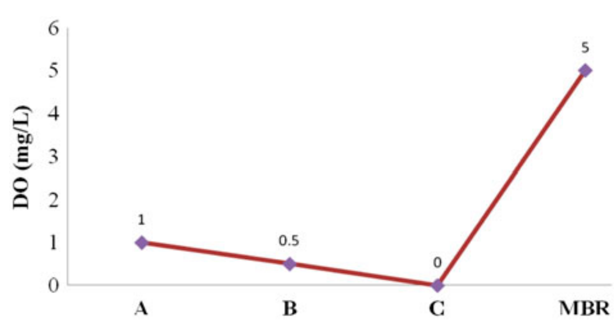

Fig. 2. DO profile in each compartment of the ABR-MBR system.

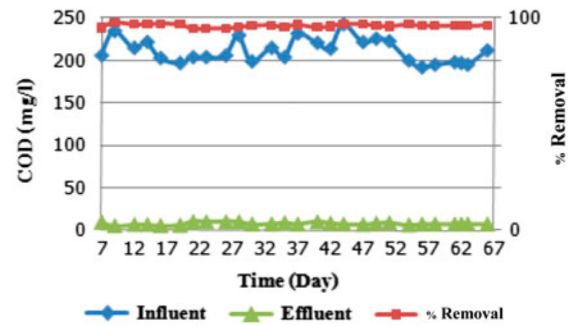

Fig. 3. Performance of COD removal by the ABR-MBR system.

Table 2
Summary of pollutant removal efficiencies of the ABR-MBR system

Parameter	Influent	Effluent	%Removal
SS (mg/L)	72.3 ± 12.7	0.12 ± 0.63	99.1 ± 0.15
COD (mg/L)	211 ± 14	7.63 ± 1.4	96.4 ± 0.69
TKN (mg/L)	56.7 ± 3.56	2.7 ± 0.24	95.2 ± 0.58
NO_2^--N (mg/L)	0.009 ± 0.004	0.054 ± 0.004	–
NO_3^--N (mg/L)	0.25 ± 0.071	0.67 ± 0.023	–
TP (mg/L)	5.26 ± 0.41	0.44 ± 0.003	91.4 ± 0.86

as a pretreatment step is that the anaerobic compartment helps sieve and filter large colloidal particles before entering the aerobic membrane compartment. As a result, large colloidal particles were removed before entering the aerobic membrane compartment. Then, the soluble COD was further removed in the following aerobic compartment by high biomass of aerobic micro-organisms that were retained by the membrane separation unit. Final effluent was proved to have excellent COD concentration that can be further reused for high-rise building application.

3.3. Performance of nitrogen removal

Fig. 4 presents the variation of TKN-N, NO_2^--N, and NO_3^--N concentrations in the ABR-MBR system during the whole experiment. The influent nitrogen mainly was in the form of organic nitrogen and soluble ammonia, and then changed into nitrate nitrogen in the aerobic MBR compartment due to a good performance of nitrification. Also, the pH value of the ABR compartment was 6.9 and of aerobic compartment it was 7.2, which were in the optimum range for ammonia-oxidizing bacteria and also nitrite-oxidizing bacteria. It is shown from Fig. 4 that a significant reduction in TKN-N concentration was obtained by the ABR-MBR system. Nitrogen was removed from the wastewater through denitrification process in the ABR compartment and nitrification process in the aerobic MBR compartment.

This significant reduction in TKN concentration from 50–60 mg/L to approximately 3 mg/L could be mainly attributed to nitrification by the aerobic membrane compartment. The very stable nitrification resulted from sufficient DO, which was rather high, up to 5.0 mg/L as shown in Fig. 2. However, high amounts of nitrate concentration could be reduced significantly by denitrification process in the ABR compartment.

As can be seen in Table 2, average TKN in influent was 56.7 mg/L, the system could remove TKN by 95.2% on average, and the average TKN in effluent was 2.70 mg/L. The concentration of NO_2^--N and NO_3^--N in the influent was 0.009 and 0.25 mg/L, respectively. The results show that NO_2^--N and NO_3^--N were produced by nitrification in aeration tank. The average NO_2^--N and NO_3^--N concentrations in effluent were 0.055 and 0.65 mg/L, respectively. Moreover, the ABR-MBR system can maintain high concentration of nitrifiers; therefore, it could achieve a high performance of nitrification efficiency.

