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Effect of organic loading on the performance of MBR for advanced treatment and water reuse

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ABSTRACT

The study investigated the effect of organic loading on nutrient and organic matter removal in a lab-scale membrane bioreactor (MBR). The effect of powdered activated carbon (PAC) addition on the performance of MBR was also considered. The results showed that the organic loading changes greatly affected the removal of total phosphorus (TP). At the end of the step increase in chemical oxygen demand (COD) from 300 mg/L to 2400 mg/L, the TP removal was completely removed. The COD and total nitrogen (TN) removals were 90% and 80%, respectively. When the COD was reduced to 1200 mg COD/L and 600 mg COD/L, the TP removal was 10% for MBR without PAC and 19% for MBR with PAC. The addition of PAC had no effect on nutrient and organic matter removal of the MBR. It only reduced membrane fouling; hence extending the operation time for MBR before membrane cleaning. The study demonstrated that MBR could maintain high effluent quality at high organic loading changes. Under low organic loading changes, TP removal deteriorated more than did the COD and TN removals. It was suggested that the dynamics of organic loading also be considered for the MBR process to sustain high effluent quality especially during start-up.

Keywords: MBR; Nitrogen removal; Organic loading; PAC; PAO

1. Introduction

The membrane bioreactor (MBR) technology has now been widely applied for advanced wastewater treatment and reuse as the legislation mandates for a more stringent effluent quality [1]. The MBR process is favourable because of the production of high quality effluent, dependent control of hydraulic retention time (HRT), being operational at high mixed liquor suspended solids (MLSS) concentrations and longer sludge age, and reduced sludge production [2]. Although MBR technology is reputed to providing high effluent quality, further improvements of the process are still necessitated. Also, the requisite for alternative water resources advocates exploiting any possibilities of reusing the effluent from MBR process. Hence, it poses a new challenge to expand the application of MBR process and develop operation strategies to achieve the best possible performance.

The MBR process works almost in the same way as any conventional biological wastewater treatment process except that the membrane separation makes the process more exceptional. However, they are generally governed

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by the same biological processes such as nitrification, denitrification, etc. The process may differ in performance as a result of variability of environmental parameters and wastewater composition. For instance, Wang et al. [3] successfully demonstrated the influence of wastewater composition on nutrients removal and process control in an anaerobic-anoxic-oxic (A^2O) process. They showed that the influent carbon/nitrogen (C/N) and carbon/phosphorous (C/P) ratios had significant effect on total nitrogen (TN) and total phosphorous (TP) removal efficiencies. Under low organic loading fluctuations, activated sludge process could be greatly affected especially the phosphorus accumulating organisms (PAOs). PAOs can take up large amounts of phosphorous and intracellularly store them in long chains as polyphosphates.

The PAOs exhibited poor adaptability to low organic loading in an enhanced biological phosphorous removal (EBPR) process [4]; hence, affecting the effluent quality. It could be that varying the influent organics may eventually alter the microbial community and change the state of biological processes. This study investigated the effect of varying influent chemical oxygen demand (COD) on organic matter and nutrient removal performance of a lab-scale MBR. The effect of powdered activated carbon (PAC) addition to the MBR performance during the organic loading fluctuations was also considered.

2. Materials and methods

2.1. The MBR system

Two lab-scale MBRs were operated under the same conditions except that MBR-2 was added with 1 g/L PAC. Each MBR consisted of four bioreactors: two anoxic, one anaerobic and one oxic. The influent was fed to the first anoxic bioreactor and withdrawn from the first and second anoxic bioreactors through a peristaltic pump (Fig. 1). The returned sludge flow rate was 100% of the influent flow rate.

2.2. Membrane and synthetic wastewater

Two 0.08 μm PVDF flat-sheet membranes with an effective filtration area of 0.024 m^2 were submerged in the oxic bioreactor of each MBR. The membrane specifications are listed in Table 1. At the transmembrane pressure (TMP) of 40 kPa, membrane fouling was observed. When this TMP value was reached, each membrane was subjected to chemical cleaning by immersing the membrane modules in 2000 mg/L NaOCl solution for 2 h followed by rinsing with deionized water.

