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Performance comparison of three different reactors (MBBR, MBR and MBBMR) for municipal wastewater treatment

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ABSTRACT

Membrane bioreactor (MBR) is an innovative wastewater treatment technology in which solid and liquid separation is done through membrane. Advantages of MBR technology involves better effluent quality, less foot print and less waste sludge generation. However, membrane biofouling is a major hindrance in the use of MBR that leads to clogging of membranes. Moving bed biofilm reactor (MBBR) encompasses use of carriers moving by aeration that provide surface to microorganism for attached growth. MBBR increases solid retention time, thus slowing down the growth rate of microorganisms. For better results, both technologies MBR and MBBR can be combined together to make moving bed biofilm membrane reactor (MBBMR), a hybrid technique which improves the removal efficiency, lessens sludge generation and minimizes biofouling. This study investigated the biofilm formation and influence of sponge and plastic carriers in MBBR and MBBMR. This study compared removal efficiency of organic matter and ammonia, effluent production and operational duration as well as waste sludge generation. The results showed COD, BOD and NH_4^+–N removal of all technologies above 90%, 95% and 98%, respectively. Hybrid MBBMR with sponge carrier showed the best performance for its high effluent production (34 L/d), longer operational duration (48 d, 193% improvement than simple MBR) and less waste sludge generation (44.2 kg dry sludge/10^6 L treated wastewater, 56% of MBR) compared with the other technologies, which makes it economically viable among other technologies.

Keywords: Membrane bioreactor (MBR); Moving bed biofilm reactor (MBBR); Moving bed biofilm membrane reactor (MBBMR); Performance evaluation; Wastewater treatment

1. Introduction

MBR has been prioritized from last two decades over the conventional procedures due to its great advantages and efficiency [1]. Membranes replace the clarifier in the wastewater treatment system. It can be operational at higher suspended biomass concentrations, resulting in long sludge retention times as well as low sludge production without problem of sludge bulking [2]. An advantage of MBR technology is that it is a single-step process in which MLSS concentration is easily maintained between 8,000 and 12,000 mg/L. However, activated sludge process (ASP) works between 2,000 to 3,000 mg/L because, greater MLSS concentration may cause settling problem in the sedimentation basin [3].

Another alternate to the ASP is the use of the moving bed biofilm reactor (MBBR) technology which was developed in 1980 in Norway [2]. In the new approach of treating wastewater, the MBBR corresponds to different variety of field. The operation of the MBBR is the same like ASP having freely moving carrier by air. The MBBR technology enriches biofilm attached on carriers which are freely moving in the reactor.

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These carriers are commonly made of plastic. As an outcome, MBBR gives positive aspects of both suspended and attached growth throughout the process because less biomass comes back from the clarifier tank [4]. Advantage of MBBR over ASP includes less footprint, less cleaning, and long solid retention time (SRT) for slow growing microorganisms [5]. In MBBR technique, submerged biofilm carriers subsequently separate solid and liquid. As a result, there is reduction of organic compound such as COD, BOD, etc. [6]. The attached growth media is an important input in the operation process. With the recent advancements, varieties of new media have been used, for example, plastic media (Kaldnes K1, K2, K3 and K5), wood chips, biodegradable polymer, activated carbon (AC), ceramic carriers, naturally occurring materials and polyvinyl alcohol gel carrier [7]. For the promotion of the attached biofilm growth, smooth cylinders, external fins and cylinders with internal crosses, rectangles and cubes are also employed [8].

For better results, both technologies MBR and MBBR can be combined together to make, so called, moving bed biofilm membrane reactor (MBBMR). Two different techniques can be utilized at the same time while operating the MBBMR process. Through this hybrid technique, the problems of the ASPs and membrane fouling by high biomass concentrations can be reduced [9]. This hybrid technique may improve the removal efficiency and also enhance the process of nitrification and denitrification. The MBBMR may have many advantages over the MBR such as higher organic loading rates, less sludge production rate, better oxygen transfer and higher biological reaction rates through the accumulation of high concentrations of active biomass [10]. The MBBMR system diminishes the issues of fouling. It also deals with the settle-ability concerns. It is attractive for users because it can overcome space constraints and efficient quality can be met through it [8].

