Evaluation of a Novel Sponge-Submerged Membrane Bioreactor (SSMBR) for Sustainable Water Reclamation

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Abstract

A novel sponge-submerged membrane bioreactor (SSMBR) to treat a high strength wastewater for water reclamation was developed in this study. The performance of this system was evaluated using two kinds of polyester-urethane sponges (coarse sponge with higher density S_{28-30}/45R and fine sponge with lower density S_{16-18}/80R) with sponge volume fraction of 10% and bioreactor MLSS of 10 g/L. The results indicated the addition of sponge in SMBR could increase sustainable flux (2 times for S_{28-30}/45R and 1.4 times for S_{16-18}/80R) and lower TMP development, thus significantly reduce membrane fouling. S_{28-30}/45R gave rise in attached growth biomass and the removal efficiencies of DOC, COD and PO_4-P whilst S_{16-18}/80R had better performance in removing NH_4-N. Although the SSMBR performed well for most of the trials, the superior recycled water quality was achieved when adding S_{28-30}/45R and S_{16-18}/80R together in SMBR with the ratio of 2:1 and without any pH adjustment during the operation.

Keywords: Sponge-submerged membrane bioreactor; Sustainable water reclamation; Membrane fouling; Sustainable flux; Organic and nutrients removal

1. Introduction

Water sustainability requires a holistic approach to water management by economic, environmental, technical and sociocultural criteria. On-going wastewater treatment technologies have been improved to produce higher quality treated effluent and satisfy more stringent regulation for sustainable water reclamation and reuse. Among the advanced treatment technologies, membrane bioreactors (MBRs) are ready to advance water sustainability. The technology encourages wastewater reuse and provides safe water to the community (DiGiano, 2004). MBR consists of a suspended growth bioreactor and a filtration on porous membrane, which leads to the total retention of biomass (high microbial concentration) and improved biological reactor operation (high sludge ages) in the bioreactor (Lee et al., 2003). In particular, this technology is simple to operate, needs modest technical support, takes up little space and can remove many contaminants from wastewater in one step.

However, MBR technology is currently facing some research and development challenges such as membrane fouling, high membrane cost and pretreatment. Membrane fouling is the most difficult challenge, which increases operational cost and shortens membrane life (Yang et al., 2006a; Yang et al., 2006b). Three approaches have been used to control membrane fouling: (i) fouling control by operating membrane system below critical flux, (ii) pretreatment of the feedwater, and (iii) membrane backwashing and cleaning (Sheikholeslami, 1999; Tchobanoglous et al., 2003). The concept of critical flux has been introduced in the mid 1990’s with theoretical and experimental evidence. The critical flux hypothesis for microfiltration (MF) is that on start-up there exists a flux below which a decline of flux with time does not occur; above it fouling is observed (Field et al., 1995). Normally, two different methods are used to determine the critical flux: (i) based on particle mass balance; (2) based on the increase in transmembrane pressure (TMP) required to maintain a constant permeate flux. Accordingly, the critical flux is the flux below which there is no increase in TMP as resistance to permeation (i.e. the TMP is constant with time). In the case of submerged membrane bioreactor (SMBR), ‘sub-critical’ flux operation does not appear to be feasible and the challenge is determination of the ‘sustainable flux’, where TMP rise is tolerable before rapid fouling and increase of TMP is seen to occur (Fane and Leslie, 2004).

Various attempts have been made to reduce the membrane fouling in MBR. Yamamoto et al. (1989) examined the influence of operational modes and found that intermittent suction greatly reduced membrane fouling compared to continuous suction. Lee at al. (2001) indicated that alum and natural zeolite addition to a submerged MBR not only reduced membrane fouling, but also increased the removal of chemical oxygen demand (COD). Furthermore, the association of SMBR and powdered activated carbon (PAC) has become a promising unit process for advanced water treatment when using PAC as pretreatment to membrane processes (e.g. microfiltration (MF) or ultrafiltration (UF)). This system could achieve more dissolved organic carbon (DOC) and disinfection by-products (DBPs) removals and mitigate membrane fouling by reducing organic loading to membrane as well as adsorbing organic matters (Kim et al., 2001;

Clark and Heneghan, 1991). Recently, Yoon and Collins (2006) have developed a novel flux enhancing method for handling the peak flow conditions in MBR using modified cationic polymers. Lee at al. (2006) found out that membrane-coupled moving bed biofilm reactor (M-CMBBR) had much lower biofouling rate than a conventional MBR when using activated carbon coated polyurethane cubes as attached growth media. Yang et al. (2006) also investigated a hybrid membrane bioreactor (HMBR) with porous, flexible suspended carriers to treat terephthalic acid wastewater. The HMBR was efficient in controlling membrane fouling, especially cake layer. In short-term experiments, the critical flux of HMBR increased by 20% and the cake resistance of HMBR decreased by 86% in comparison with conventional MBR.