3.4. Performance of phosphorus removal

During the whole operation period for the ABR-MBR system, changes in concentration of TP in the

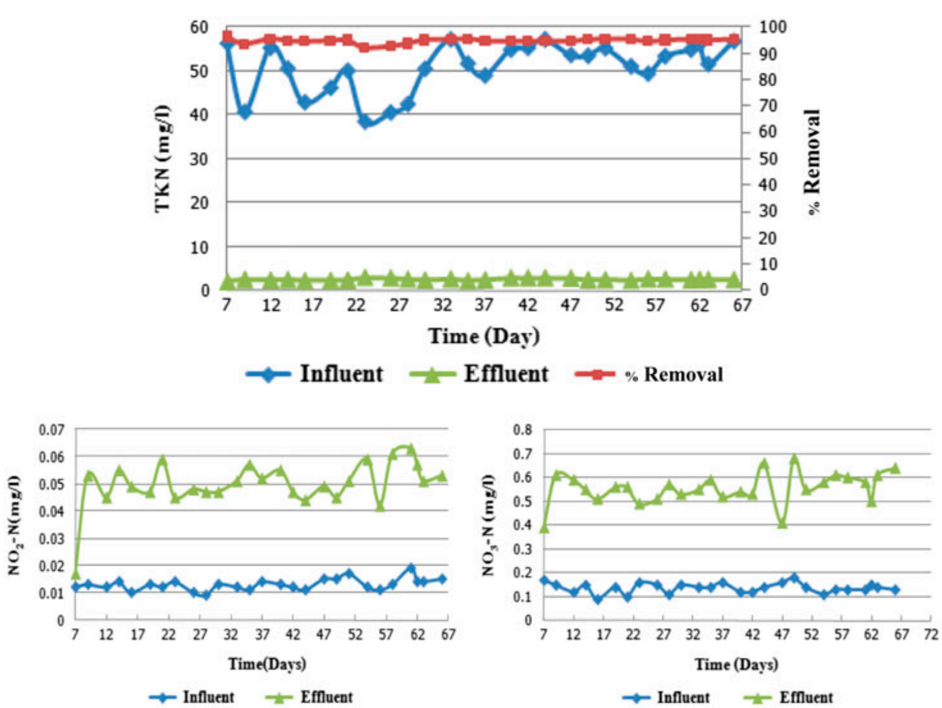

Fig. 4. The variation in TKN-N, NO_2^--N, and NO_3^--N concentrations.

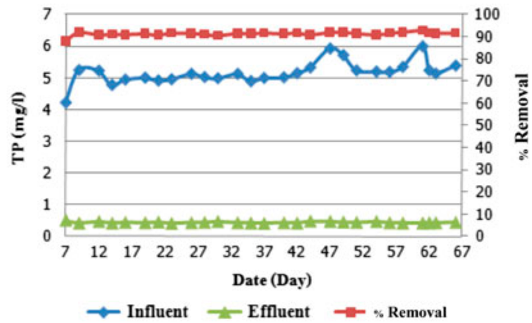

Fig. 5. The variation in phosphorus concentration.

influent, ABR compartments, aerobic compartment, and effluent are shown in Fig. 5. TP concentration in the feed wastewater could be found in the range of 4.5–5.0 mgP/L. Significant amount of phosphorus removal could be achieved with the ABR-MBR system. From Table 2, it was found that the average TP in the influent was 5.26 mg/L; the system could remove TP by 91.4% on average and in the effluent was 0.44 mg/L on average. The main phosphorus removal process is caused by the biological phosphorus removal mechanism inside the ABR-MBR system as shown in Fig. 8(b) which presents the phosphorus release and uptake phenomena of the ABR-MBR system. As the phosphorus release was significantly observed in the ABR compartment, enhanced biological phosphorus removal was dominant. The advantage of the proposed ABR-MBR system is that simultaneous carbon, nitrogen, and phosphorus removal can be highly achieved.