This study investigates biofilm formation in MBR and influence of sponge and plastic suspended carriers in MBBR and MBBMR to improve performance of wastewater treatment by comparison of three technologies (MBR, MBBR and MBBMR) in terms of effluent production, operational duration and sludge generation. This aims to find out the easiest and the most efficient way to improve the performance of MBR by hybridization of MBBR and MBR. In order to make the performance comparison logical and easy, operational condition particularly hydraulic retention time (HRT) of membrane involving technologies was set half of that of conventional technologies (ASP, moving bed biofilm reactor) to have equal treatment efficiency from all the technologies applied in this study.

2. Materials and methods

2.1. Wastewater

Synthetic wastewater which simulates domestic wastewater was prepared in lab in which organic compound such as COD, BOD, phosphorus and ammonia were present. The synthetic wastewater contains several components, such as glucose (120 mg/L), peptone (90 mg/L), yeast extract (12 mg/L), $(NH_4)_2SO_4$ (96 mg/L), KH_2PO_4 (17 mg/L), $NaHCO_3$ (300 mg/L), $CaCl_2$ (2.40 mg/L), $MgSO_4·7H_2O$ (24 mg/L), $MnSO_4·5H_2O$ (2.16 mg/L), $FeCl_3·6H_2O$ (0.12 mg/L) [11].

2.2. Attached growth media

Two reactors were filled with 20% of Kaldnes1 (plastic carrier) and polyurethane foam (sponge carriers) separately as bulk volume of total volume of reactor as used in previous study [7]. Physical characteristics of the plastic carrier and sponge carrier and their photos are shown in Table 1 and Fig. 1, respectively

2.3. Membrane module

The membrane module was prepared with hollow fiber poly-vinylidene difluoride (PVDF) membrane provided by PHILOS Korea. Specification of membrane module for this research and its photo are shown in Table 2 and Fig. 2, respectively

2.4. Reactor and operational setup

Bioreactors made up of poly-acrylic plastic sheet were used in this study. ASP was operated first as control group (no media in the reactor) as shown in Fig. 3. And then MBBRs, MBR and MBBMRs were operated as research groups. Plastic carriers as attached growth media were added in the reactor to make MBBR1 and sponge carriers were added in the reactor to make MBBR2. These two reactors were operated in parallel. The size and operational condition were the same with those of ASP. For the membrane involving technologies, the same sized reactor was used for MBRs. No media, plastic and sponge carriers were added in each MBRs to make simple MBR, MBBMR1 and MBBMR2, respectively. The working volume of all reactors was 8 L each. At the top of the reactors floating valve was installed to maintain the level of mixed liquor in the reactor and synthetic wastewater was fed through gravity. Air diffusers were installed at the bottom of all reactors to provide oxygen to microorganisms and the mixed liquor was homogenized. The aeration rate was set at 3 L/min. Peristaltic pumps (Longer Pump BT100-1 L) were used for precise flow control of effluent, recycling sludge and backwash of membrane. Schematic diagrams of different treatment technologies are shown in Figs. 3 and 4.

The HRT was kept at 10 h for ASP and MBBRs and 5 h for MBR and MBBMRs. Intentionally two times longer HRT was maintained for ASP and MBBRs than for membrane involving technologies (MBR and MBBMRs) to achieve the same effluent quality in all different operations. ASP was not able

Table 1
Physical characteristics of plastic and sponge carriers

Parameters	Plastic carrier	Sponge carrier
Material	Polyethylene (PE)	Polyurethane (PU)
Shape	Cylindrical with external fins and internal cross	Cubic
Size	Φ 10 mm × H 7 mm	1 cm × 1 cm × 1 cm
Average weight	140 mg	40 mg
Specific surface area	5.0×10^{-3}(m^2/g)	–

Fig. 1. Plastic and sponge carriers.