In aerobic MBRs, almost complete nitrification can be achieved, while denitrification needs the addition of an anaerobic tank prior to the aeration tank with conventional recycle (Gander et al., 2000). However, the concept of simultaneous phosphorus and nitrogen removal significantly depreciated the most favorable characteristics of long sludge retention time (SRT) control in MBR. To solve this problem, aerated MBR systems could either be coupled with chemical treatment process such as coagulation and adsorption (Yoon et al., 2004; Genz et al., 2004), or be associated with a separated anoxic tank for denitrification (Ahn et al. 2003; Hibiya et al., 2003). In present situation, although these MBR systems have shown an improvement of nitrogen removal, phosphorus has not been removed significantly through these systems. Thus, anaerobic condition was added to enhance phosphorus removal. Ahn et al. (2003) reported that approximately 93% phosphorus was removed in an improved sequencing anoxic/anaerobic MBR. Zhang et al. (2006) examined a sequencing batch membrane bioreactor (SBMBR) for enhancing nitrogen and phosphorus removal by sequential operation of a MBR in alternating aerobic and anoxic/anaerobic condition. Both of the ammonium nitrogen and total phosphorus removals of the SBMBR were maintained approximately 90%. Meanwhile, attached growth bioreactors using specific material bioreactors have been used to modified biological processes. Sponge has been considered as an ideal attached growth media because it can act as a mobile carrier for active biomass, reduce the cake layers formed on the surface of membrane and retain microorganisms by incorporating a hybrid growth system (both their attached and suspended growth) (Ngo et al., 2006; Psoch and Schiewer, 2006; Chae et al., 2004; Pascik, 1990). Deguchi and Kashiwaya (1994) have reported that the nitrification and denitrification rate coefficients of a sponge suspended biological growth reactor were 1.5 and 1.6 times respectively higher than the coefficients of conventional activated sludge reactor.

In this study, a new concept of sponge-submerged membrane bioreactor (SSMBR) has been developed for alleviating membrane fouling, enhancing permeate flux and improving phosphorus and nitrogen removals simultaneously (Ngo, 2004). The objective of this study is to evaluate the application of SSMBR in synthetic domestic wastewater treatment for water reclamation. The performance of SSMBR was assessed in terms of the removal efficiencies of DOC, COD, nitrogen, phosphorus, TMP, molecular weight distribution (MWD) and pH adjustment. The acclimatization of two kinds of sponges was evaluated in terms of biomass growth on sponge and sustainable flux of SSMBR. Specific oxygen uptake rate (SOUR) was used to indicate the biological activities in the bioreactor, including the suspended growth in SSMBR and attached growth on sponge.

2. Materials and Methods

2.1. Wastewater

The experiments were conducted using a synthetic wastewater to avoid any fluctuation in the feed concentration and provide a continuous source of biodegradable organic pollutants such as glucose, ammonium sulfate and potassium dihydrogen orthophosphate (Lee et al., 2003). It was used to simulate high strength domestic wastewater (just after primary treatment process). The synthetic wastewater has DOC of 120-130 mg/L, COD of 330-360 mg/L, ammonium nitrogen (NH_4-N) of 12-15 mg/L and orthophosphate (PO_4-P) of 3.3-3.5 mg/L (COD: N: P = 100:5:1). $NaHCO_3$ or H_2SO_4 were used to adjust pH in MBR reactor to a constant value of 7.

2.2. Sponge

Two kinds of reticulated porous polyester-urethane sponge (PUS) cubes were used in SSMBR system, namely S_{28-30}/45R (density of 28-30 kg/m^3 with 45 cells per 25 mm, tensile strength of 120 kPa.min and tear resistance of 780 N/m.min) and S_{16-18}/80R (density of 16-18 kg/m^3 with 80 cells per 25 mm, tensile strength of 100 kPa.min and tear resistance of 650 N/m.min). The dimensions of S_{28-30}/45R and S_{16-18}/80R cubes are 10×10×10 mm. The predetermined volume of sponge cubes were added directly into the SMBR reactor before the experiment.

2.3. Sponge-submerged membrane bioreactor (SSMBR) set-up

A polyethylene hollow fiber membrane module was used with the pore size of 0.1 μm and surface area of 0.195 m^2 (Mitsubishi-Rayon, Japan). The schematic diagram of the SSMBR is shown in Fig. 1. The effective volume of the bioreactor was 7 L. Synthetic wastewater was pumped into the reactor using a feeding pump to control the feed rate while the effluent flow rate was controlled by a suction pump. Level sensor was used to control the wastewater volume in the reactor. A pressure gauge was used to measure the TMP and a soaker hose air diffuser was used to maintain a high air flow rate (9 L/min or 2.77 $m^3/m^2_{(membrane\ area)}.h$). For physical cleaning of the membrane, filtrate backwash was used every half an hour for 1 min duration at a backwash rate of 30 $L/m^2.h$. The SSMBR was filled with sludge from local Wastewater Treatment Plant and acclimatized to synthetic wastewater. Sponge volume fraction of 10% (bioreactor volume) was used in this study, which was determined according to previous sustainable flux experiments (Ngo et al., 2007).