3.5. Profile of pollutant reduction in the ABR-MBR system

3.5.1. Profile of oxygen depletion rate in the ABR compartment

The ABR compartment was operated without air supply, however the remaining DO was found at 1 and 0.5 mg/L in ABR compartments 1 and 3 (points A and B), respectively, due to the recirculation of sludge from the aerobic MBR. Fig. 6 presents the oxygen depletion rate in the ABR compartment. The ABR sampling points were points A, B, and C (Fig. 1), corresponding to the HRTs of 12, 60, and 108 min, respectively. The DO profile suggests that low DO condition (less than 0.5 mg/L) in the ABR compartment could be achieved from compartments 3–5 (points B and C). Low DO condition in the ABR compartment is considered important to promote denitrification and phosphorus release activities for the ABR-MBR system. The oxygen depletion rate obtained in the ABR compartment was 6 $mgO_2/gMLSS\,h$.

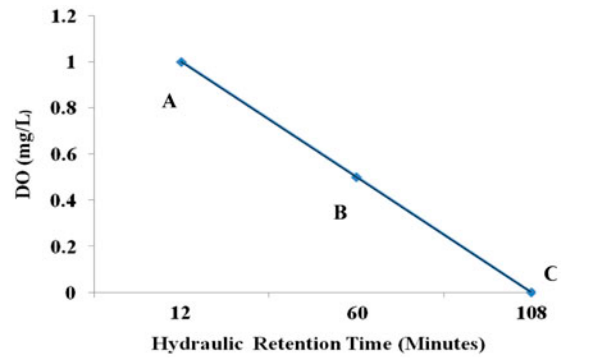

Fig. 6. Oxygen depletion as a function of HRT in the ABR compartment.

3.5.2. Biomass profile in the ABR-MBR system

The MLSS content to represent the biomass in each compartment of the ABR-MBR system was found rather stable for the ABR-MBR system with operating HRTs of 3 h. The MLSS concentrations in ABR compartments 1, 3, and 5 (points A, B, and C) were approximately 4,950, 4,400, and 4,950 mg/L, respectively. While MLSS concentration of the aerobic MBR compartment was approximately 3,000 mg/L at steady state condition. Therefore, biomass in the ABR-MBR system was still in stable performance (Fig. 7).

3.5.3. Profile of COD removal in the ABR-MBR system

When analyzing the profile of COD in the system at steady state condition, Fig. 8(a) shows that the COD value decreased rapidly in the ABR compartments 1–3 since high amount of biodegradable organic carbon was significantly consumed by the accumulated biomass inside the ABR compartment. Moreover, the microbe utilized carbon source from the wastewater for biological nutrient removal. In addition, the pore size of membrane is very small. Bacteria could be kept inside

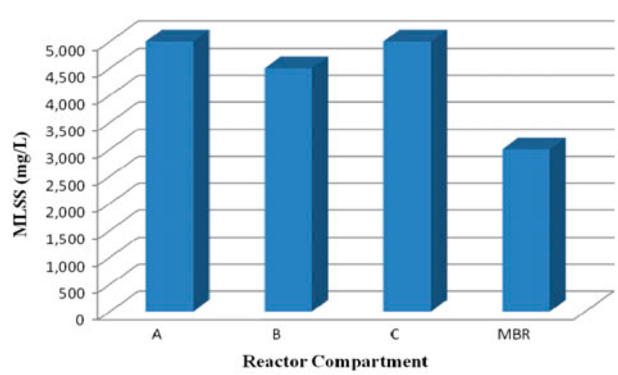

Fig. 7. Biomass profile in the ABR-MBR system.