Table 2
Specifications of membrane module

Specification	Description
Module design	Loop Type
Effective length/fiber	50 cm = 25 cm × 2 cm
No. of module/reactor	1
Surface area	578.04 cm^2/module
Flux	27 LMH
Max TMP	4.8 psi (33 kPa)

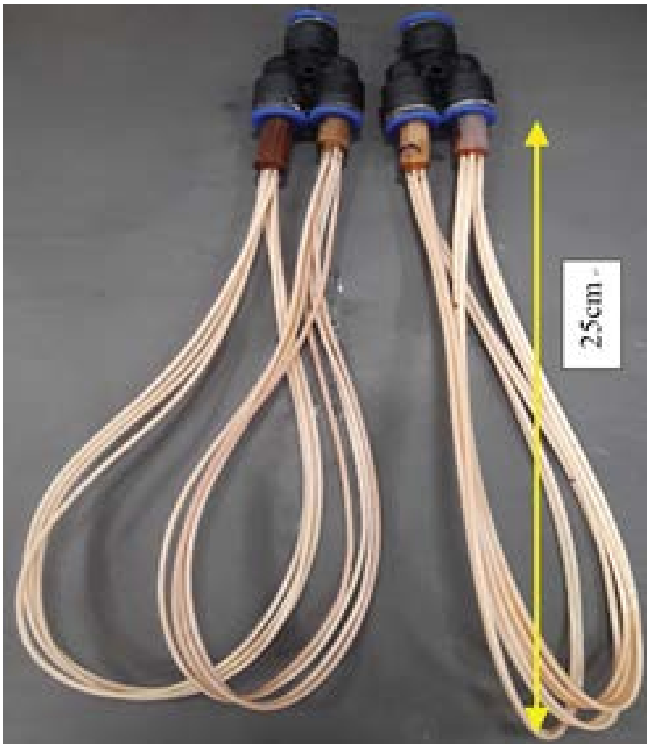

Fig. 2. Membrane module used in MBR and MBBMR.

to treat wastewater well enough in HRT of 5–8 h. Therefore extended HRT was applied for ASP and MBBRs. 100% sludge return flowrate (compared with influent flowrate) was used and some of the sludge was wasted from the sedimentation basin in ASP and MBBRs to maintain proper amount of biomass in the bioreactor. In the membrane involving technologies, a set of 10 min filtration and 1 min backwash was repeated. A part of mixed liquor was taken out from the bioreactor directly after checking mixed liquor suspended solids (MLSS) to maintain target MLSS concentration. Temperature of mixed liquor in the reactors was maintained 25°C–30°C throughout the research period. Totally six different operations were run to compare their performance. Simple MBR operation with backwash was run as one of research operation as well as control operation against two MBBMRs. Two hybrid MBBMRs were run as research operations that are expected to show better performance. MBBMRs had the same operational conditions with those of MBR except carriers in the bioreactor. MBBMR with plastic carriers was named as MBBMR1 and MBBMR with sponge carriers was named as MBBMR2. Operational conditions used in this research are summarized in Table 3.

2.5. Analysis of water quality and operational parameters

MLSS was done five times a week to check the growth of microorganisms. Transmembrane pressure (TMP) was monitored to check membrane fouling through super scientific data logging manometer at 1 min interval and it was downloaded to PC later. COD, BOD and NH_4^+–N was done three, two and two times a week, respectively. Water quality analysis was conducted according to the Standard Method for the Examination of Water and Wastewater [12]. After completion of each operations, suspended and attached biomass of each reactor were determined. Attached biomass on the carriers was washed by distilled water and those still remain inside carriers were detached by 1 h ultrasonication (Nexul, Model NXPC). All washed out biomass and washing water were taken into beaker and dried at 105°C. The dried solid was calculated as attached biomass. Waste sludge generation for each operation was determined from total volume

