Roles of sponge sizes and membrane types in a single stage sponge-submerged membrane bioreactor for improving nutrient removal from wastewater for reuse

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Abstract

Sponges not only can reduce membrane fouling by means of mechanical cleaning and maintain a balance of suspended-attached microorganisms in submerged membrane bioreactor (SMBR), but also can enhance dissolved organic matter and nutrient removal. This study investigated the performance of three different sizes of sponge ($S_{28\text{-}30}$/45R, $S_{28\text{-}30}$/60R and $S_{28\text{-}30}$/90R) associated with continuous aerated SMBR. A laboratory-scale single stage sponge-SMBR showed high performance for removing dissolved organic matter (>96%) and PO_4-P (>98.8), while coarse sponges such as $S_{28\text{-}30}$/45R, $S_{28\text{-}30}$/60R could achieve more than 99% removal of NH_4-N. When three-size sponges ($S_{28\text{-}30}$/45R, $S_{28\text{-}30}$/60R and $S_{28\text{-}30}$/90R) were mixed at a ratio of 1:1:1 and in conjunction with two kinds of membranes (0.1 μm hollow fiber and 2 μm nonwoven), the sponge SMBR system has proved its generic merits of superior treated effluent quality and less membrane fouling. The NH_4-N and PO_4-P removal were found excellent, which were more than 99.8% and over 99% respectively. Molecular weight distribution also indicated that major fractions of organic matter could be successfully removed by sponge SMBR.

Keywords: Biological nutrient removal; Sponge submerged membrane bioreactor (SSMBR); Fouling control; Hollow fiber membrane; Nonwoven membrane; Wastewater treatment for reuse

1. Introduction

Nowadays, nutrient removal has attracted great attention in wastewater treatment for reuse. A number of biological processes, which apply various combinations of anaerobic, anoxic and aerobic or multiple compartments, have been developed to remove nutrients [1]. In particular, there is a growing interest in using low-pressure membrane bioreactor (MBR) coupled with microfiltration (MF) or ultrafiltration (UF) for simultaneous organic and nutrient removal.

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MBR is the key element in wastewater treatment for reuse and ready to advance water sustainability. The main feature of MBR is a compact treatment technology which has several advantages over conventional biological systems, such as high effluent quality, excellent microbial separation ability, absolute control of sludge and hydraulic retention times (SRTs and HRTs), high biomass content, low-rate biomass production, small footprint and flexibility in operation [2]. In MBR applications, biological nitrogen removal can be achieved by two types of MBR systems: the single-reactor-type MBR and the modified Luzack-Ettinger (MLE)-type MBR. The single-reactor-type MBR introduced the alternating aerobic and anoxic conditions to a submerged MBR (SMBR) by intermittent aeration in the aerobic tank. However, filtration operation in this type of MBR is limited during only the aeration period due to minimize fouling of the membrane. Therefore, the MLE-type MBR (a continuous aerated MBR together with a separated anoxic tank) was developed for continuous filtration operation, in which the mixed liquor is recycled continuously from aerobic zone to anoxic zone [3, 4]. Although these MBRs have shown improved nitrogen removal with almost complete nitrification, phosphorus has not been removed significantly through these systems. Thus, some modified MBR systems have been developed and evaluated to enhance phosphorus removal, such as vertical submerged MBR with anoxic and aerobic zones (78% removal) [1], alternating of anoxic and anaerobic MBR process (AAAM, 94.1% removal) [4], sequencing anoxic/anaerobic MBR (SAM, 93% removal) [5], sequencing batch membrane bioreactor (SBMBR, 90% removal) [6], and anoxic/aerobic MBR with addition of clinoptilolite powder followed by rapid coagulation process (92-96%) [7], nevertheless, the higher removal efficiencies were hardly achieved.