Fig. 1. Experimental set-up of SSMBR

2.4. Analysis

DOC of the influent and effluent was measured using the Analytikjena Multi N/C 2000. The analysis of COD and the measuring of mixed liquor suspended solids (MLSS) and biomass (monitored as mixed liquor volatile suspended solids, MLVSS) were according to Standard Methods (APHA, 1998). For measuring MLSS and biomass, three samples were taken each time and the average values were then calculated. NH_4-N and PO_4-P were measured by photometric method called Spectroquant® Cell Test (NOVA 60, Merck). The bacterial activity during operation of MBR can be evaluated by measuring the oxygen consumption (by respirometric procedure). YSI 5300

Biological Oxygen Monitor was used to measure SOUR due to its usefulness in measuring samples including respiration, oxidative activity, and cellular metabolism studies. The use of oxygen electrode with oxygen permeable Teflon membrane can measure oxygen consumption. Voltage generated from the reaction is proportional to the oxygen concentration of the sample and produces oxygen uptake or evolution curves in 2 to 15 minutes. Total viable counts were determined using spread plate technique on nutrient agar. All samples were diluted using 0.1% bacteriological peptone water. Nutrient agar and bacteriological peptone were obtained from OXOID®. Molecular weight distribution (MWD) of dissolved organic matters was analysed prior to and after the pretreatment. High pressure size exclusion chromatography (HPSEC, Shimadze, Corp., Japan) with a SEC column (Protein-pak 125, Waters, Milford, USA) was used to determine the MW distributions of organics. The equipment was calibrated using the standards of MW of various polystyrene sulphonates (PSS: 210, 1800, 4600, 8000 and 18000). The MW distribution results were analysed using the response (mV) data of HPSEC with elapsed time.

3. Results and Discussion

3.1. Biomass growth on sponge during acclimatization

Before running the SSMBR experiments, $S_{28\text{-}30}$/45R and $S_{16\text{-}18}$/80R cubes (1.5 L each) were acclimatized to synthetic wastewater in two 10 L aeration tanks with initial MLSS of 5 g/L. Certain volume of sponge was taken out from the tanks to measure biomass. Sponge was squeezed and rinsed with milli-q water thoroughly in order to get all biomass out of the sponge. The biomass on $S_{28\text{-}30}$/45R sponge reached stable growth phase (around 16.7 g/L(sponge)) after 15-day acclimatization, while the biomass on $S_{16\text{-}}$

$_{18}$/80R sponge took about 20 days to reach steady state (approximately 24.8 g/L$_{\text{(sponge)}}$). SOUR was used to study the dissolved oxygen (DO) consumption rates of biomass on sponges. This relates to the microbial activity on sponge at different periods of acclimatization. During the acclimatization, the sponge cubes withdrawn from the aeration tank at different periods were monitored. As can be seen from the figure, the SOUR of $S_{16\text{-}18}$/80R (Fig. 2a) could reach equilibrium much faster than that of $S_{28\text{-}30}$/45R and had higher DO consumption values (Fig. 2b). However, the total viable counts (bacteria) of $S_{28\text{-}30}$/45R and $S_{16\text{-}18}$/80R were 2.1×10^7 and 3.2×10^5 cfu/ml$_{\text{(sponge)}}$ respectively. This means $S_{16\text{-}18}$/80R have more aerobic bacteria compared with $S_{28\text{-}30}$/45R even though $S_{16\text{-}18}$/80R had less number of bacteria.

Fig. 2. SOUR of the biomass on two different sponges at 16 mins with biomass growth

3.2. Performance of SSMBR with different types of sponge

Sustainable flux experiments were carried out using acclimatized sponges. The initial MLSS concentration of SSMBR was 10 g/L. Every 60 minutes flux-step, 1 minute backwash was provided at a backwash rate of 30 L/m^2.h using membrane filtrate. The purpose of backwash was mainly to minimize the TMP increase due to reversible fouling during every experimental flux-step, which could lead to TMP development. Table 1 summarized the sustainable flux and effluent quality of $S_{28\text{-}30}$/45R-SMBR and $S_{16\text{-}18}$/80R-SMBR systems. According to the results, suspended sponge could significantly reduce the membrane fouling and enhance sustainable flux. With the sponge volume fraction of 10%, the sustainable fluxes of $S_{28\text{-}30}$/45R-SMBR and $S_{16\text{-}18}$/80R-SMBR were 2 times and 1.4 times higher than that of SMBR alone (without sponge addition) respectively. Meanwhile, $S_{28\text{-}30}$/45R-SMBR also had lowest TMP development with TMP increase of 5.9 kPa during 60 minutes at filtration flux of 55 L/m^2.h. Thus, the sponge addition could significantly reduce membrane fouling and enhance sustainable flux by extensive attached biomass as well as physical cleaning the membrane surface. In addition, both of the SSMBR systems could achieve high DOC removal during 13 hours operation, whereas $S_{28\text{-}30}$/45R-SMBR was only good for PO_4-P removal whereas $S_{16\text{-}18}$/80R-SMBR could get better removal efficiency of NH_4-N.