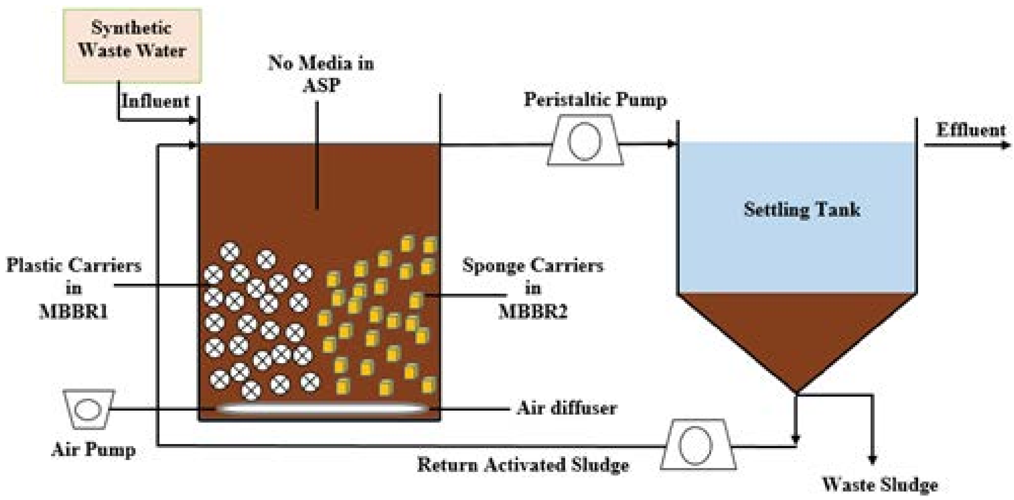

Fig. 3. Schematic diagram of ASP and MBBR plants.

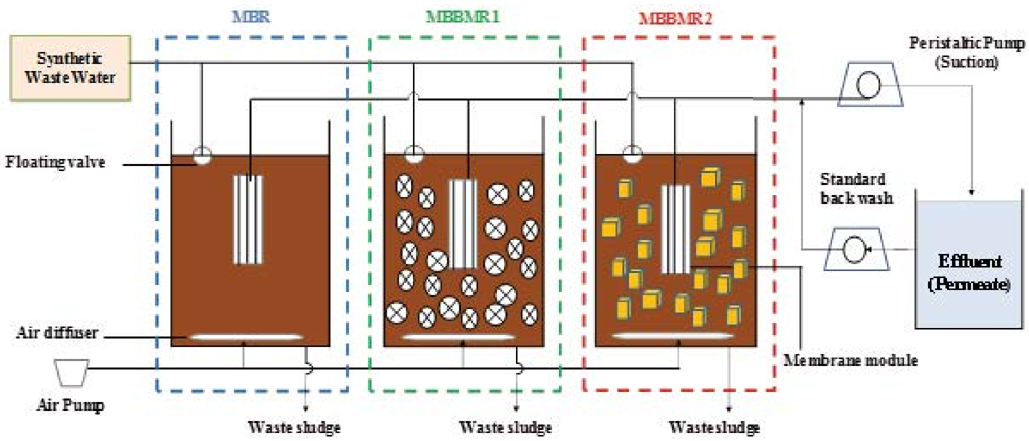

Fig. 4. Schematic diagram of MBR and MBBMR plants.

Table 3
Operational condition of different technologies used in this research

Type of operation	Carrier filling ratio (%)	Influent and effluent flowrate (mL/min)	Backwash flowrate (mL/min)	Return ratio[a] (%)	HRT (h)	SRT (d)	Target MLSS conc. (mg/L)
ASP (control)	–	13	–	100	10	7~8	3,000
MBBR1 (plastic)	20	13	–	100	10	8~9	3,000
MBBR2 (sponge)	20	13	–	100	10	9~10	3,000
MBR	–	26	52	–	5	17~19	8,000
MBBMR1 (plastic)	20	26	52	–	5	21~23	8,000
MBBMR2 (sponge)	20	26	52	–	5	31~33	8,000

[a]Sludge return flowrate compared to influent flowrate.

of repeated sludge withdrawal and MLSS concentration of the sludge.

2.6. Statistical analysis

In order to compare the performance of different technologies on the basis of the same effluent quality, HRT of ASP and MBBRs was set two times longer than that of membrane involving technology as mentioned in section 2.4. To confirm the pre-condition of producing the same removal efficiencies, statistical analysis was conducted to test whether the removal efficiencies of different technologies were equal or not. To accomplish this, several statistical tests, that is, ANOVA (analysis of variance) test, normality test

(Kolmogorov–Smirnov, Shapiro–Wilk) and Kruskal–Wallis test [13] were performed by SPSS (Statistical Package for the Social Sciences) software.