The composition of the synthetic wastewater fed into the system per liter was as follows: 300 mg glucose, 300 mg $NaHCO_3$, 450 mg NH_4HCO_3, 25.369 mg KH_2PO_4, 50 mg $MgSO_4·7H_2O$, 0.0288 mg $MnSO_4·H_2O$, 0.035 mg $ZnSO_4·7H_2O$, 10 mg $CaCl_2·2H_2O$, 0.3175 mg $FeCl_2·4H_2O$ and 50 mg yeast extract. Both MBRs were intended to remove COD, TN and TP. The operating conditions were summarized in Table 2.

2.3. Effects of organic loading changes on nutrient and organic matter removals

Each MBR was operated in 100 days with varying influent COD: 300 mg/L, 600 mg/L, 1200 mg/L and 2400 mg/L. Afterwards, the influent COD was reduced to 1200 mg/L and 600 mg/L. By the end of influent feed-

Table 1
Membrane specifications

Shape	Flat sheet type
Pore size, μm	0.08
Material	PVDF
Filtration flux, $m^3/m^2·d$	0.2–1.5
pH	5–10
Temperature, °C	5–40
Membrane area, m^2	0.024
Dimension (l × w × t), mm	110 × 110 × 7

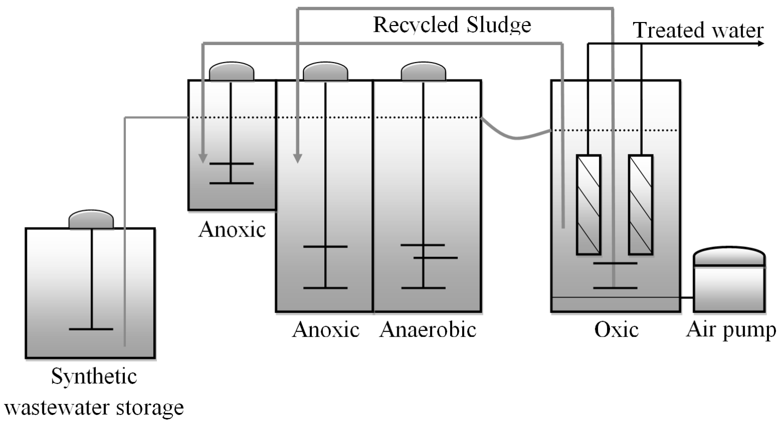


Fig. 1. Configuration of the MBR system.

Table 2
Operating conditions of MBR system

Parameters	Set values
Aeration intensity, L/min	3
Hydraulic retention time, h	7
Sludge retention time, d	50
Total filtration volume, L/d	17
Permeate flux, m/d	0.3
Returned sludge (% of influent flow rate)	
Anoxic-1	100
Anoxic-2	100
Intermittent suction (or filtration)	
Time: on/off, min	9/1
PAC concentration in MBR-2, g/L	1

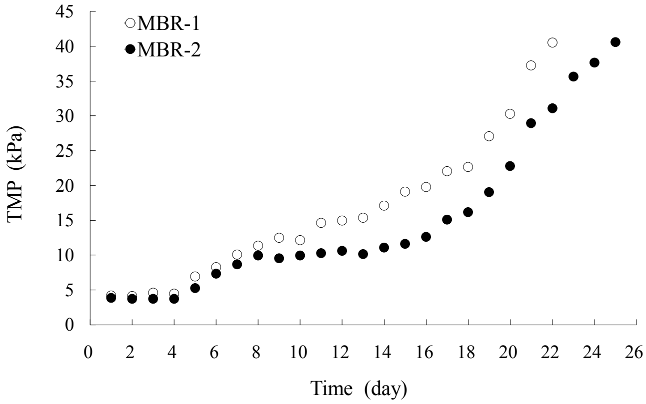


Fig. 2. The effect of PAC addition in membrane fouling.

ing at 600 mg COD/L, the TMP was already unstable and started to exceed 40 kPa. The influent COD was not further reduced to 300 mg/L. The effect of organic loading n the MBR performance was evaluated by means of percentage removals of COD, TN and TP. These were measured using Hach COD, TN and TP test kits following the manufacturer's protocol. Samplings were daily conducted and analyzed in duplicate. Nitrite (NO_2^-), nitrate (NO_3^-) and phosphate (PO_4^{3-}) were analyzed by ion chromatography (Alltech) with Allsep Anion 7μ column (Grace Davison Discovery Sciences) using the manufacturer's test conditions. The chromatogram was generated by EZ Chrome software. Ammonia (NH3), mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) were measured based on the Standard Methods.