Table 1 Sustainable flux and effluent quality in $S_{28\text{-}30}$/45R-SMBR and $S_{16\text{-}18}$/80R-SMBR systems (Influent DOC =120-130 mg/L, NH_4-N = 12-15 mg/L and PO_4-P = 3.3-3.5 mg/L; bioreactor MLSS= 10 g/L)

3.3. Effect of pH adjustment on the performance of SSMBR

SSMBR system was operated at a constant permeate flux of 30 L/m^2.h for 8 days under the hydraulic retention time (HRT) of 1.2 hours. The activated sludge concentration was kept constant with MLSS of 15 g/L and SRT of SSMBR was approximately 35 days. $S_{28\text{-}30}$/45R-SMBR sponge cubes were used and sponge volume was 10% of the effective volume of the bioreactor (7L). The system was evaluated with and without pH adjustment. It is noted that the synthetic wastewater had a pH about 7.18 to 7.2. With pH adjustment, the pH of mixed liquor in reactor was maintained at around 7. Without pH adjustment, the pH of mixed liquor was fluctuated between 4.8 and 5.5. The pH of mixed liquor decreased to 4.8-5.5 mainly due to the nitrification-denitrification process in the bioreactor. Biological nitrification reduces alkalinity, which can result in lower pH. Meanwhile, denitrification function of $S_{28\text{-}30}$/45R sponge builds some alkalinity because of the anoxic/anaerobic condition inside the sponge. Therefore, the values of pH in the mixed liquor could maintain between 4.8 and 5.5. Fig. 3 shows the DOC and COD removal efficiencies of the SSMBR system. The results indicated that both operation conditions achieved excellent DOC and COD removals of over 96% and 97% respectively. Both pH conditions showed similar PO_4-P removal results (over 98% removal and effluent PO_4-P concentration <0.05 mg/L). However, the NH_4-N removal with pH adjustment presented slightly higher removal efficiency (>88%) compared with no pH adjustment (79%) (Fig. 4). The variation of TMP values were measured during the operation (Fig. 5). As can be seen from the results, the TMP development only increased 14 kPa without pH adjustment, but there was 42.5 kPa TMP development in case of pH adjustment. The SOUR of the mixed liquor was measured on 2nd and 5th day for examining whether pH adjustment affected the activity of microbial community. The results exhibited no changes in the variation of DO concentration for both pH conditions. Therefore, the microbial community could keep active in SSMBR system without pH adjustment during operation.

Fig. 3. DOC and COD profile of SSMBR system with and without pH adjustment (filtration flux = 30 $L/m^2.h$; backwash rate = 30 $L/m^2.h$; backwash = 1 minute every half an hour; HRT = 1.2 hours; SRT = 35 day)

Fig. 4. PO_4-P and NH_4-N profile of SSMBR system with and without pH adjustment (filtration flux = 30 $L/m^2.h$; backwash rate = 30 $L/m^2.h$; backwash = 1 minute every half an hour; HRT = 1.2 hours; SRT = 35 day)

Fig. 5. TMP development of SSMBR system with different operation conditions (filtration flux = 30 $L/m^2.h$; backwash rate = 30 $L/m^2.h$; backwash = 1 minute every half an hour; HRT = 1.2 hours; SRT = 35 day)

3.4. Performance of SSMBR with mixed sponge cubes

Since S_{28-30}/45R sponge was good for PO_4-P removal and S_{16-18}/80R sponge could achieve higher NH_4-N removal, two configurations of sponge cubes were mixed with the ratio S_{28-30}/45R:S_{16-18}/80R of 2:1. The total sponge volume was remained at 10% of bioreactor volume. The mixed sponge-SMBR system was operated at activated sludge

MLSS of 15 g/L and no pH adjustment. Around 97% DOC removal and over 97% COD were removed (Fig. 6). The system also had lowest TMP development which only increased 10.5 kPa after 8 days run at a constant permeate flux of 30 L/m^2.h (Fig. 5). For nutrients removal, the system had extremely high NH_4-N removal (over 99.5% and NH_4-N concentration of effluent less than 0.04 mg/L), while resulted in an imperceptibly lower PO_4-P removal (over 97% with effluent PO_4-P concentration <0.1 mg/L) compared with SSMBR using 10% S_{28-30}/45R sponge alone. The ratio of the mixed sponge cubes should be investigated in order to improve perfect nutrients removal.

