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Performance of suspended and attached growth MBR systems in treating high strength synthetic wastewater

S. Jamal Khan [a,*], Shazia Ilyas [a], Sadaf Javid [a], C. Visvanathan [b], V. Jegatheesan [c]

[a] Institute of Environmental Science and Engineering, School of Civil and Environmental Engineering, National University of Sciences and Technology (NUST), Islamabad, Pakistan
[b] Environmental Engineering and Management Program, School of Environment, Resources and Development, Asian Institute of Technology, Klong Luang, Pathumthani, Thailand
[c] School of Engineering, James Cook University, Townsville, Queensland, Australia

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A B S T R A C T

The performance of laboratory-scale attached growth (AG) and suspended growth (SG) membrane bioreactors (MBRs) was evaluated in treating synthetic wastewater simulating high strength domestic wastewater. This study investigated the influence of sponge suspended carriers in AG-MBR system, occupying 15% reactor volume, on the removal of chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP), and compared it to that of SG-MBR. Results showed that the removal efficiencies of COD, TN and TP in AG-MBR were 98%, 89% and 58%, respectively as compared to 98%, 74% and 38%, respectively in SG-MBR. Improved TN removal in AG-MBR systems was primarily based on simultaneous nitrification and denitrification (SND) process. These results infer that the presence of small bio-particles having higher microbial activity and the growth of complex biomass captured within the suspended sponge carriers resulted in improved TN and TP removal in AG-MBR.

1. Introduction

In the last century global water demand has increased six folds, that is more than twice of the global population growth rate. Currently 40% of the world population (3 billion people) lives in conditions where water is scarce and this is expected to increase to 60% by the year 2025. If current rate of consumption remains the same (although rate of consumption might increase with time), then by the year 2025, 90% of fresh water resources will be consumed (Hoffmann, 2009). So with increasing pressure on water resources worldwide, now there is a need to consider recycling and reuse options for wastewater. For sustainable water reclamation and reuse, wastewater treatment technologies have been improved to produce better quality treated effluent and to satisfy more stringent regulations. In this context, compact wastewater treatment plants like membrane bioreactors (MBRs) are rapidly becoming popular and a promising technology for future wastewater treatment. MBR combines the aerobic degradation with a direct solid–liquid separation of activated sludge using either microfiltration or ultrafiltration (Stephenson et al., 2000). MBR process has been widely applied to treat various types of industrial and domestic wastewaters.

New and more stringent legislation, local water scarcity, the introduction of state incentives to encourage improvements in wastewater technology and particularly recycling, decreasing investment costs and increasing confidence in and acceptance of MBR technology are the main drivers for the implementation of MBR technology (Judd, 2006). MBR has many advantages over conventional wastewater treatment processes, i.e., activated sludge process. These include small footprint and reactor volume requirements, high effluent quality in terms of nutrient removal, good disinfection capability, higher volumetric loading, shock-load protection and less sludge production (Melin et al., 2006; Metcalf and Eddy, 2003). Membrane property, membrane module structure, operating conditions and bioreactor design are the main factors that affect the performance of the MBR (Wang et al., 2009).

Normally, intensive aeration is carried out in a submerged MBR for supplying oxygen to microorganisms and scouring of the membrane surface. However, one obvious drawback in the use of intensive aeration is poor removal of nitrogen in the submerged MBRs (Kimura et al., 2007). In order to overcome this problem a baffled reactor in which simultaneous nitrification/denitrification takes place within a single reactor could be a better option. MBR can achieve better nitrification as compared to conventional activated sludge (CAS) process because of high sludge age and low food/microorganisms (F/M) ratio which facilitates the growth of slow growing nitrifying bacteria. Better nitrification in MBR can also be attributed due to smaller floc size that allows greater mass

* Corresponding author. Tel.: +92 51 90854353; fax: +92 51 90854202.
E-mail addresses: s.jamal@iese.nust.edu.pk, sherjamal@hotmail.com (S. Jamal Khan).

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transport of nutrients and oxygen into sludge flocs (Gander et al., 2000).