3. Results and discussion

3.1. *Effect of PAC in membrane fouling*

The effect of PAC addition on MBR at subcritical flux operation was determined. At 40 kPa, membrane fouling was observed in both MBRs. Membrane fouling occurred at MBR-1 on 21st day and at MBR-2 on 25th day of operation (Fig. 2). The results showed that PAC addition reduced the membrane fouling and favoured longer operation time at subcritical flux. The effects of dosing with PAC are attributed to the decrease in the level of organic compounds [1]. The soluble organics are adsorbed to the PAC and degraded by the microorganisms that constitute the biological activated carbon (BAC). BAC has been shown to effectively reduce exopolymeric substances (EPS) and soluble microbial products (SMP) which are both implicated on membrane fouling.

3.2. *COD removal during organic loading changes*

The effect of organic loading changes on the performance of MBR was determined. Each MBR was subjected to various COD inputs with glucose. At 300 mg COD/L, the average COD removal of MBR-1 and MBR-2 were 97% and 98% respectively (Table 3). The COD removal rates were unstable during the first 46 days. This period could represent the acclimatization stage when the microorganisms still adapt to the environment. This could be the reason for the observed dynamics in COD removal rates.

The average COD removal rate increased when the COD concentration was gradually increased to 600 mg/L, 1200 mg/L and 2400 mg/L. The gradual increase in average COD removal rate was accompanied by increase in MLSS and MLVSS. This happened because the high inputs of COD provided sufficient carbon source for the microorganisms to produce more active biomass. The

Table 3
COD removal rate of MBR during organic loading changes

Time (d)		1–46	47–60	61–67	68–74	75–81	82–100
Influent COD (mg/L)		300	600	1200	2400	1200	600
Effluent	MBR-1	8	7	5	9	5	6
	MBR-2	8	6	4	11	7	5
Removal (%)	MBR-1	97	99	100	100	100	99
	MBR-2	98	99	100	100	99	99

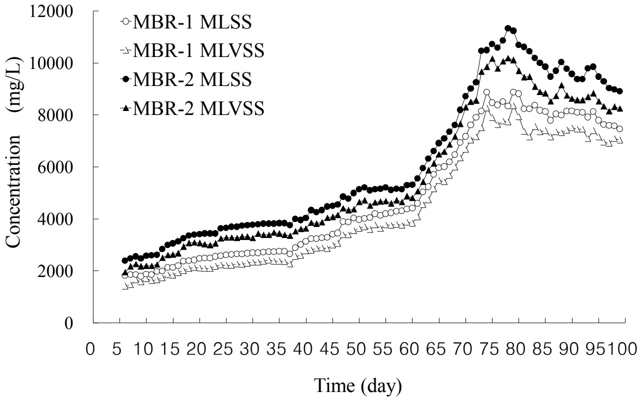


Fig. 3. MLSS and MLVSS profile of MBR during organic loading changes.

active biomass contributes to the efficiency of organic matter removal in the MBR. The MLSS and MLVSS concentrations were higher in MBR-2 than in MBR-1 (Fig. 3) but there was no significant difference between their average COD removals.