Fig. 6. DOC, COD, PO_4-P and NH_4-N profiles of SSMBR system with mixed sponge cubes (filtration flux = 30 L/m^2.h; backwash rate = 30 L/m^2.h; backwash = 1 minute every half an hour; HRT = 1.2 hours; SRT = 35 day)

3.5. Molecular weight distribution (MWD)

Municipal wastewater consists of organic matters with the wide range of MW fraction which can play an important role in membrane fouling of SMBR. In this study, the main purpose of the MWD data was show which MW range of organic matter could be removed by the SSMBR. The synthetic wastewater consists of organic matters with the MW fractions of 1530, 730, 390 and 90 daltons. In SMBR system, the MW fractions (1530, 390 and 90 daltons) of the synthetic wastewater were almost completely removed by SSMBR, while major part of small MW molecules (730 daltons) still remained in the effluent. Mixed sponge-SMBR presented the best results for removal all MW fractions, while S_{16-18}/80R-SMBR still remained part of MW fraction of 90 daltons. The MWD results could correspond to the DOC and COD removals of the three SSMBRs.

4. Conclusions

S_{16-18}/80R sponge had more attached growth biomass (24.8 g/L) than that of S_{28-30}/45R sponge (16.7 g/L) after 25-day acclimatization. Sponge addition to the SMBR reactor could significantly reduce membrane fouling and enhance sustainable flux. With the sponge volume fraction of 10%, the sustainable fluxes of S_{28-30}/45R-SMBR and S_{16-18}/80R-SMBR were 2 times and 1.4 times respectively higher than the sustainable flux of SMBR alone (25 L/m^2.h). Without pH adjustment, S_{28-30}/45R-SMBR could maintain very high removal efficiencies of DOC, COD and PO_4-P and had much lower TMP development.

S_{28-30}/45R-SMBR had better PO_4-P removal (effluent PO_4-P <0.1 mg/L) while S_{16-18}/80R-SMBR was good at removing NH_4-N (effluent NH_4-N < 1 mg/L). Mixed sponge with the ratio S_{28-30}/45R:S_{16-18}/80R of 2:1 exhibited superior NH_4-N removal (over 99.5%) associated with over 97% of PO_4-P removal and lowest TMP development (10.5 kPa over 8 days of operation). S_{28-30}/45R-SMBR, S_{16-18}/80R-SMBR and mixed sponge-SMBR could removal the major MW fractions (90-1530 daltons) presented in the synthetic wastewater.

Acknowledgment

This research was funded by Institute of Water and Environmental Resource Management (IWERM) and Chancellor's Postdoctoral Research Fellowships of UTS.

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Table 1
Sustainable flux and effluent quality in $S_{28\text{-}30}$/45R-SMBR and $S_{16\text{-}18}$/80R-SMBR systems (Influent DOC =120-130 mg/L, NH_4-N = 12-15 mg/L and PO_4-P = 3.3-3.5 mg/L; bioreactor MLSS = 10 g/L)

System	Sustainable flux ($L/m^2.h$)	Effluent DOC (mg/L)	Effluent NH_4-N (mg/L)	Effluent PO_4-P (mg/L)	TMP increase at next flux-step during 1 hour
SMBR only	25	< 6	> 4	> 2	8.5 kPa at 30 $L/m^2.h$
$S_{28\text{-}30}$/45R-SMBR	50	< 4	< 4	< 0.1	5.9 kPa at 55 $L/m^2.h$
$S_{16\text{-}18}$/80R-SMBR	35	< 5	< 1	< 1	7 kPa at 40 $L/m^2.h$