The use of media in hybrid MBR could be a better alternative to conventional MBR which may increase the treatment performance by high biomass concentrations and reduce the membrane fouling (Leiknes and Ødegaard, 2001). Wilderer et al. (2000) compared different biofilm support materials (granular activated carbon, zeolite, blasted clay granules and Kaldnes carriers) in moving bed bioreactor (MBBR) as a temporary sink and source during peak loadings. Many researchers have worked with different growth media like polyurethane cubes, polystyrene beads, polyethylene carriers (Kaldnes), activated carbon (granular and powdered), polymers like MPE50 and sponge in MBR (Lee et al., 2006; Yang et al., 2006; Yoon and Collins, 2006). So the choice of the support media determines the efficiency and performance of the reactor in attached growth systems (Nguyen et al., 2010).

Simultaneous nitrification and denitrification (SND) occurs as a result of DO concentration gradient within microbial flocs arising due to diffusional limitations (Puznava et al., 2000). Yang et al. (2009a) have reported better nitrogen removal via SND at different COD/N ratio between 8.9 and 22.1. The introduction of media can make SND possible in the continuously aerated bioreactor and as a result, the total nitrogen removal could be enhanced. Monclús et al. (2010) have reported nitrogen removal efficiency in the range of 89–93% and phosphorus removal efficiencies in the range of 80–92% at COD/N ratio of 9.0. The COD/N ratio of influent is one of the most critical parameters for wastewater nitrogen removal process, because it directly affects functional microorganism population. It has been reported that by decreasing COD/N ratio below 9.0, removal efficiencies of nitrogen and phosphorous also decreased in conventional MBR (Fu et al., 2009).

Sponge has been considered as a reasonable attached growth media because it can act as a mobile carrier for active biomass resulting in improved organic and nutrients removal as well as reduce fouling of the membrane (Chae et al., 2004; Guo et al., 2009; Ngo et al., 2006; Psoch and Schiewer, 2006). Also the thick biofilm which is formed on the surface of foam is regularly removed by friction of individual sponge cubes with each other, while the fixed microorganisms within the sponge are very stable and active (Chae et al., 2004).

The aim of present study was to investigate the performance of a laboratory-scale attached growth membrane bioreactor (AG-MBR) and suspended growth membrane bioreactor (SG-MBR) in treating synthetic wastewater simulating high strength domestic wastewater. Sponge cubes as attached growth media were used in AG-MBR and its treatment performances and sludge characteristics were compared with that in SG-MBR.

2. Methods

2.1. Wastewater

Synthetic wastewater with COD concentration of 1000 mg/L and COD:N:P ratio of 100:5:2 was used to simulate high strength wastewater. The synthetic wastewater constituted glucose (1031 mg/L), NH_4Cl (191 mg/L) and KH_2PO_4 (87 mg/L) as primary nutrients, while $CaCl_2$ (10 mg/L), $MgSO_4{\cdot}7H_2O$ (10 mg/L), $FeCl_3$ (3 mg/L), $MnCl_2{\cdot}4H_2O$ (2 mg/L) as trace nutrients. $NaHCO_3$ (200 mg/L) was added to adjust pH between 7 and 8.

2.2. Reactor setup

Two identical acrylic reactors, each of 14 L effective volume were used as SG-MBR and AG-MBR to simultaneously conduct comparative study of MBRs with and with-out moving media. Each reactor was divided into three compartments with porous baffles. Hollow fiber membrane module (Mitsubishi Rayon, Japan) with filtration area of 0.2 m^2 and nominal pore size of 0.4 μm was submerged in the central compartment. The membrane-filtered effluent was extracted intermittently (10 min on/2 min off) with a suction pump (Master Flex, Cole-Parmer, USA) connected to the membrane module. Diffused aeration was used to meet the oxygen demand of microorganisms and for effective membrane scouring. SG-MBR and AG-MBR were run continuously for about 90 days.

2.3. Operating conditions

The operating conditions were similar for both the reactors. The hydraulic retention time (HRT) was kept at 8 h and the solids retention time (SRT) was maintained at 30 days. The aeration rates were maintained at 7 L/min (0.42 m^3/h) (4 L/min in membrane compartment and 3 L/min in side compartments). DO was maintained in the range of 3–5 mg/L. Organic-loading rate (OLR) and nitrogen loading rate (NLR) were 3 and 0.15 kg/m^3/d, respectively. The trans-membrane pressure (TMP) was used as an indicator of membrane fouling rate and was monitored continuously using data logging manometer (Sper-Scientific 840099, Taiwan). When the TMP reached 40 kPa membrane modules were taken out of operation and cleaned physically followed by chemical cleaning protocol as per the guidelines of the manufacturer (Mitsubishi Rayon, Japan). Initially, the membrane fibers were washed with tap water to remove the cake layer on the membrane surface followed by chemical cleaning using sodium hypochlorite (effective chlorine concentration of 3000 mg/L) and 4% (v/v) sodium hydroxide. The membrane module was immersed for 8 h in the solution. Following the immersion period, the membrane unit was thoroughly rinsed with de-ionized (DI) water to remove the chemical and this procedure was able to recover intrinsic membrane permeability to about 90–95%.