3. Results and discussion

3.1. Removal efficiency comparison and statistical analysis

All the operations showed fairly good removal efficiency. COD, BOD, NH_4^+–N removal of all technologies were above 90%, 95% and 98%, respectively. The removal efficiency of COD, BOD and NH_4^+–N across six operational groups are shown in Figs. 5–7, respectively. These graphs seem to have some differences in removal efficiencies. MBBMR1 and 2 seem slightly more stable than others. In order to check if the pre-condition (the same removal efficiencies for all the operations) was met or not, statistical analyses were conducted.

Averages of more than two sample groups can be tested whether there is meaningful difference between groups by

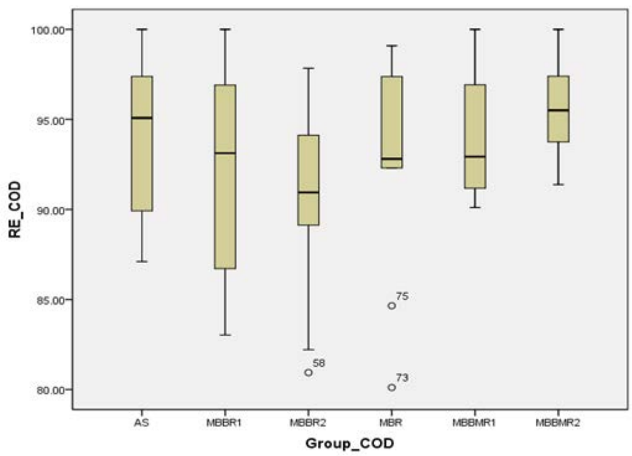

Fig. 5. Distribution of removal efficiency of COD across all operations.

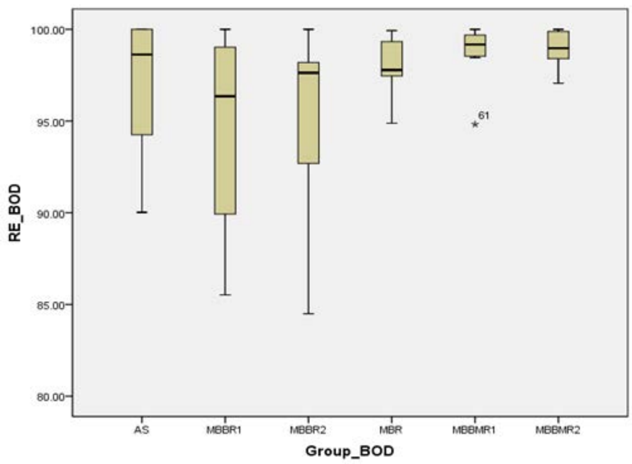

Fig. 6. Distribution of removal efficiency of BOD across all operations.

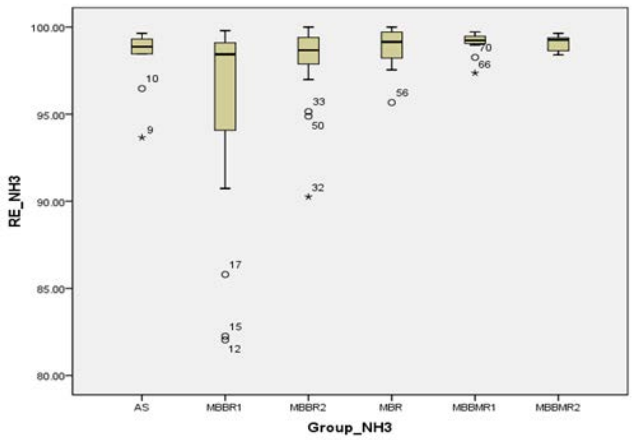

Fig. 7. Distribution of removal efficiency of NH_4^+–N across all operations.

one-way ANOVA (analysis of variance) test. But this ANOVA test has assumptions to be applied such as normality, homogeneity of variances of each group, independence of samples [13]. Therefore normality was tested by Kolmogorov-Smirnov and Shapiro–Wilk test before applying ANOVA test. The results of normality test for COD, BOD and NH_4^+–N were shown in Table 4. Some of the significant values in Kolmogorov–Smirnov and Shapiro–Wilk test are greater than 0.05, which mean the data do not follow normal distribution. Not all of them follow normal distribution, therefore, one-way ANOVA test cannot be applied here. Because of non-normality of data, non-parametric counter part of ANOVA, which does not require the normality assumption, that is, Kruskal–Wallis test was applied for testing difference between groups instead of one-way ANOVA [14].