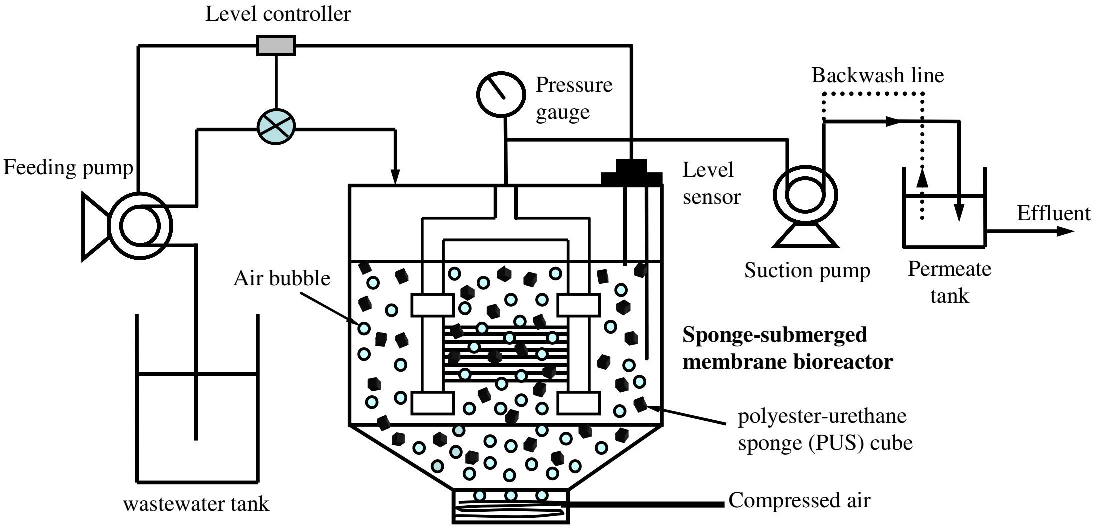
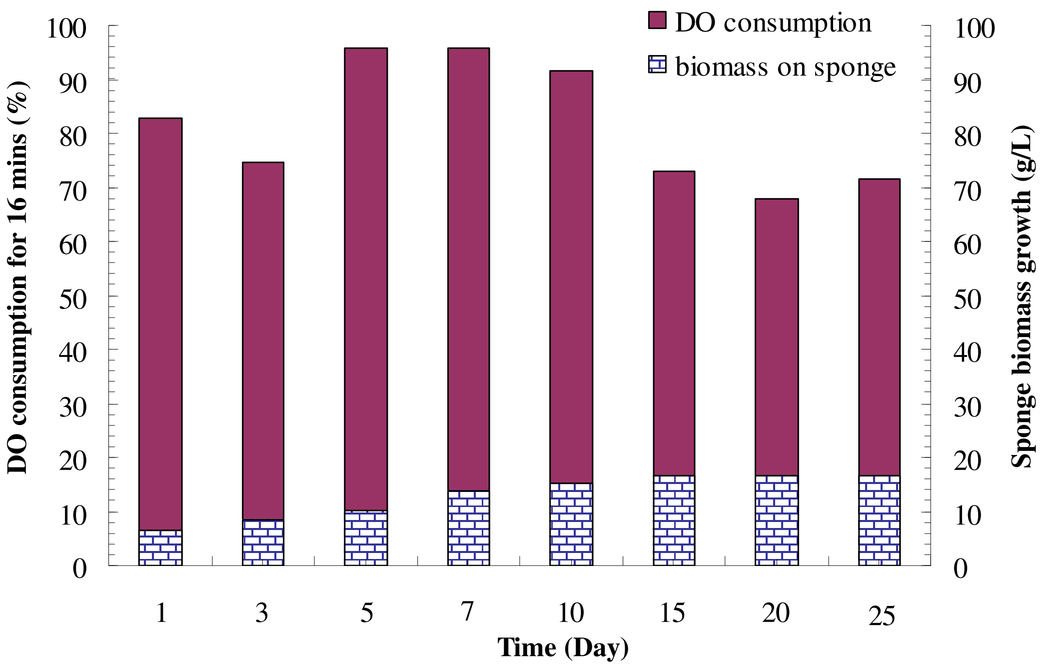
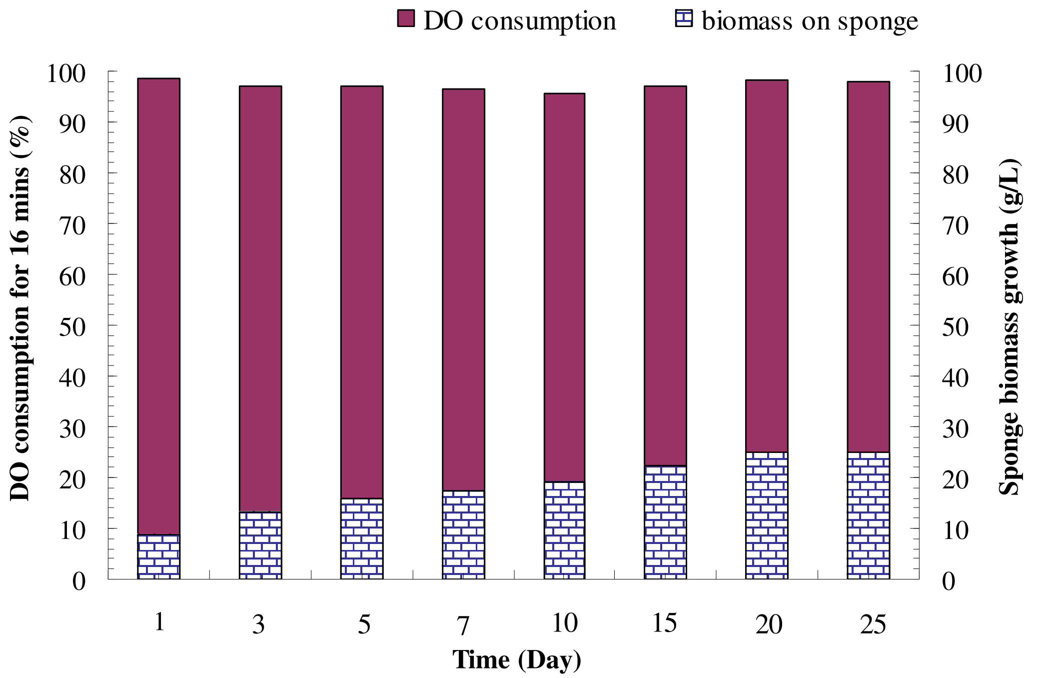