2.4. Attached growth media

Polyurethane sponge with a density of 30 kg/m^3, commercially knows as Unifoam from United Foam Industries (Pvt.) Ltd. Pakistan, was used as the moving media. Sponge cube of 1 cm^3 was selected as optimized earlier by Guo et al. (2010). The sponge cubes were added in the side compartments of AG-MBR proportional to 15% of the effective reactor volume.

2.5. Analytical methods

Chemical oxygen demand (COD), mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS), were analyzed according to Standard Methods (APHA et al., 2005). The protocol for determining attached biomass fixed in sponge was adapted from Yang et al. (2009a). Sponge cubes proportionate to 15% fill volume were taken out of the reactor in a 250 mL beaker and were re-suspended in 100 mL distilled water. Then, the sponge cubes were stirred with a magnetic stirrer at 300 rpm for 60 min. After squeezing, sponge cubes were returned back to the reactor. MLSS and MLVSS of the suspension was then determined according to Standard Methods (APHA et al., 2005). Soluble COD samples were obtained by settling the sludge sample for 30 min and filtering the sample with 1.2 μm filter (GF/C, Whatman, USA). Respirometric activity of the sludge was measured in terms of specific oxygen uptake rate (SOUR) by DO meter (YSI 5100, USA) having an built-in SOUR software. Diluted sludge (4000–5000 mg/L) was transferred into 300 mL BOD bottle. Immediately substrate, i.e., synthetic wastewater was added to obtain the ratio between COD concentration (S_o) and MLVSS (X_o) at around 0.14–0.16. DO probe with self stirring device (YSI 5010 BOD probe, USA) was immersed in the BOD bottle and SOUR values were determined directly using MLVSS values. Results are reported in mg O_2/g VSS/h. Dissolved oxygen and pH in the reactors were measured regularly by DO/pH meter (Oakton PD 300, USA). Sludge particle size distribution was analyzed using a particle size analyzer based on laser scattering principle (LA-300, Horiba, Japan) and the results were reported in percentage volume.

Total nitrogen (TN) in the influent was measured in the form of ammonia nitrogen (NH_4^+–N). Effluent TN was determined as a sum of NH_4^+–N, nitrite nitrogen (NO_2^-–N) and nitrate nitrogen (NO_3^-–N) in the effluent. NH_4^+–N, NO_2^-–N, NO_3^-–N and phosphate phosphorous (PO_4^{3-}–P) were determined by spectrophotometric method with DR 2400 (HACH, USA).

$$TN_{influent} = NH_4^+ - N_{influent}$$
$$TN_{effluent} = NH_4^+ - N_{effluent} + NO_2^- - N + NO_3^- - N$$

2.6. Sludge acclimatization

The activated sludge from I-9 Sewage Treatment Plant, Islamabad was acclimatized with synthetic wastewater for a period of 60 days in two sequencing batch reactors (SBRs) simultaneously, one with sponge media and the other one without media. The sludge acclimatization was ensured by COD removal efficiency above 90% and biological growth of microorganisms from 2000 to 6000 mg VSS/L without sludge wasting. After acclimatization, the sludges were transferred to their respective MBRs. The results presented here are based on 90 days steady-state MBRs operation.

3. Results and discussion

3.1. Performance evaluation

3.1.1. Evaluation of COD removal

The average COD removal efficiency in both reactors during the operating period is shown in Fig. 1a. It was observed that the COD concentrations in effluent were found to be 20.8 ± 12.9 and 18.9 ± 12.0 mg/L in SG-MBR and AG-MBR, respectively. The removal efficiencies remained high and throughout the operation period an average COD removal efficiency of 97.7 ± 1.3% was observed in SG-MBR and 97.9 ± 1.3% in AG-MBR at an average OLR of 3 kg/m^3/d. This data indicated that both the systems AG-MBR and SG-MBR were able to achieve high and consistent COD removal efficiency in treating high strength synthetic wastewater.

