New MBBR Carriers for High Loading Applications

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ABSTRACT

In Hong Kong, the food and beverage industry generates large amount of industrial effluents with high COD concentrations of around 3,000-4,000 mg/L. The industrial effluent is required to be properly pretreated to <2,000 mg/L COD before discharge to municipal sewage treatment plants. Nevertheless, the space limitation in these factories imposes a great challenge to the application of biological wastewater treatment processes.

This study investigated the application of MBBR process in treating the food and beverage industrial effluents to meet the pretreatment requirement in Hong Kong, focusing on identifying the maximum organic loading that the MBBR process can handle so as to develop the most compact MBR configuration. New mobile carriers were specially designed to increase effective specific surface area and optimize the carrier configuration. Lab scale set-up with artificial soymilk at 3,000 mg/L was employed for testing the MBBR system with new developed carriers. Also, the carrier surface properties were modified with different physical-chemical methods to increase surface roughness and change the surface contact angle for the purpose of enhancing the biofilm build-up.

Three new carrier designs were developed and tested. Laboratory studies showed that all the three carriers have the same SCOD removal based on surface area organic loading rate (SALR). The carrier with corner fin has the greatest specific surface area (615 m^2/m^3) which can be operated at very high loading up to a maximum of about 46 kg SCOD/m^3.d (equivalent to about 175 g SCOD/m^2.d) achieving about 54% SCOD removal. The study also showed that the surface roughness and hydrophilicity would affect the biofilm build-up on the carrier surface. The carrier surface roughness could be increased from 336 nm to 1,360 nm by adding foam into the carrier base material, which may be a possible method to achieve a faster start-up of MBBR.

As compared with activated sludge (AS) and MBR, MBBR process using the new carrier would require a retention time of 1.6 hrs only for the bioreactor, offering the most compact process for pretreating the high strength food and beverage industrial effluents before discharge into the foul sewers. This could be a viable solution to assist the local food and beverage industry to achieve the compliance in the Hong Kong context.

1. INTRODUCTION

Owing to the growing population and the continuous industrial production expansion, many wastewater treatment facilities encounter the problems of increasing loading. Many of them need to be expanded to provide additional capacity but are constrained by the limited space. As a result, compact treatment processes are developed to address the site constraints faced by municipal and industrial wastewater treatment facilities. One of these processes is the Moving Bed Biofilm

Reactor (MBBR). Mobile carriers have been proven to be effective media in biofilm processes. (Ødegaard et al. 1994)

In Hong Kong, there exist many food catering, food and beverage production plants that discharge large amount of industrial effluent with high COD (Chemical oxygen demand) concentrations, normally around 3,000-4,000 mg/L. The industrial effluent is required to be properly treated to comply with the "Standards for effluent discharged into foul sewers leading into government sewage treatment plants". In terms of COD, the discharge limit is normally ≤2,000mg/L, which means no full treatment is required. In general, common physio-chemical treatment, like chemical coagulation or electro-flocculation, is not adequate to achieve the required COD reduction. Biological treatment is definitely the most effective way to meet the treatment requirement. Nevertheless, the space limitation in Hong Kong, especially for those factories located in multi-storey buildings, imposes a great challenge to the application of biological wastewater treatment processes. Moreover, the safety and odour concerns as well as the relatively long retention time render the anaerobic processes unsuitable to be used. Therefore, compact aerobic biological treatment processes, like MBBR, may offer the most viable solution to assist the local industry to achieve the compliance in the Hong Kong context.

Being one of the biofilm processes, the MBBR process is regarded to be compact, robust and easy to operate. It is a continuous flow process which uses small floating carriers to provide sites for active bacteria attachment in a suspended medium [1]. This allows a higher concentration of active biomass to be maintained in the reactor for biological treatment without increasing the reactor size. This provides a higher treatment capacity within a given reactor volume, resulting in a smaller footprint compared to a conventional activated sludge process. Apart from the compactness, the unique features of MBBR include:

a. Much lower MLSS than conventional activated sludge, resulting in lower sludge loading to the final clarifier and more choices in the methods of final clarification;
b. No sludge return from the final clarifier to the bioreactor tank;
c. More specialised biomass developed in different compartments of the bioreactor train.