To solve this problem, attached growth bioreactors using specific material have been used to modified biological processes. Sponge has been considered as an ideal attached growth medium 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 growths) [8, 9, 10]. Deguchi and Kashiwaya [11] 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, an innovative sponge-submerged membrane bioreactor (SSMBR) has been developed at UTS for improving simultaneous phosphorus and nitrogen removal, alleviating membrane fouling and enhancing permeate flux. The main objective of this study was to evaluate the significance and practical use of the novel single stage SSMBR for wastewater treatment for reuse. The performance of SSMBR was assessed in terms of the removal efficiencies of ammonium nitrogen (NH_4-N), orthophosphate (PO_4-P), dissolved organic carbon (DOC), chemical oxygen demand (COD) and transmembrane pressure (TMP).

2. Experimental

2.1. Wastewater

The experiments were conducted using a synthetic wastewater containing glucose, ammonium sulphate, potassium dihydrogen phosphate and trace nutrients [12]. It was used to simulate high strength domestic wastewater (just after primary treatment process). The synthetic wastewater had DOC of 130-145 mg/L, COD of 340-390 mg/L, NH_4-N of 15-20 mg/L and PO_4-P of 3.5-4.0 mg/L. $NaHCO_3$ or H_2SO_4 was used to adjust pH to 7.

2.2. Sponge

Different pore sizes of reticulated polyester urethane sponge (S_{28-30}/45R, S_{28-30}/60R and S_{28-30}/90R) from Joyce Foam Products, Australia, were used in SSMBR system. The dimensions of the sponge cubes were 10×10×10 mm and Table 1 gives the characteristics of three different sizes of sponge. The predetermined volume of acclimatized sponge cubes were added directly into the SSMBR reactor during the experiments.

Table 1
Characteristics the different pore sizes of sponges

Sponge	Density (kg/m3)	Tensile strength (kPa)	Tear resistance (N/m)	Cell count (cells per 25 mm)
S_{28-30}/45R	28	120	780	45 ± 8
S_{28-30}/60R	28	135	760	60 ± 10
S_{28-30}/90R	28	150	650	90 ± 10

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

The schematic diagram of the SSMBR is shown in Fig. 1. 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 (12 L/min). After each experiment, the membrane was cleaned by chemical cleaning method (using citric acid and NaOCl) and filtrate backwash was adopted for physical cleaning of the membrane during the operation. The SSMBR was filled with sludge from the local Wastewater Treatment Plant and acclimatized to synthetic wastewater. In all cases, the systems were operated at activated sludge mixed liquor suspended solids (MLSS) of 15 g/L. Sponge volume fraction of 10% (bioreactor volume) was employed in this study, which was determined according to previous sustainable flux experiments [13]. The experimental details for the different sets of experiments are listed in Table 2.

2.4. Analysis

DOCs of the influent and effluent were measured using the Analytikjena Multi N/C 2000. The analysis of COD and the measuring of MLSS and biomass (monitored as mixed liquor volatile suspended solids, MLVSS) were according to the Standard Methods [14]. For measuring MLSS and biomass, three samples were taken each time and the average value was then calculated. NH_4-N and PO_4-P were measured by photometric method called Spectroquant® Cell Test (NOVA 60, Merck). High pressure size exclusion chromatography (HPSEC, Shimadze, Corp., Japan) with a SEC column (Protein-pak 125, Waters, Milford, USA) was used to determine the Molecular weight distributions (MWD) of organics. The equipment was calibrated using the standards of MW of various polystyrene sulphonates (PSS: 210, 1800, 4600, 8000 and 18000).

Table 2
Experimental details for the different sets of experiments

System	Sponge	Permeate flux ($L/m^2.h$)	Reactor volume (L)	Membrane type, pore size	Membrane area (m^2)
SSMBR performance with different sizes of sponge	No sponge	20	6	PE, 0.1 μm	0.1
	S_{28-30}/45R	20	6	PE, 0.1 μm	0.1
	S_{28-30}/60R	20	6	PE, 0.1 μm	0.1
	S_{28-30}/90R	20	6	PE, 0.1 μm	0.1
SSMBR performance with mixed sizes of sponge	S_{28-30}/45R: S_{28-30}/60R: S_{28-30}/90R = 1:1:1	30	8	PE, 0.1 μm	0.195
		30	8	Nonwoven, 2 μm	0.04