Fig. 1. Experimental set-up of SSMBR



(a) S_{28-30}/45R



(b) S_{16-18}/80R

Fig. 2. SOUR of the biomass on two different sponges at 16 mins with biomass growth

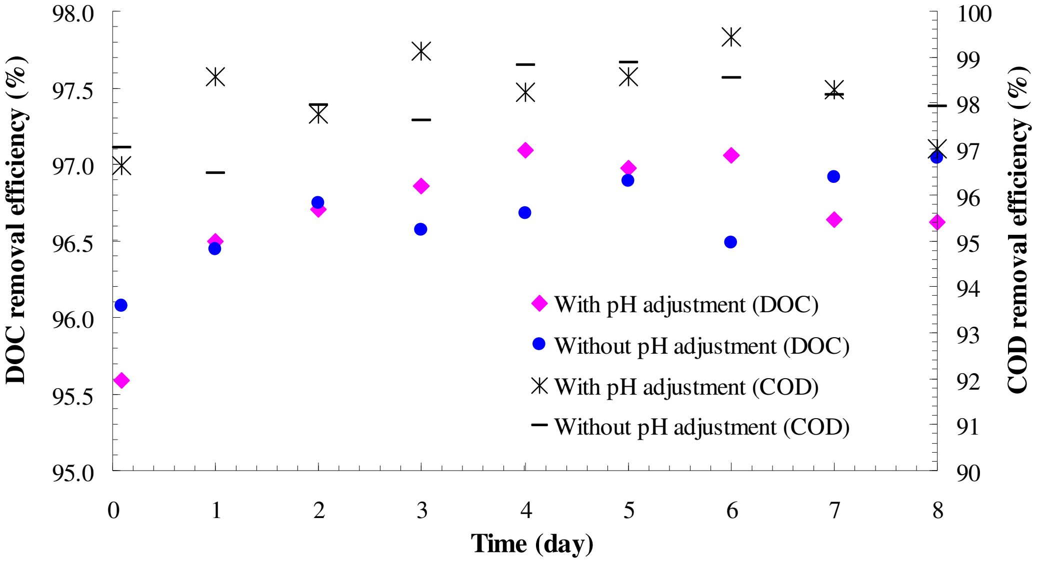


Fig. 3. DOC and COD profile of SSMBR system with and without pH adjustment (filtration flux = 30 L/m^2.h; backwash rate = 30 L/m^2.h; backwash = 1 minute every half an hour; HRT = 1.2 hours; SRT = 35 day)

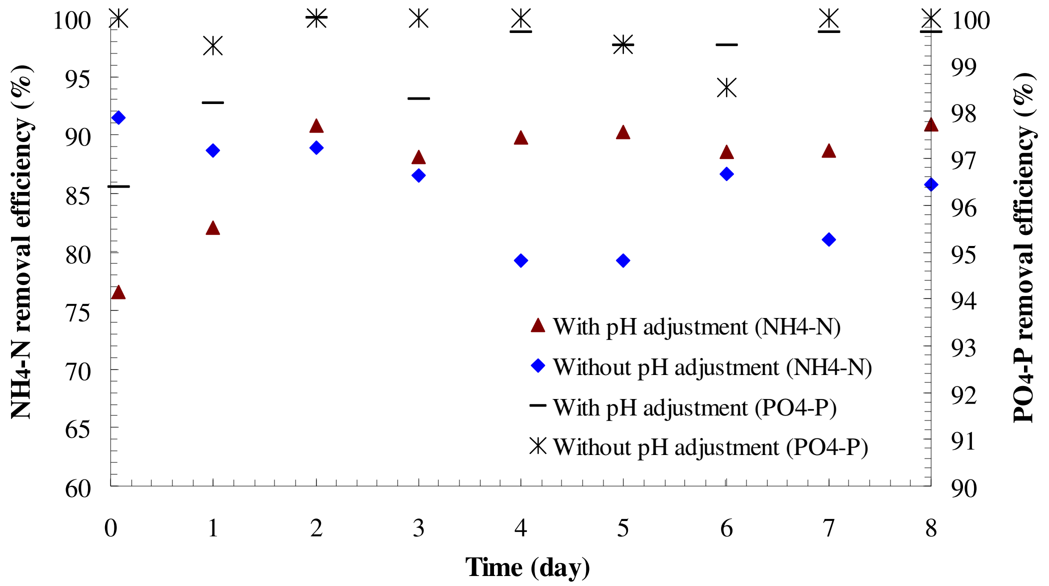


Fig. 4. NH_4-N and PO_4-P profile of SSMBR system with and without pH adjustment (filtration flux = 30 L/m^2.h; backwash rate = 30 L/m^2.h; backwash = 1 minute every half an hour; HRT = 1.2 hours; SRT = 35 day)