The reactor COD prior to membrane filtration known as soluble COD (sCOD) was also determined and it was found that both the systems exhibited above 95% sCOD removal efficiencies as shown in Fig. 1b. Thus, a comparison of effluent and soluble COD indicates effective biological degradation and the role of membrane filtration to remove soluble substrate was minimal as reported earlier (Jamal Khan and Visvanathan, 2008).

3.1.2. Evaluation of nitrogen removal

In wastewater treatment processes nitrogen could be removed in two ways: (1) assimilation into biomass (2) biological nitrification under aerobic conditions and denitrification process under depleted oxygen levels or anoxic conditions (Metcalf and Eddy, 2003). In this study, both the mechanisms of nitrogen removal were evaluated at COD/N ratio of 20 and nitrogen loading rate (NLR) of 0.15 kg/m^3/d. Since MLSS concentrations in both reactors were almost the same, the nitrogen removal via assimilation can be assumed as constant. Average concentrations with standard deviations of NH_4^+–N, NO_2^-–N, NO_3^-–N and TN in both reactors are summarized in Table 1. During the operation period, the NH_4^+–N removal efficiencies in both MBRs were 90.5% and 95.6% in SG-MBR and AG-MBR, respectively which implies slightly better nitrification in AG-MBR system. Guo et al. (2009) have reported NH_4^+–N removal more than 99% with 10% sponge media at an influent NH_4^+–N concentration of 15–20 mg/L. Wang et al. (2005) have also associated the increased NH_4^+–N removal with the biomass attached to the surface of the moving carriers as compared to that in the conventional MBR. Average NO_2^-–N and NO_3^-–N concentrations in SG-MBR were higher than that in AG-MBR. TN removal efficiency of SG-MBR was 73.9% as compared to 89.0% in AG-MBR. The better TN removal in AG-MBR than in SG-MBR is attributed to enhanced denitrification in AG-MBR. Although both reactors were kept completely oxic, denitrification is expected to occur inside the sponge cubes in AG-MBR.

Sponge microenvironment can be divided into two sub-microenvironments on the basis of DO gradient. DO concentration tends to decrease from periphery to the inside of the sponge, providing oxic/aerobic zone at periphery for heterotrophs and nitrifiers and inner anoxic/anaerobic zone for denitrifiers. Hence, nitrification takes place at peripheral zones and denitrification in the deeper zones of the sponge. This phenomenon is termed as simultaneous nitrification and denitrification (SND). Therefore, SND occurs in sponge media because of the biomass captured within sponge zones and DO gradient has resulted in better TN removal in

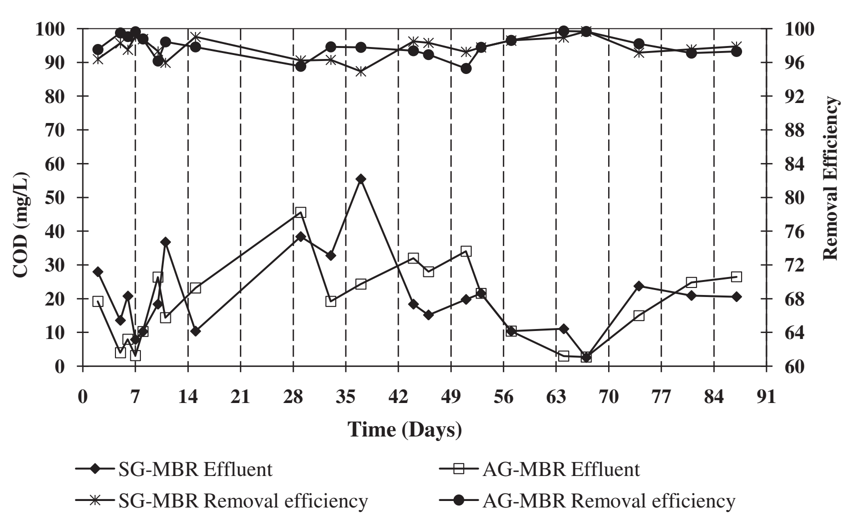

Fig. 1a. Effluent COD concentrations and removal efficiencies of SG-MBR and AG-MBR.