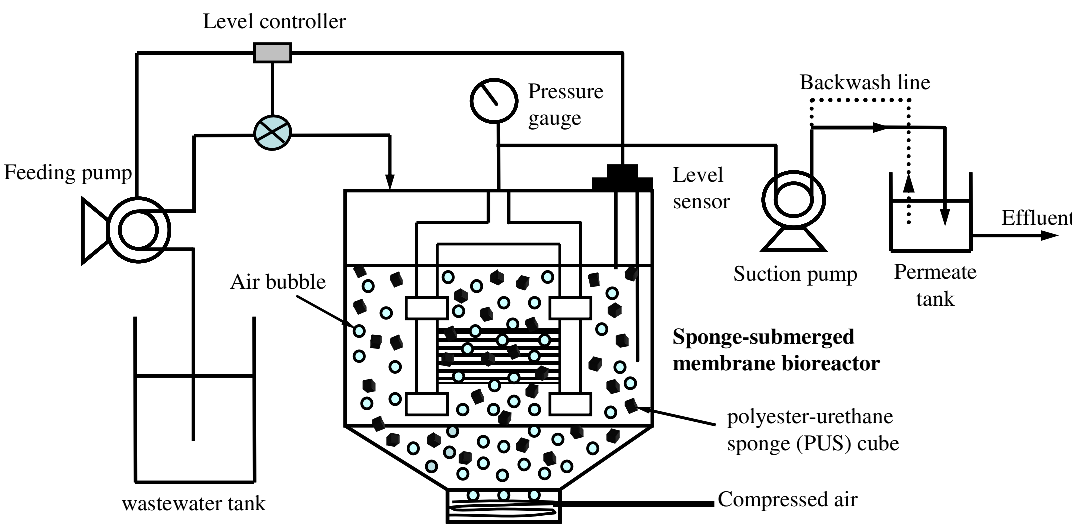

Fig. 1. Experimental set-up of SSMBR.

3. Results and Discussion

3.1. The performance of sponge with different pore sizes

The attached biomass on three different pore sizes of sponge cubes, namely S_{28-30}/45R, S_{28-30}/60R and S_{28-30}/90R, was measured after sponge acclimatization. The results indicated that sponge is an ideal attached growth medium for SMBR system as an active mobile carrier for active biomass. $S_{28\text{-}30}$/90R and $S_{28\text{-}30}$/60R had the higher biomass of 1.37 $g_{biomass}/g_{sponge}$ and 1.35 $g_{biomass}/g_{sponge}$ respectively, while $S_{28\text{-}30}$/45R only had 1.09 $g_{biomass}/g_{sponge}$ of biomass. The performance of SMBR only and SMBR with three different sponges were investigated for 15 days using a submerged hollow fiber MBR (Mitsubishi-Rayon, Japan). The results are summarized in Table 3. Without sponge addition, the DOC removals of the proposed system were similar to those with sponge addition, while NH_4-N and PO_4-P removal were lower than 93% and 77.8% respectively. With sponge addition, in spite of different pore sizes, all of the sponges could help in achieving excellent phosphorus removal, which resulted in the PO_4-P of effluent less than 0.05 mg/L. Meanwhile, $S_{28\text{-}30}$/45R and $S_{28\text{-}30}$/60R could lead to better NH_4-N removal (over 99%) when compared to that of $S_{28\text{-}30}$/90R.

Table 3
The effluent quality of SMBR, $S_{28\text{-}30}$/45R-SMBR, $S_{28\text{-}30}$/60R-SMBR and $S_{28\text{-}30}$/90R-SMBR (Influent DOC =130-145 mg/L; NH_4-N = 15-20 mg/L; PO_4-P = 3.5-4.0 mg/L; permeate flux = 20 L/m^2.h; effective volume of bioreactor = 6 L; MLSS = 15 g/L; HRT = 3 hours; SRT = 35 days; backwash = 1 min every hour at 30 L/m^2.h; aeration rate = 12 L/min)