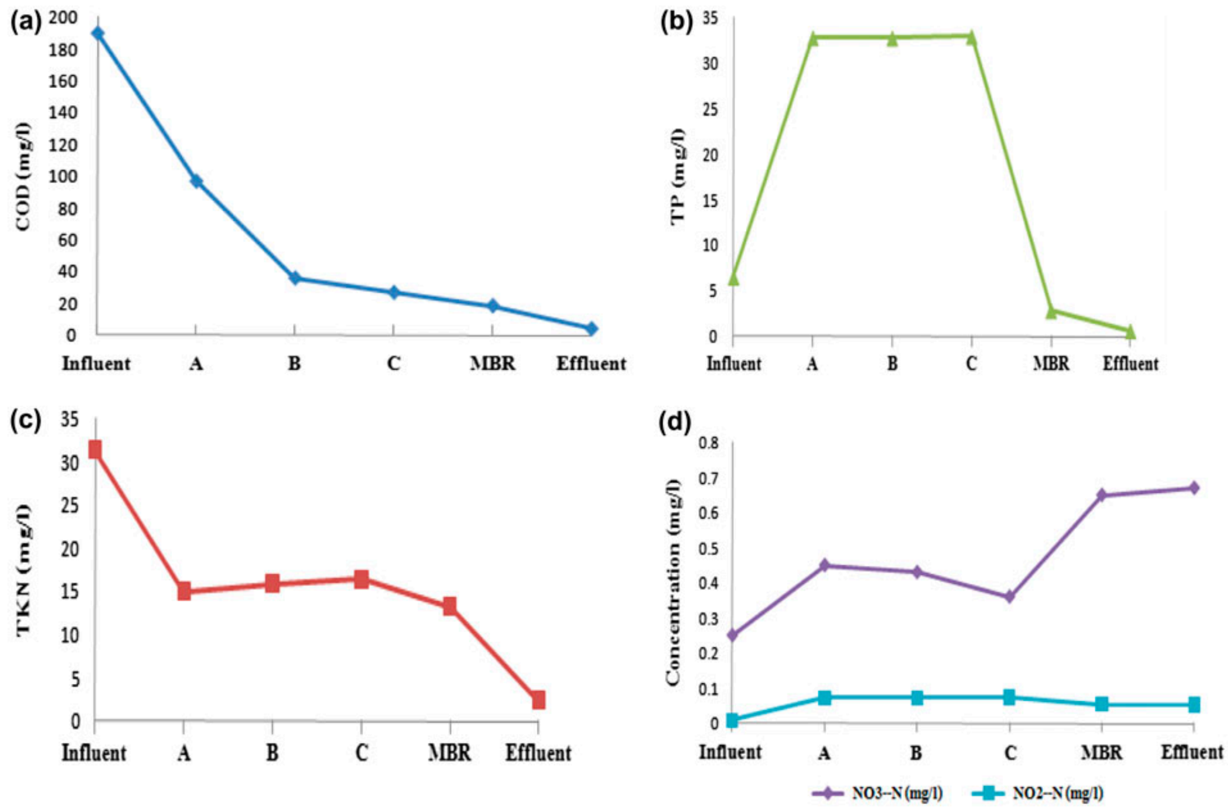

Fig. 8. Profiles of COD (a), TP (b), TKN nitrogen (c), NO_2^--N and NO_3^--N (d) in each compartment of the ABR-MBR system. Note: A: sample from ABR at A, B: sample from ABR at B, and C: sample from ABR at C; see Fig. 1.

the ABR-MBR system. Therefore, high biomass maintained in the system help remove COD in wastewater.

3.5.4. Profile of TP removal in the ABR-MBR system

From Fig. 8(b), it is found that phosphorus concentration was higher in the ABR compartment due to phosphorus release, and then decreased very rapidly in the MBR tank due to phosphorus uptake phenomenon. This implies that PAOs biomass inside the system seems to be very active. The soluble phosphorus was released outside the cell. The decomposition of phosphorus resulted in the formation of PHA in PAOs cells [9]. Phosphorus release in the reactor was higher than 30 mgP/L. The results clearly suggested that the growth and activity of PAOs were apparent in this study. The PAOs biomass could be significantly kept in the ABR-MBR system, meaning that the ABR-MBR system can prevent the wash out of the PAOs biomass from the system. Specific phosphorus uptake rate (SPUR) by the biomass in the aerobic MBR compartment was analyzed as shown in Fig. 9. The obtained SPUR by the MBR was 4.82 mgP/gMLSS h.

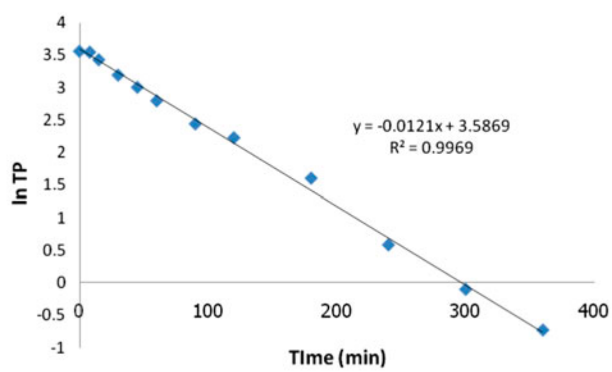

Fig. 9. SPUR by the biomass in the MBR compartment.