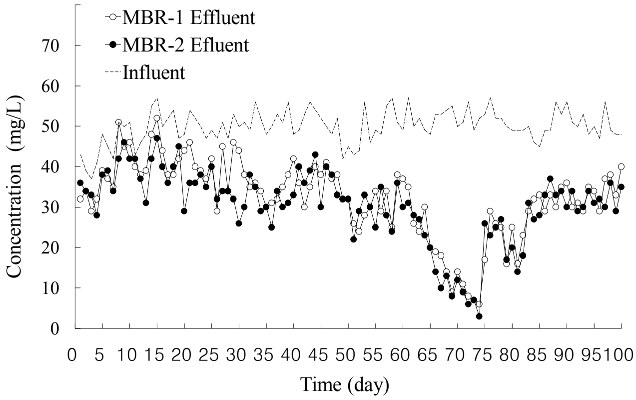
When the COD loading was reduced from 2400 mg/L to 1200 mg/L on 75th day, the COD removal of both MBRs declined along with their MLSS and MLVSS concentrations. PAC addition showed no significant effect on COD removal.

3.3. *Effect of organic loading changes on nutrient removal*

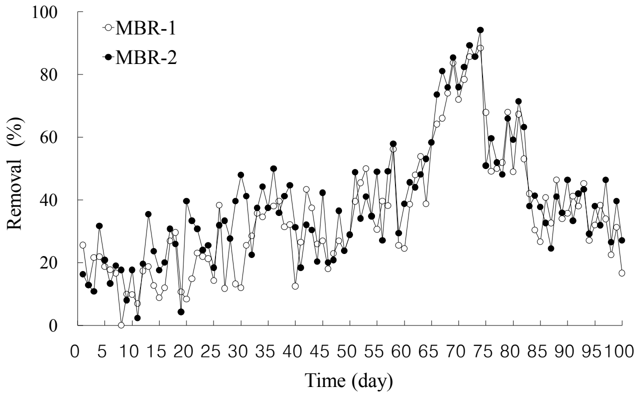
The total nitrogen did not significantly differ between MBR-1 and MBR-2 based on the one-way analysis of variance (data not shown). At the end of high organic loading (2400 mg COD/L), the average TN removal increased (Fig. 4).

The stepwise decrease in organic loading also resulted to stepwise reduction of TN in both MBRs. This effect on TN removal was similar to the effect on COD removal during the stepwise decrease of COD inputs. In this study, variation in the organic loading could represent an environmental disturbance.

Microbial community might be resistant, resilient or redundant to a given disturbance. In response to changing environmental conditions, microorganisms could change but the biological processes may not be altered [5]. For example, organic matter and nutrient removal of the MBR would be unaffected by organic loading changes if the microbial communities were resistant to it. It would also remain unaffected despite the microbial communities are sensitive to organic loading changes if the microbial communities are functionally redundant or can perform the process (organic and nutrient removal) at rates similar to that of the original communities. Lastly, the organic matter and nutrient removal might change but quickly return to its predisturbed condition. This could be true to



(a) TN concentration



(b) TN removal

Fig. 4. Total nitrogen removal in MBR during organic loading fluctuations.

the observations made on MBR-1 and MBR-2. The COD and TN removal of both MBR changed in the same way as the organic loading. The addition of PAC did not show any significant effect on TN removal.

During low organic loading, NH_3^+ was consumed in the oxic bioreactor but still remained in the anaerobic and anoxic bioreactors. This indicated that an effective nitrification occurred. NO_2^- represented only a small fraction of the TN in the anaerobic and anoxic bioreactors and almost absent in the oxic bioreactor. On the other hand, NO_3^- successively accumulated on 76th day and the effluent quality was deteriorated (Fig. 5). The removal of ammonia in the oxic bioreactor with NO_3^- accumulation in the anoxic and anaerobic bioreactors showed that extensive nitrification occurred and denitrification failed. This could explain the reduction in TN removal of the MBR during low organic loading changes.