System	DOC		NH_4-N		PO_4-P	
	Effluent (mg/L)	Removal efficiency (%)	Effluent (mg/L)	Removal efficiency (%)	Effluent (mg/L)	Removal efficiency (%)
SMBR only	<5.0	>95.0	>1.1	<93.0	>0.8	<77.8
$S_{28\text{-}30}$/45R-SMBR	<5.0	>96.5	<0.05	>99.4	<0.04	>98.9
$S_{28\text{-}30}$/60R-SMBR	<5.1	>96.3	<0.05	>99.4	<0.04	>98.9
$S_{28\text{-}30}$/90R-SMBR	<5.4	>96.1	<1.65	>90.5	<0.04	>98.8

3.2. SSMBR performance with mixed sizes of sponge

According to the different capacities to remove ammonium nitrogen and phosphorus, three sizes of sponge cubes were mixed with volume ratio of 1:1:1. The mixed-SSMBR was then evaluated through two different membranes (0.1 μm hollow fiber membrane and 2 μm nonwoven membrane), which was operated at a high filtration flux of 30 L/m^2.h.

3.2.1. Mixed-SSMBR with hollow fiber membrane

Table 4 presents the average values and standard deviation of the influent quality, effluent quality and removal efficiency of the mixed-SSMBR during a 15-day operation. The system resulted in superior treated water quality. The organic removal was stable and excellent (DOC removal >96% and COD removal > 96%) with low TMP development of 18 kPa (Fig. 2). The high performance of nitrification (effluent NH_4-N < 0.04 mg/L) in this system indicated complete aerobic condition in the reactor. The complete PO_4-P removal (effluent PO_4-P<0.01 mg/L) also implied that enhanced biological phosphorus reremoval as well as excess phosphorus uptake could be achieved by phosphate accumulating organisms attached to the sponge cubes. Although the reactor kept totally oxic, denitrification was expected to occur inside the sponge. The series of kinetic experiments has been done to prove sponge could remove P and the acclimatized sponge cubes indeed could remove P even without the suspended growth and cell growth. The new findings will be published soon. In addition, the biomass attached to the sponge and in mixed liquid has contributed partially to remove phosphorus biologically because P is one of the essentials for biomass growth [4].

Table 4
Overall treatment performance (average values ± standard deviation) of mixed-SSMBR with 0.1 μm hollow fiber membrane (filtration flux = 30 $L/m^2.h$; backwash rate = 30 $L/m^2.h$; backwash = 1 min every half an hour; MLSS = 15 g/L; HRT = 1.4 hours; SRT = 30 days)

Parameter (mg/L)	Influent (mg/L)	Effluent (mg/L)	Removal efficiency (%)
DOC	140.7 ± 1.4	4.48 ± 0.45	96.8 ± 0.3
COD	361.9 ± 14.9	10.6 ± 3.5	97.6 ± 0.9
NH_4-N	17.2 ± 1.7	0.0 ± 0.0	99.9 ± 0.1
PO_4-P	3.8 ± 0.1	0.0 ± 0.0	100.0 ± 0.1

Mixed-sizes of sponge showed the excellent ability to reduce membrane fouling with low TMP development. Thus, MWD measurement was carried out to show which MW range of organic matter could be removed by the Mixed-SSMBR (Fig. 3). The synthetic wastewater consists of dissolved organic matters with the MW fractions of 1530, 730, 390 and 90 Daltons. Both of the Mixed-SSMBRs could remove the MW fractions (1530, 390 and 90 Daltons) completely from the wastewater. However, a small portion of low MW molecules (730 Daltons) still remained in the effluent of both systems. Mixed-SSMBR with hollow fiber membrane presented better results compared to the MW removal of Mixed-SSMBR with nonwoven membrane, and this is mainly due to the bigger pore size of the nonwoven membrane. The MWD results could correspond to the DOC and COD removals of the two mixed-SSMBRs.