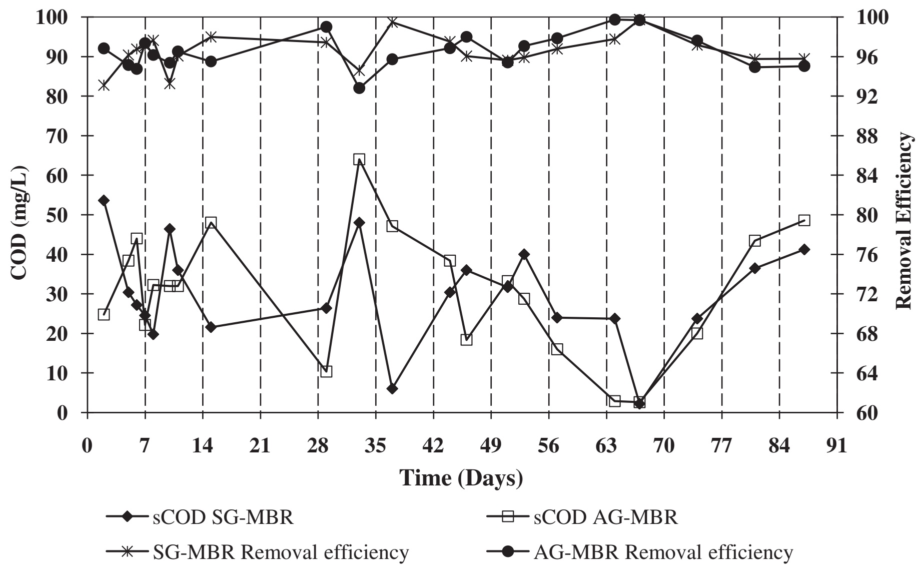

Fig. 1b. sCOD concentrations and removal efficiencies of SG-MBR and AG-MBR.

Table 1
Concentrations of NH_4^+–N, NO_3^-–N, NO_2^-–N, TN and PO_4^{3-}–P in effluent and respective removal efficiencies.

Parameter/system	Effluent concentrations (mg/L)		Removal efficiency	
	SG-MBR	AG-MBR	SG-MBR	AG-MBR
NH_4^+–N	4.5 ± 1.5	1.9 ± 1.0	90.5	95.6
NO_2^-–N	1.4 ± 0.9	0.3 ± 0.2	–	–
NO_3^-–N	6.7 ± 2.4	3.0 ± 1.9	–	–
TN	12.6 ± 1.2	5.2 ± 2.7	73.9	89.0
PO_4^{3-}–P	11.4 ± 1.1	8.1 ± 1.8	38.3	58.4

AG-MBR as compared to SG-MBR having no media. These results add strength to previous studies supporting SND phenomenon due to DO gradient along media depth (Yang et al., 2009a).

3.1.3. Evaluation of phosphorus removal

With influent PO_4^{3-}–P concentration of 20 mg/L, the average PO_4^{3-}–P in effluent of SG-MBR was 11.4 ± 1.1 mg/L while that in AG-MBR was 8.1 ± 1.8 mg/L corresponding to PO_4^{3-}–P removal efficiencies of 38.3% and 58.4% in SG-MBR and AG-MBR, respectively. As phosphorous is one of the essential nutrients for microbial growth, biomass in the suspension as well as attached to sponge has contributed to biological phosphorous removal. Better phosphorus removal in AG-MBR may be attributed to phosphorus accumulating organisms (PAOs) which may have developed within anoxic/anaerobic zones of the sponge media. Guo et al. (2010) have shown phosphorus removal of 77.8% in suspended MBR and 98% in sponge submerged MBR with 20% sponge volume at influent PO_4^{3-}–P concentration of 3.5–4 mg/L (low strength wastewater). The low influent PO_4^{3-}–P concentration could have been mostly assimilated by the microorganisms to meet their nutrient requirements and consequently both the MBRs exhibited relatively better nutrients removal.

3.2. Sludge characterization

3.2.1. General appearance of sludge and the concentrations of MLSS and MLVSS

Sludge color of both MBRs differs because of the addition of sponge media in AG-MBR. Sludge appeared khaki-brown in SG-MBR and yellow in AG-MBR. Same difference in color was reported by Yang et al. (2009a). MLSS and MLVSS of both the systems were determined regularly at SRT of 30 days. It was found that the MLSS and MLVSS concentrations in SG-MBR were 9.9 ± 1.7 and 7.6 ± 1.4 g/L, respectively. Biomass in AG-MBR was present in two forms, either suspended in reactor termed as AG-MBR (suspended) or attached to the sponge media termed as AG-MBR (attached). The biomass was entrapped only within the sponge cubes and apparently, there was almost no biofilm observed on the media surface due to physical scouring of the moving media against each other as well as against the walls of the reactor. MLSS of AG-MBR in suspended and attached forms was 8.7 ± 2.4 and 1.6 ± 0.9 g/L, respectively making a total of 10.3 ± 3.3 g/L. Whereas, MLVSS of AG-MBR in suspended and attached forms was 6.1 ± 1.6 and 0.9 ± 0.4 g/L, respectively making a total of 7.0 ± 2.0 g/L. The MLSS and MLVSS concentrations of SG-MBR, AG-MBR (suspended) and AG-MBR (attached) are shown in Fig. 2.