Fig. 6 shows that the TN removal increased with increasing input of COD. C/N ratio determines the concentration of NO_x-N [6] but the COD concentration has

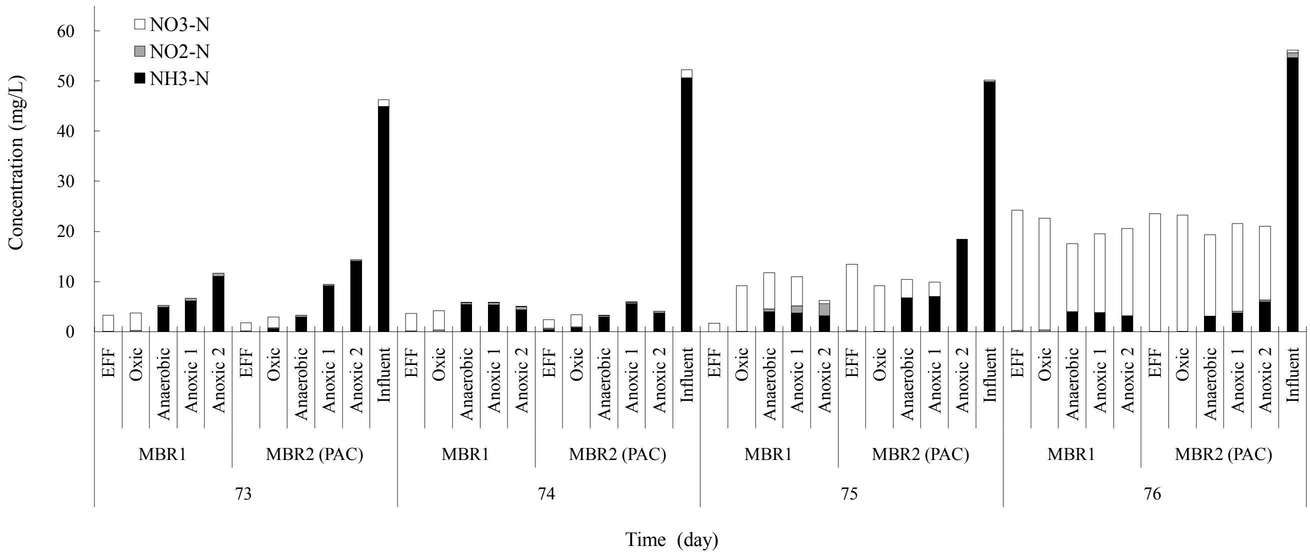


Fig. 5. Variations in NO_2^-, NO_3^-, NH_3^+ concentrations of MBR during organic loading fluctuations.

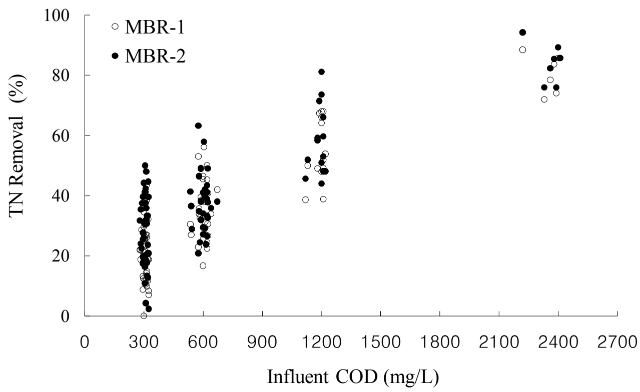


Fig. 6. Effect of influent COD on TN removal of MBR.

no direct influence on TN removal [7]. Apparently, the average TN increased during high organic loading and decreased at low organic loading. At high C/N ratio, more carbon source would be utilized for anoxic denitrification and anaerobic phosphorus release.

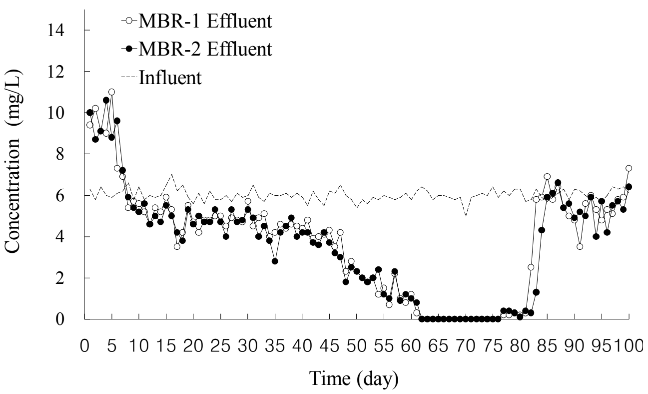
However, the accumulation of NO_3^- from day 73 until 78 was observed. The build-up of NO_3^- in the anoxic bioreactors could be the result of extensive nitrification in the oxic bioreactor and when NO_3^- was introduced to the anoxic bioreactor, the available carbon source was insufficient for a complete denitrification to occur. We thought that the high recirculation rate might have introduced NO_3^- to the anoxic zones. Under aerobic condition, the main biochemical reaction is nitrification and aerobic phosphorus uptake [3] and whenever NO_3^- is higher in the aerobic zone, NH_3^+ would be low. Hence, the concentration of NH_3^+ and NO_3^- in the anoxic bioreactors were greatly contributed by recirculation.