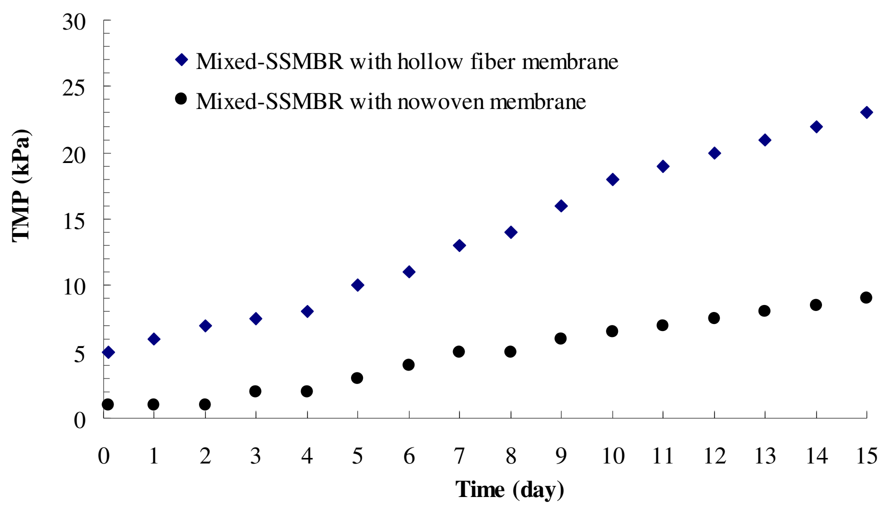

Fig. 2. TMP development in mixed-SSMBR system with two different membranes.

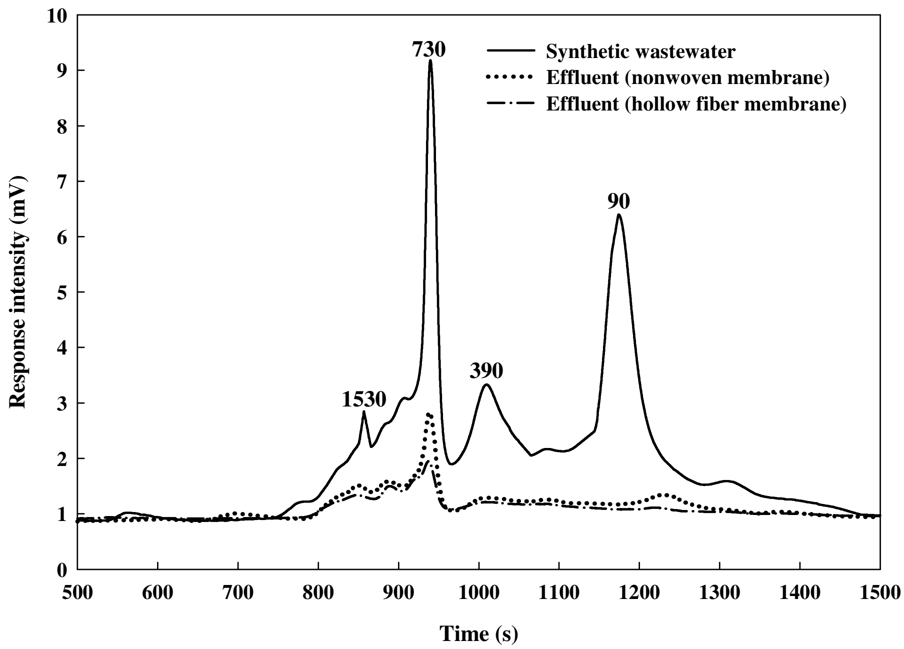

Fig. 3. The MWD of mixed-SSMBR system with different membranes (filtration flux = 30 L/m^2.h; backwash rate = 30 L/m^2.h; MLSS= 15 g/L).