3.2.2. Microbial floc size and distribution

The particle size distributions were evaluated on the basis of mean floc diameter by its percentage volume in the sample. Fig. 3 shows particle size distribution of microbial flocs in both the systems and the floc sizes of SG-MBR were clearly larger than that of AG-MBR. The average mean floc size of the SG-MBR was

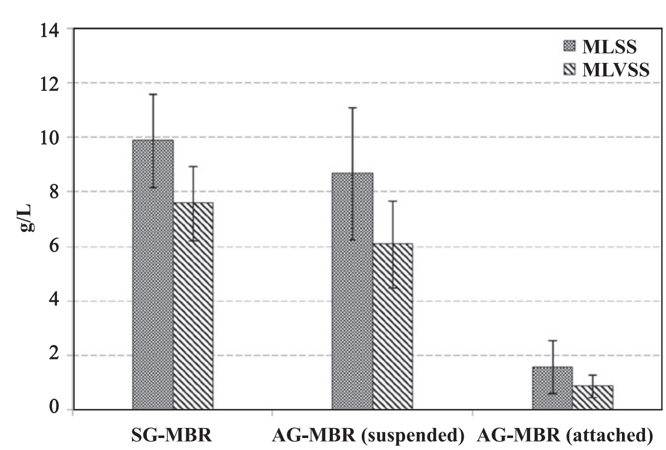

Fig. 2. Average MLSS and MLVSS (g/L) in SG-MBR and AG-MBR.

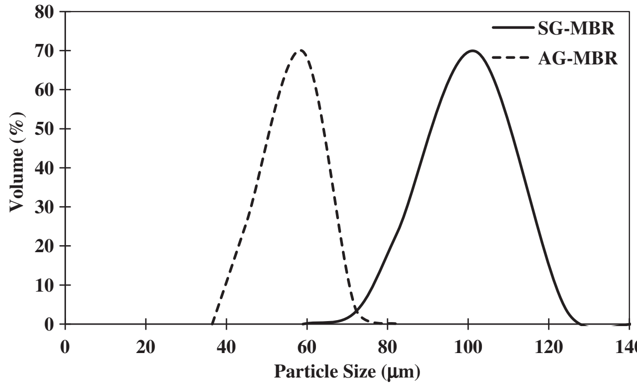

Fig. 3. Particle size distribution of microbial flocs in SG-MBR and AG-MBR.

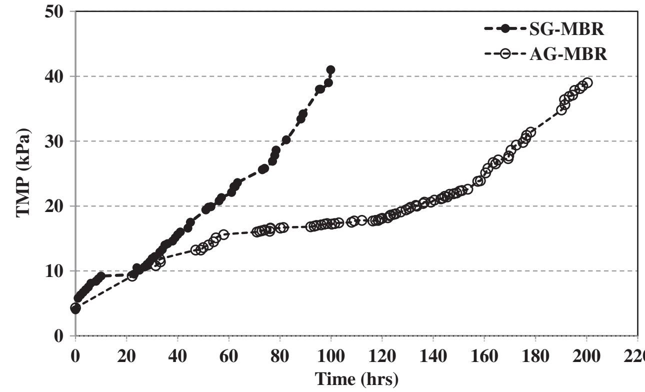

Fig. 5. Typical TMP profiles in SG-MBR and AG-MBR.