This study will investigate the application of MBBR process in partially treating the industrial effluent from food and beverage industry to comply with the required discharge standard in Hong Kong. Focus will be put on identifying the maximum organic loading that the MBBR process can cater for so as to develop the most compact configuration of the MBBR system.

Besides the system configuration, MBBR process in fact heavily relies on the mobile biofilm carriers which move freely in the reactor tanks. Therefore, the reactor performance depends not only on the reactor volume, but also on the effective specific surface area of the carrier type [2]. In order to fit for the targeted high loading applications, new mobile carriers will also be specially designed and tested in this study. For most of the commercially available mobile carriers, the size of compartments inside the carrier are not even, which may cause small compartments more easily clogged in treating high strength organic wastewater under high loading applications. The clogging would hinder the dissolved oxygen and soluble substances from diffusing into the biofilm, affecting the biological activity and biomass growth. It would also lead to poor pollutant removal performance. Long restoration period would be required to recover the treatment performance after the occurrence of biomass overgrowth on the carriers. Besides, it often takes time to grow biofilm on MBBR carrier surface, leading to long system start-up time. Hence, new mobile carriers are to be developed aiming at tackling these shortfalls.

2. MATERIALS AND METHODS

2.1 Development of New Mobile Carriers

When developing new carriers, both geometric design and surface properties of the carriers would be taken into consideration.

For the geometric design, the protected surface area for biofilm growth, the void space and size of the MBBR carrier are all inter-related and need to be considered. New geometric design would aim at maximizing the protected surface area but still maintaining adequate size of void space to avoid clogging problem under high loading conditions. Computer-aided design was used to work out some optimized carrier design options for testing so as to identify the best geometric design.

It is assumed that biomass adhesion may be promoted by changing the surface roughness and hydrophilicity of the carrier surface. While surface roughness is a direct measurement, hydrophilicity is represented by the contact angle with water. Smaller contact angle implies better hydrophilicity. It is assumed that biomass will grow easier on rougher surface with higher hydrophilicity. Three methods were tried to modify the carrier surface properties. Two types of materials were blended with raw HDPE during the carrier fabrication: foam addition (3% nitrogen gas) and calcium carbonate (10%) for improvement of carrier surface roughness. Plasma surface treatment was applied on the new carrier for improvement of the surface hydrophilicity. The surface roughness and contact angle of the carrier samples were measured and compared with an unmodified carrier sample to evaluate the degree of improvement.

2.2 Procedures for Biofilm Build up

Artificial wastewater was prepared using diluted soymilk in order to come up with the desired high organic loadings. Activated sludge was added into the reactors to provide the seed to stimulate bacteria growth and adhesion. The carriers suspended in the solution are used as the attached growth medium for microorganism. Theoretically, microorganisms (in activated sludge) will attach to the carrier surface and develop biofilms. Biofilm-associated cells can be differentiated from their suspended counterparts by generation of an extracellular polymeric substance (EPS) matrix. Attachment is a complex process regulated by diverse characteristics of the growth medium, substratum, and cell surface [3].

The reactors were initially operated in batch mode (SBR mode). Diluted soymilk with SCOD of about 1,000 mg/L was added into the reactor as feeding solution twice per day to achieve an F/M of 0.8 kg/kg.d. During the experiment, SCOD removal efficiency was checked daily to monitor the biofilm build-up progress. Two weeks later, the reactors were switched to continuous running mode, feeding with wastewater at SCOD of about 3,000 mg/L to speed up biofilm growth.

2.3 Method of Quantifying the Biomass

The biofilm quantification was calculated by weighting the carriers. 5-10 carriers were taken from the reactor, dried at 105°C overnight and weighted. Then, the carrier samples were soaked into 6% NaOH solution until all biofilm was detached and scraped clean. The carrier samples were dried again at 105°C and weighted. The difference of the dry weights before and after alkaline cleaning represents the amount of biofilm [4].