The results of Kruskal–Wallis test were summarized in Table 5. p-value of COD, BOD and NH_4^+–N are all greater than 0.05 which means all the sample distributions are equal. It can be concluded that the removal efficiencies of all six operations have no significant difference. MBR, MBBMR1 and MBBMR2 did not have adverse effect on effluent quality in spite of short HRT. And ASP, MBBR1 and MBBR2 also showed good removal efficiencies to be equal to those of MBR, MBBMR1 and MBBMR2 because of long HRT. So, it was statistically proved that the pre-condition in this research (the same removal efficiencies for all the operations) was met.

3.2. Performance evaluation

Performance of wastewater treatment technology can be evaluated in aspect of effluent quality (removal efficiency), amount of treated water (effluent production), operational duration of membrane module (in case of membrane technology) and waste sludge generation. In this research, treatment efficiencies of all different technologies were equally good, and no significant difference was found. So, the overall performance comparison was made in aspect of effluent production, operational duration of membrane module, biomass holding capacity and waste sludge generation. All the data were obtained when the operations were running at steady state.

Table 4
Normality test results

Water quality parameter	Operations	Kolmogorov–Smirnov			Shapiro–Wilk		
		Statistic	Df	Significance	Statistic	Df	Significance
COD	ASP	0.190	12	0.200[a]	0.917	12	0.266
	MBBR1	0.132	29	0.200[a]	0.927	29	0.046
	MBBR2	0.113	25	0.200[a]	0.946	25	0.205
	MBR	0.273	9	0.052	0.878	9	0.149
	MBBMR1	0.208	14	0.103	0.907	14	0.141
	MBBMR2	0.108	14	0.200[a]	0.964	14	0.780
BOD	ASP	0.246	9	0.125	0.796	9	0.018
	MBBR1	0.244	19	0.004	0.844	19	0.005
	MBBR2	0.238	19	0.006	0.861	19	0.010
	MBR	0.216	5	0.200[a]	0.936	5	0.638
	MBBMR1	0.328	9	0.006	0.721	9	0.002
	MBBMR2	0.163	9	0.200[a]	0.917	9	0.371
NH_4^+–N	ASP	0.343	10	0.001	0.720	10	0.002
	MBBR1	0.309	20	0.000	0.703	20	0.000
	MBBR2	0.231	21	0.005	0.724	21	0.000
	MBR	0.273	7	0.125	0.844	7	0.108
	MBBMR1	0.284	12	0.008	0.780	12	0.006
	MBBMR2	0.206	12	0.171	0.901	12	0.164

[a]This is a lower bound of the true significance.

Table 5
Removal efficiencies of COD, BOD and NH_4^+–N with Kruskal–Wallis test results

Operation name	COD			BOD			NH_4^+–N		
	Median	stdev	*n*	Median	stdev	*n*	Median	stdev	*n*
ASP	95.1	4.4	12	98.6	4.1	9	98.9	1.9	10
MBBR1	93.1	5.6	29	96.3	5.3	19	98.4	5.8	20
MBBR2	90.9	4.7	25	97.6	4.6	19	98.7	2.3	21
MBR	92.8	6.3	9	97.8	2.0	5	99.1	1.6	7
MBBMR1	92.9	3.4	14	99.2	1.6	9	99.2	0.7	12
MBBMR2	95.5	2.6	14	99.0	1.1	9	99.3	0.4	12
Kruskal–Wallis Test	p-value = 0.141 > 0.05			p-value = 0.089 > 0.05			p-value = 0.093 > 0.05		

3.2.1. Effluent production

Effluent productions of each operation during unit of time (daily production, daily treatment capacity) are shown in Fig. 8. Conventional technology (ASP, MBBRs) produced 18.7 L of effluent per day while membrane involving technologies (MBR, MBBMRs) produced 27.2 L of effluent per day (net production). Membrane involving technologies actually treated 34 L of wastewater per day, however, as 20% of total production (6.8 L/d) was used for standard backwash, so net production was smaller than total. Membrane involving technologies were superior to conventional ones in terms of effluent production because they can be operated at lower HRT than conventional ones while maintaining equally good effluent quality.