95.5 µm while that of the AG-MBR was 55.8 µm. The different size ranges of microbial flocs in both the MBRs are shown in Fig. 4. In SG-MBR, 70% of flocs were in the range of 88–116 µm whereas 67–77 µm was the dominant range of floc size in AG-MBR. Addition of media in AG-MBR could be responsible for small floc sizes attributed to abrasion of microbial flocs by moving media. Same phenomenon was depicted in Lee et al. (2006) study, in which particle size decreased significantly with increased media volume fraction and Sombatsompop et al. (2006) also reported similar observations. Huang et al. (2008) have also indicated that the sludge flocs are continuously broken up by the circulated suspended carriers in the bioreactor. However, this study contradicts with the findings of Yang et al. (2009b) who used new kind of non-wovens carriers, cylindrical in shape with outer diameter and height of 20 and 18 cm, respectively. The difference between this study and Yang et al. (2009b) study may be related to the size of the carriers and hence their number in the reactor as well. It can be inferred that size, shape and fill volume fraction of the carriers influence the particle size distribution in attached growth or moving bed MBRs.

3.2.3. Specific oxygen uptake rate

The SOUR values in this study were observed to be lower in SG-MBR than that in AG-MBR. The higher microbial activity in the AG-MBR could be responsible for the rapid consumption of the available substrate and nutrients and subsequently responsible for improved treatment performance as discussed earlier in performance evaluation section. In general, SOUR values reported in this study were relatively higher as compared to that reported in Satyawali and Balakrishnan (2009) because of higher S_o/X_o ratio. It was observed that for an average particle size of 95.5 µm, the average SOUR was 76.9 mg O_2/g VSS/h in SG-MBR and for average particle size of 55.8 µm, the average SOUR value was 115.9 mg O_2/g VSS/h in AG-MBR. It infers that the smaller particle sizes provide larger effective surface area for substrate utilization and oxygen transfer, thus exhibiting higher respirometric activity of microbes and consequently better overall treatment performance. The range of SOUR for OLR of 3 kg/m^3/day was found to be 104–138 mg O_2/g VSS/h for AG-MBR and 67–90 mg O_2/g VSS/h for SG-MBR.

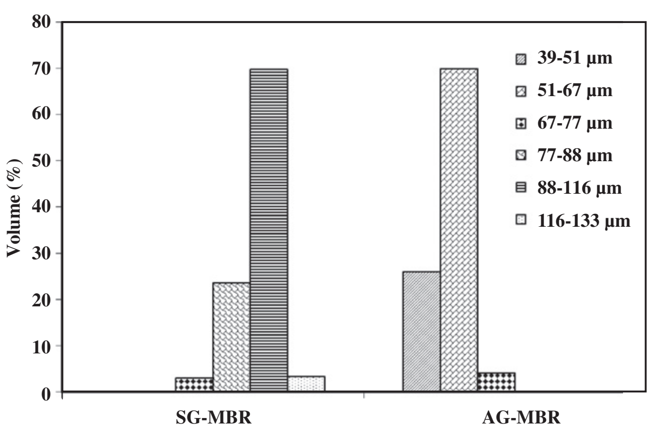

Fig. 4. Microbial floc size ranges in SG-MBR and AG-MBR.

3.3. Fouling behavior

In order to investigate the fouling behavior, the change in TMP with operational time was monitored at constant flux of 8.75 L/m^2 h (sub-critical flux) in both MBRs. The typical TMP profiles for SG-MBR and AG-MBR are shown in Fig. 5. Average fouling period for SG-MBR was observed to be 4 days while for AG-MBR it was observed to be 8 days. So the filtration duration was almost double in AG-MBR as compared to SG-MBR which is in agreement with most of the MBR studies comparing filtration performances between SG-MBR and AG-MBR (Huang et al., 2008; Lee et al., 2006; Sombatsompop et al., 2006). However, further investigation into factors affecting fouling tendencies in SG-MBR and AG-MBR is necessary.

The results infer that the nutrients removal as well as membrane filtration efficiencies were relatively enhanced in AG-MBR as compared to SG-MBR. Thus, this study reveals that sponge cubes with size 1 cm^3 can be considered as a media of choice in AG-MBR for effective organic and nutrients removal and prolong filtration duration keeping in view its economic viability.

4. Conclusions

This study investigated the treatment performance and sludge characteristics of sponge carrier fed MBR (AG-MBR) with conventional MBR (SG-MBR). It was demonstrated that AG-MBR exhibited better treatment performance with TN removal of 74% and 89% and PO_4^{3-}–P removal of 38% and 53% in SG-MBR and AG-MBR, respectively. COD removal in both MBRs was above 95%. Better nutrients removal efficiencies in AG-MBR could be attributed to the smaller floc sizes corresponding to higher microbial activity (SOUR) and diverse microbial consortium trapped within the complex sponge structure. Moreover, relatively less fouling tendency was observed in AG-MBR.

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