3.2.2. Mixed-SSMBR with nonwoven membrane

Nonwoven (NW) fabric materials are extensively used for the removal of particles larger than 1μm in decontamination process, especially for airfiltration and sludge thickening. Recent research has considered nonwoven as a substitute for microporous membrane in MBR application because it has the merits of cheaper capital cost compared to membrane, high permeated flux and low filtration resistance [15]. According to a few previous researches on nonwoven membrane, the nonwoven membrane can not mitigate membrane fouling compare to polymer membrane. In addition, due to the tortuous nature of nonwoven membrane pores, they are likely to be more susceptible to internal fouling than polymer membrane and indicate greater internal fouling when operating at high rate [16, 17]. In this study, a flat sheet nonwoven membrane (KNH Enterprise Co. Ltd., Taiwan) was in conjunction with mixed-sponge to treat the synthetic wastewater. The removal efficiencies of DOC, COD, NH_4-N and PO_4-P are shown in Fig. 5. Although the pore size of nonwoven membrane is much bigger than the hollow fiber membrane, the results indicated that mixed-SSMBR with nonwoven membrane could exhibit high treated effluent quality (DOC removal >95%, COD removal >94%, PO_4-P removal >99%), especially, the absolute 100% nitrification gave nonwoven membrane another credit for ammonium nitrogen removal. As can be seen in Fig. 2, the development of TMP was lower than that of the hollow fiber membrane (e.g. 8 kPa compared to 18 kPa over 15 days of operation), which indicated that sponge addition could reduce nonwoven membrane internal fouling.

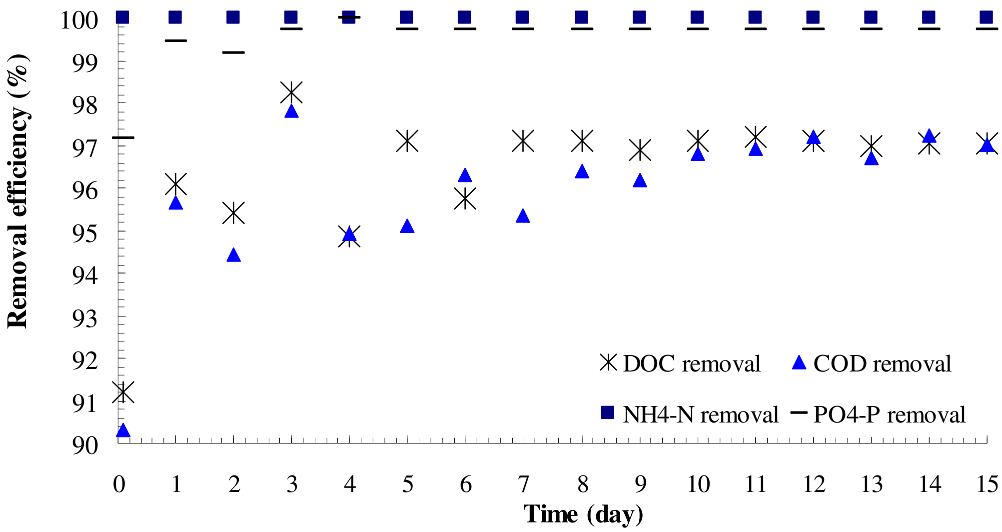

Fig. 5. The performance of mixed-SSMBR with 2 µm nonwoven membrane (filtration flux = 30 $L/m^2.h$; backwash rate = 30 $L/m^2.h$; backwash = 1 minute every hour; MLSS = 15 g/L; HRT = 6.7 hours; SRT = 60 day).

4. Conclusions

Three different sizes of polyester urethane sponge (S_{28-30}/45R, S_{28-30}/60R and S_{28-30}/90R) were evaluated through the performance in SMBR in terms of the removal efficiencies of NH_4-N, PO_4-P DOC, COD and biomass concentration. The results indicate that the denser the sponge, the more biomass can grow on the sponge. All of the sponge showed excellent DOC, PO_4-P removal ability whereas S_{28-30}/45R and S_{28-30}/60R could eliminate more than 99% NH_4-N in wastewater. The single size SSMBR system presented good results according to organic and nutrient removal. When mixed sponge in conjunction with hollow fiber SMBR and nonwoven SMBR, S_{28-30}/45R:S_{28-30}/60R:S_{28-30}/90R ratio of 1:1:1 exhibited superior NH_4-N removal (over 99.8%) associated with over 99% of PO_4-P removal and low TMP development during 15 days of operation. Two mixed sponge-SMBRs could remove the major MW fractions (90-1530 Daltons) presented in the synthetic wastewater. Besides, although further investigation is inevitable, nonwoven membrane could be a good alternative for polymer membrane.

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