The TP removal of both MBRs showed flexibility to high organic loading fluctuations (Fig. 7). The one-way analysis of variance (data not shown) showed no significant difference between the TP removal of MBR-1 and MBR-2. Hence, PAC addition did not have any significant effect to TP removal.

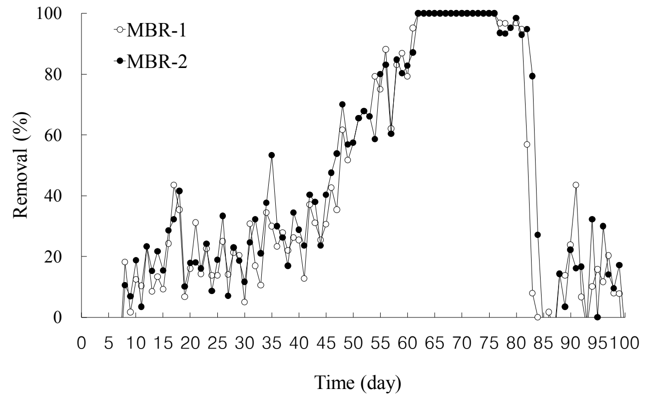
At the start-up of both MBRs, the TP removal oscillated. During the first week at 300 mg/L input of COD, the effluent TP exceeded that of the influent. This was also observed at the start of low organic loading with 1200 mg COD/L. The reason could be that the cake layer formed on the membrane module facilitated the anaerobic release of phosphate [8]. Another reason could be the slow growth of PAOs resulting to low net phosphorous uptake under aerobic condition. Fu et al. [9] observed that the average phosphate concentration in the anoxic bioreactor of an anoxic/oxic (A/O) MBR was larger than that in the influent while the phosphorus uptake in the oxic bioreactor was greater than 95.8%.

The TP removal improved at 2400 mg/L input of COD. However, when the organic loading was lowered to 1200 mg/L and finally to 600 mg/L, the TP removal has deteriorated (Table 4). The results implied that the MBR systems showed flexibility to remove the TP at high organic loading fluctuation but susceptible to TP removal depreciation during low organic loading fluctuation.

Under low organic loading changes, TP removal of both MBRs drastically declined. Although the MBR system was able to sustain high quality effluent (0.0–0.2 mg/L PO_4^{3-}) from day 61 to 81, it suddenly dropped at the end of 600 mg/L COD loading. These observations clearly demonstrated the microbial adaptability to organic loading fluctuations of phosphate-accumulating organisms (PAOs) in MBR.



(a) TP concentration



(b) TP removal

Fig. 7. Effect of organic loading changes on TP removal.

Fig. 8 shows that the influent COD greatly affects TP removal. At 2400 mg/L COD the TP removal remained stable. The higher influent COD provided sufficient organic substrate that was used by the PAOs to produce PHA with the release of P to the bulk solution. Anaerobic phosphorus release and aerobic uptake are greatly affected by the C/P ratio more than C/N ratio. However, C/N ratio indirectly affects the T-P removal [10] since phosphorus release also requires external carbon source aside from the glycogen and intracellular polyphosphates produced aerobically.

In the anaerobic bioreactor, PAOs take up substrate using internally stored glycogen and convert into poly-3-β-hydroxyalkanoates (PHAs). In the aerobic bioreactor, PAOs utilize the synthesized PHAs and restore glycogen. During the process, PAOs anaerobically release internal polyphosphate in the bulk solution and aerobically take up more phosphate.