3.5.5. Profile of nitrogen removal in the ABR-MBR system

From Fig. 8((c) and (d)), TKN decreased rapidly in compartment A of the ABR and then TKN was finally lower than 3 mgN/L in the permeate from the MBR at steady state condition. For the aerobic MBR tank, nitrification took place significantly due to high nitrogen removal performance. Nevertheless, nitrate

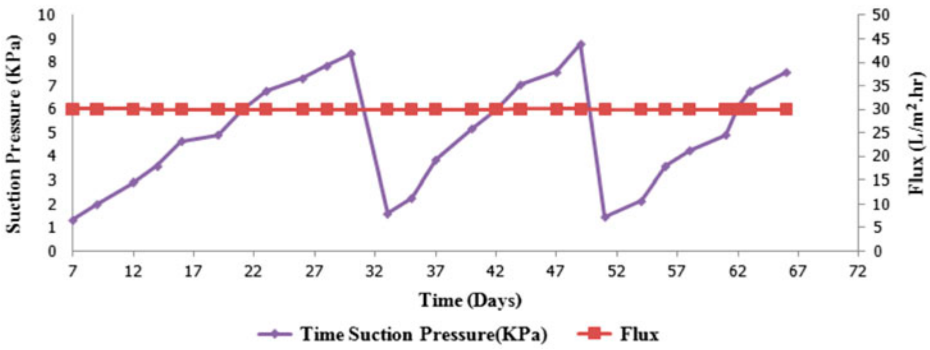

Fig. 10. Transmembrane pressure and membrane permeate flux of the ABR-MBR system.

concentration was found to be very low in the aerobic MBR tank (only 0.7 mgN/L) due to the simultaneous nitrification–denitrification phenomena inside the MBR tank [10]. For nitrification, NO_2^--N was oxidized to NO_3^--N almost completely due to the NO_2^--N concentration which was less than 0.1 mgN/L.

3.6. Performance of membrane filtration system

For the whole experimental runs, the suction pressure was kept less than 10 kPa. The pressure increase in the system could affect the membrane performance, causing membrane fouling and decline in flux. From Fig. 10, it can be observed that the suction pressure increased with operation time as membrane flux was kept at about 30 L/m^2-h throughout the experiment. When the suction pressure reached about 10 kPa (in day 32 and 51 of system operation), membrane washing process by water jet cleaning was carried out to remove membrane foulants from membrane surface and then the permeate flux of membrane could be recovered.

3.7. Potential wastewater reuse application

The potential wastewater reuse application after treatment with the ABR-MBR system was evaluated here by comparing the treated effluent quality with the Japanese Ministry of Land, Infrastructure and Transport's Reuse water quality criteria, 2005 for building application. The wastewater reuse application for toilet flushing and garden watering has been highly concerned here due to large amount of water demand for many high-rise buildings. From Table 3, these data show that the effluent quality from the ABR-MBR system in terms of pH, SS, turbidity, COD, total nitrogen (TN), TP, odor, appearance, and *E. coli* could comply with the reuse water quality criteria that are required for toilet flushing and garden watering. From the overall parameter comparison with the standard, the ABR-MBR system has proved to be a high-performance decentralized wastewater treatment system for high-rise building wastewater recycling purpose.

Table 3
Comparison of effluent quality from the ABR-MBR reactor with Japanese Ministry of Land, Infrastructure and Transport's Reuse water quality criteria, 2005

		Wastewater reuse criteria	
Parameters	Effluent quality from this study	Toilet flushing	Garden watering
pH	7.2–7.5	5.8–8.6	5.8–8.6
SS (mg/L)	0.05	–	–
Turbidity (NTU)	0–0.1	Less than 2	Less than 2
COD (mg/L)	6.2–9.0	–	–
TN (mgN/L)	2.5–3.6	–	–
TP (mgP/L)	0.43–0.45	–	–
Odor	Not unpleasant	Not unpleasant	Not unpleasant
Appearance	Not unpleasant	Not unpleasant	Not unpleasant
E. coli	Not detected	Not detected	Not detected

4. Conclusions

The developed ABR-MBR system could remove organics and nutrients in terms of COD, TN, and TP in wastewater from high-rise building, higher than 90% at total HRT of only 3 h (2 h for ABR and 1 h for MBR). The suction pressure of membrane filtration could be kept less than 10 kPa. The effluent quality from the ABR-MBR could comply with the wastewater reuse standard for toilet flushing and garden watering purposes. Therefore, the ABR-MBR system can be considered as one of promising wastewater treatments and reclamation technologies for large cities with land limitation.

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