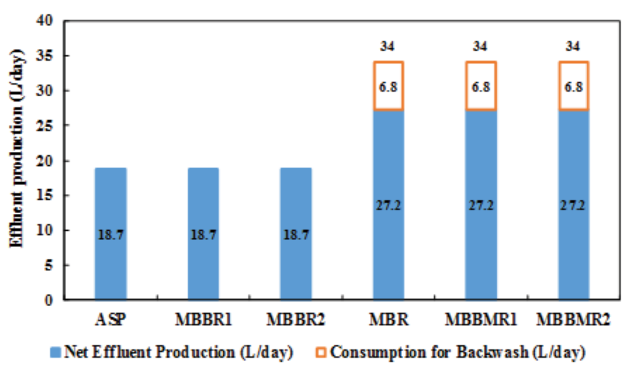

Fig. 8. Effluent production of all different technologies.

3.2.2. Operational duration

One cycle of each operation continued from the time that new membrane module was immersed until the time the membrane module got fouled (when TMP reached to maximum, 4.8 psi = 33 kPa) under steady-state condition of treatment. Per cycle operational durations of membrane involving technologies were compared as shown in Fig. 9. Simple MBR without any carriers got fouled after 16.4 d, MBBMR1 with plastic carriers got fouled after 37.3 d and MBBMR2 with sponge carriers got fouled after 48 d. MBBMR1 worked 20.9 d longer (128% improvement) and MBBMR2 worked 31.6 d longer (193% improvement) than MBR. Although daily net effluent production (27.2 L/d) was the same for MBR, MBBMR1 and MBBMR2, operational duration per cycle is quite different. Longer operational duration means it needs less recovery cleaning of membrane modules. Frequent recovery cleaning will cost time and chemical and furthermore reduce life time of membrane [15]. So in terms of operational duration, MBBMR2 was superior to others. It was considered that the moving sponge carriers can scour the surface of membrane and detach the biofilm from the membrane better than plastic carriers. Therefore it can be suggested that hybrid MBBMR2 with sponge carrier was a better technology than others.

3.2.3. Biomass in the bioreactor and waste sludge generation

Fig. 10 shows the suspended and attached biomass of different operations. MBBR1 and MBBR2 had 25.3 and 28.7 g of biomass in the reactor, respectively, while ASP had only 18.1 g. MBBMR1 and MBBMR2 had 69.8 and 67.2 g of biomass in the reactor, respectively, while MBR had 63.7 g. It was observed that membrane involving technologies had more biomass because higher MLSS was maintained as designed. And it was observed that carrier involving technologies (MBBR1, 2, MBBMR1 and 2) have more total biomass in the reactor because attached biomass was added on top of suspended one. When plastic carriers and sponge carriers were compared (MBBR1 vs. MBBR2; MBBMR1 vs. MBBMR2), sponge carriers had more attached biomass. Cheaper and easily available sponge carriers showed better biomass holding capacity than expensive commercial plastic carriers. It could be because sponge carriers have greater surface area inside the structure of sponge. More biomass in the reactor is beneficial since it can treat more wastewater within short time and leads longer SRT as well as less sludge generation. Picture of attached biomass on plastic and sponge carriers are shown in Fig. 11.

After wastewater treatment, by-product in form of sludge is generated which needs additional cost to treat. Therefore a technology that generated less sludge is preferable. Waste sludge generated during the operations of different technologies was determined and shown in Fig. 12. The amount was calculated based on the amount of withdrawal of sludge to maintain target MLSS concentration for each operation per the amount of wastewater treated during the period. Waste sludge generation of MBR,

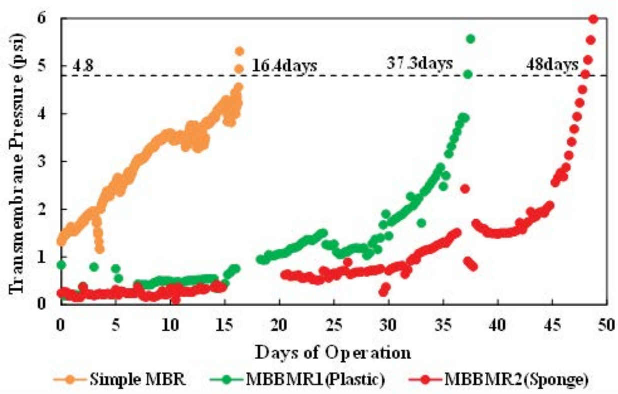

Fig. 9. TMP profile of simple MBR, MBBMR1 and MBBMR2.