Ahn et al. [4] successfully demonstrated the effect of organic loading changes in an EBPR process. It was thought that if an additional stress such as organic loading

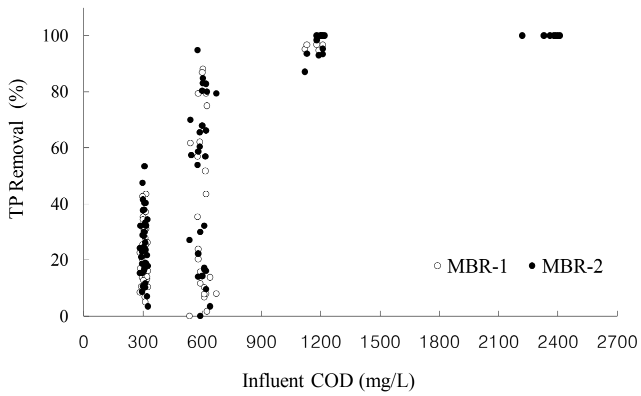


Fig. 8. Effect of organic loading changes on TP removal.

Table 4
Nutrient removal in MBR during organic loading changes

Time (d)		1–46	47–60	61–67	68–74	75–81	82–100
Influent COD (mg/L)		300	600	1200	2400	1200	600
Influent TN: 51 ± 1.5 mg/L							
Effluent (mg/L)	MBR-1	39	32	25	10	22	32
	MBR-2	36	31	22	8	22	31
Removal (%)	MBR-1	22	35	53	82	58	35
	MBR-2	27	37	58	84	58	38
Influent TP: 6± 0.1 mg/L							
Effluent (mg/L)	MBR-1	5	2	0	0	0.2	5
	MBR-2	5	2	0.1	0	0.2	4.9
Removal (%)	MBR-1	9	69	99	100	97	10
	MBR-2	12	69	98	100	96	19

fluctuation is provided, PAOs may not perform properly. It is believed that a low organic loading fluctuation greatly affects the activity of activated sludge especially the PAOs. The low adaptability of PAOs in low organic loading changes could explain the sharp decrease in TP removal of the MBR system. Nevertheless, the flexibility of MBR to remove TP during high organic loading could be attributed to the high resilience of PAO to abrupt increase in COD loading. This could explain the increasing effluent TP quality within 81 days' operation. PAOs' strong tendency to balance their metabolism and recovery at high organic loading changes [4] had been observed.

Another reason for the drastic decline in TP removal of the MBR at the end of low organic loading at 300 mg/L COD was the accumulation of NO_3^- in the anoxic bioreactor. It is possible that the phosphorus released during the last stage of high organic loading were not completely taken up during the onset of low organic loading. As a result, the accumulation of NO_x-N in the oxic and anoxic bioreactors prevented effective phosphorus release and uptake and the effluent quality deteriorated.

4. Conclusions

The effect of organic loading fluctuations in the MBR performance was investigated. The influence of PAC addition in the MBR operation during the investigation was also studied. The MBR system exhibited flexibility to high organic loading changes. The COD, TN and TP removal increased with increasing organic loading. At the end of high organic loading, the removal or COD, TN and TP were approximately 99%, 80% and 100%, respectively. High biomass concentration was also observed indicating high microbial activities. PAC addition had good implication on the control of membrane fouling in the course of study. The MBR system with added PAC (MBR-2) was able to operate below the critical flux four days longer than the system without PAC added (MBR-1). The biomass concentration was also higher in MBR-2 but there was no significant difference between MBR-1 and MBR-2 in terms of organic matter and nutrient removal. Thus, the addition of PAC was found necessary only in reducing the membrane fouling.

It was observed in this study that the TP removal of the MBR system was more affected by low organic loading changes than were the COD and TN removal. This could be attributed to the low adaptability of PAOs to low organic loading stress. Attention must be given to the changes in organic matter content of the influent especially at low COD input level because it could bring drastic effect on the biological nutrient removal efficiency of the MBR system. It was suggested that the dynamics of organic loading also be considered for the MBR process to sustain high effluent quality especially during start-up.

Acknowledgment

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