2.4 Experimental Set-up for Carrier Comparison

Each type of carriers with well built-up biofilm was transferred into a 12 L rectangular MBBR reactor for performance comparison and evaluation. The carrier filling ratio was kept at 42% for all the reactors which were run in parallel and shared a common feed tank. The surface area organic loading rate (SALR) started from a normal level of around 24 g SCOD/m^2.d with a corresponding volumetric loading rate (VLR) of around 6 kg SCOD/m^3.d (12 hr HRT) and was gradually increased to 240 g/m^2.d with a VLR of 60 kg SCOD/m^3.d (1.2 hr HRT) by means of increasing the feed flow rate to the reactors so as to reach stressed loading level finally.

Diluted soymilk was chosen as the feeding solution in order to represent the industrial effluent from the food and beverage industry. On-line pH adjustment was installed for maintaining neutral pH in the MBBR reactors. DO was maintained at over 2.0 mg/L for each individual reactor. Air mixing was provided to keep the carriers moving inside the reactor. The treated effluent was collected from the overflow pipe of each reactor for analysis.

3. RESULTS AND DISCUSSION

3.1 Different Geometric Designs for New MBBR Carriers

Three new geometric designs were developed for the carrier (Figure 1):

(i) No fin design - uniform hexagonal cells with side length of 2.3 mm and without any fin which fill up a circular carrier of diameter 25 mm.

(ii) Corner fin design - three layers of uniform hexagonal cells with side length of 2.6 mm and three fins located at the alternate corners of each cell which fill up a circular carrier of diameter 22 mm.

(iii) Side fin design - same as the corner fin design except for the location of the fins which are located on the alternate sides of each cell.

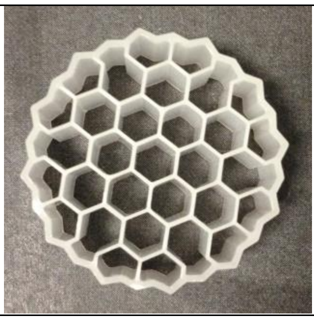
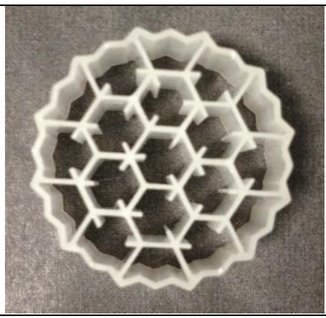
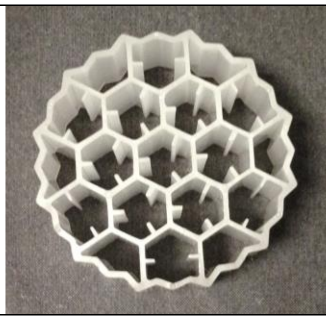
No fin	Corner fin	Side fin
		

Figure 1: New carrier designs

The specifications of the new carriers are provided in Table 1.

Table1. Specifications of different carrier designs

Parameters	No fin	Corner fin	Side fin
Carrier diameter (mm)	25	22	22
Bulk density (number of carriers/liter)	130	168	168
Specific surface area (m^2/m^3)	547	615	613

3.2 Performance Evaluation of Different Carriers

The new carriers were tested under different loading which was increased step by step. At each loading, the experiment was run for about one week before proceeding to a higher loading. Figure 2 and 3 show the SCOD removal rates at different SALR and VLR respectively. In this study, SALR started from about 24 g SCOD/m^2.d with corresponding VLR of around 6 kg SCOD/m^3.d. At this loading, the three carriers perform equally well. The figures show the clear trend that SCOD removal rate increases linearly with the increasing loading until it reaches the stressed loading and then it seems to level off or even decline gradually. However, the data points are quite scattered especially under the stressed loading conditions. It reflects that the treatment performance is rather fluctuating under the stressed loading and may be limited by various factors, such as reduction of HRT, restricted diffusion inside the biofilm and sloughing of biofilm.