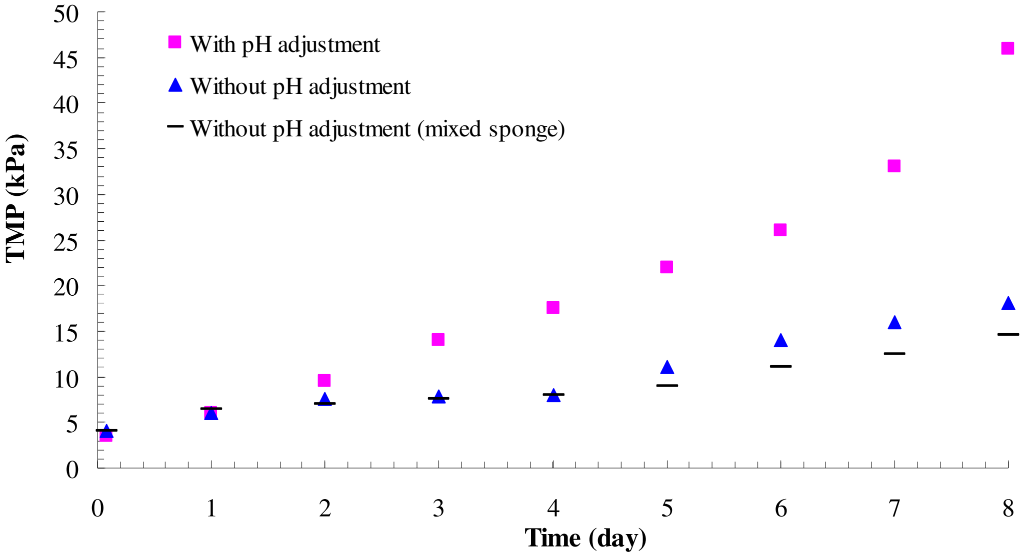


Fig. 5. TMP development of SSMBR system with different operation conditions (filtration flux = 30 L/m^2.h; backwash rate = 30 L/m^2.h; backwash = 1 minute every half an hour; HRT = 1.2 hours; SRT = 35 day)

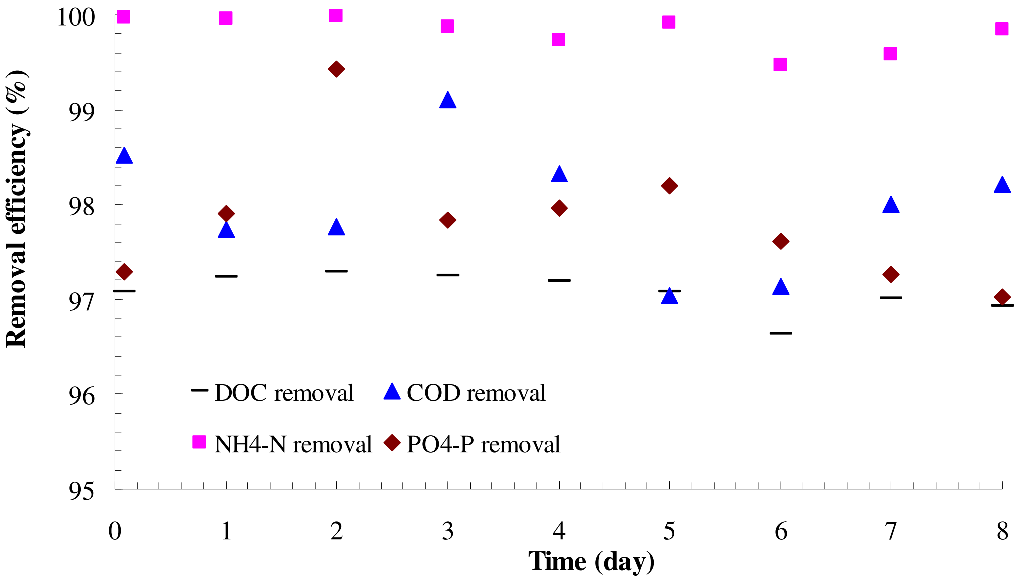


Fig. 6. DOC, COD, PO_4-P and NH_4-N profiles of SSMBR system with mixed sponge cubes (filtration flux = 30 $L/m^2.h$; backwash rate = 30 $L/m^2.h$; backwash = 1 minute every half an hour; HRT = 1.2 hours; SRT = 35 day)