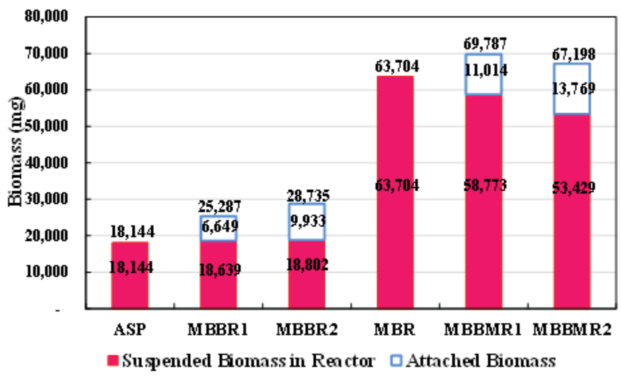

Fig. 10. Comparison of biomass in different operation.

Fig. 11. Attached biomass on the plastic and sponge carriers.

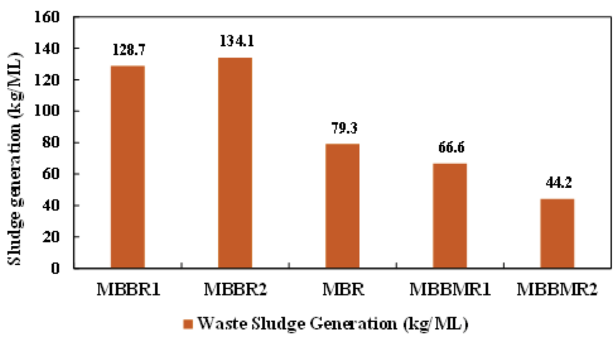

Fig. 12. Waste sludge generation of different technologies.

MBBMR1 and MBBMR2 was smaller than MBBR1 and MBBR2. Out of all, MBBMR2 generated the least sludge (44.2 kg dry sludge/10^6 L treated wastewater). So, in terms of by-product generation, MBBMR2 with sponge carrier is superior to others.

4. Conclusion

All the operations representing ASP, MBBRs, MBR and MBBMRs showed fairly good removal efficiencies for COD, BOD, NH_4^+–N to be above 90%, 95% and 98%, respectively. No significant difference was found in all technologies in effluent quality under the operational condition of this research and it was confirmed by statistical analysis (Kruskal–Wallis Test).

Membrane involving technology (MBR, MBBMRs) can treat more wastewater than conventional ones (ASP, MBBRs) while maintaining equally good treatment efficiency. A half HRT (5 h) of the membrane involving technology did not deteriorate effluent quality as compared with that of double HRT (10 h) of conventional ones.

Physical cleaning effect by sponge carriers was proven to be one of the useful options for improving MBR performance by mitigating biofouling as moving carriers physically wash biofouling layer from the membrane. Operational duration of MBBMR with sponge carrier (48 d) was longer than that of simple MBR (16.4 d) and MBBMR with plastic carrier (37.3 d). Simple addition of sponge carrier into bioreactor of MBR lead 193% improvement of operational duration.

Sponge carrier was proven to be useful to increase biomass in bioreactor and to reduce waste sludge generation. Biomass holding capacity of sponge carrier (attached biomass, 13.8 g/reactor) was greater than that of plastic carrier (11.0 g/reactor) and the waste sludge generation of MBBMR with sponge carrier (44.2 kg dry sludge/10^6L treated wastewater) was smaller than that of simple MBR (79.3 kg/10^6 L) and MBBMR with plastic carrier (66.6 kg/10^6 L).

It was concluded that hybridization of MBR and MBBR with sponge carrier was the best method to improve performance of wastewater treatment among the evaluated methods in this research as it had high effluent production, the longest operational duration and the least waste sludge generation, which makes it more economically viable among other technologies.

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