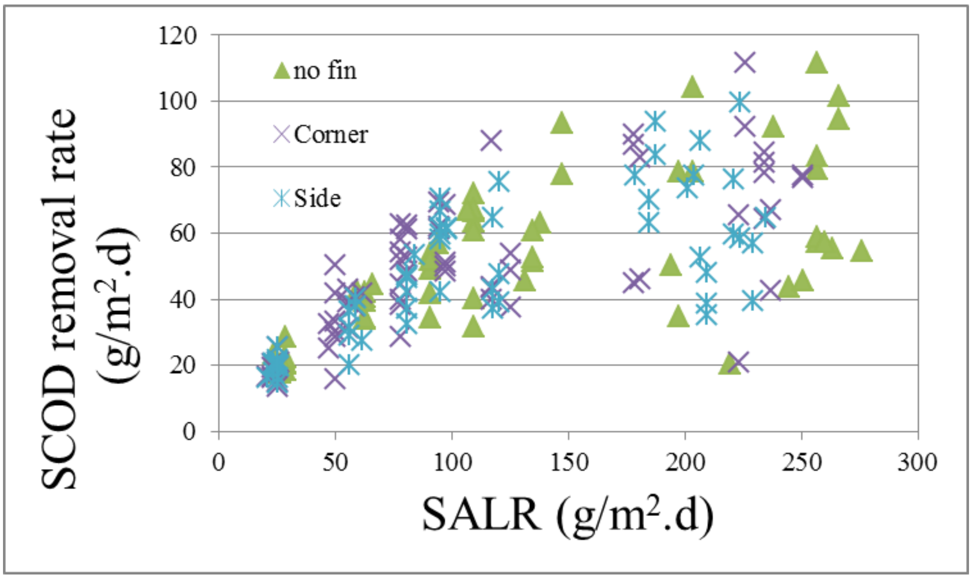


Figure 2: SCOD removal rates versus surface area organic loading rates

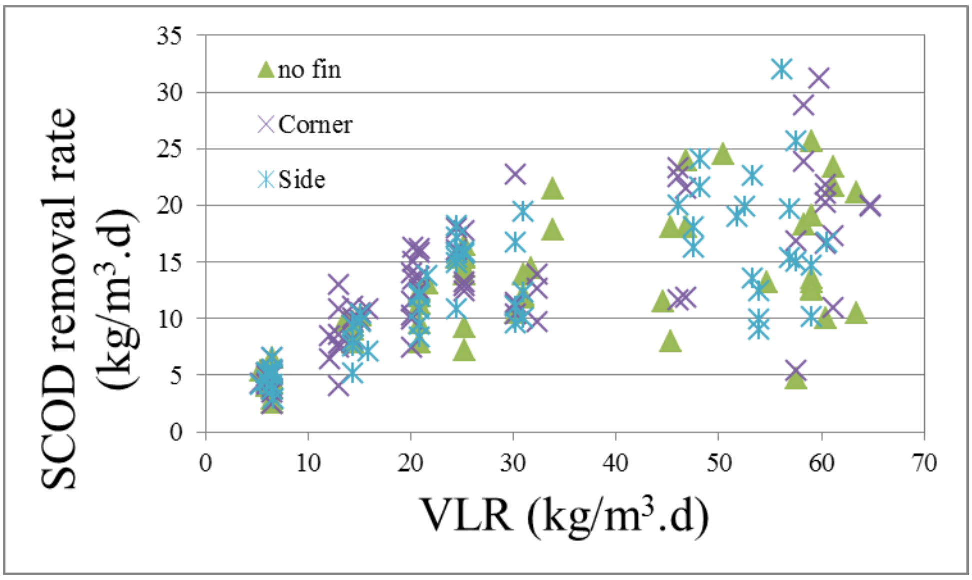


Figure 3: SCOD removal rates versus volumetric loading rates

The averaged SCOD removal rate for each organic loading rate is plotted against the SALR and VLR in Figures 4 and 5 respectively. Figure 4 shows that the SCOD removal rates of all the three carriers seem to fall along the same line, which is basically linear to the loading rate until it reaches the stressed loading of 175 g SCOD/m^2.d. At this loading point, the removal rate reaches its maximum of about 95 g SCOD/m^2.d (equivalent to about 54% SCOD removal efficiency) and the carriers are covered by biofilm with optimal thickness. Theoretically, the organic removal rate should then level off. However, it can be seen that the removal rate in fact starts declining after the maximum point. Probably, the organic removal efficiency is restricted under the stressed loading condition.

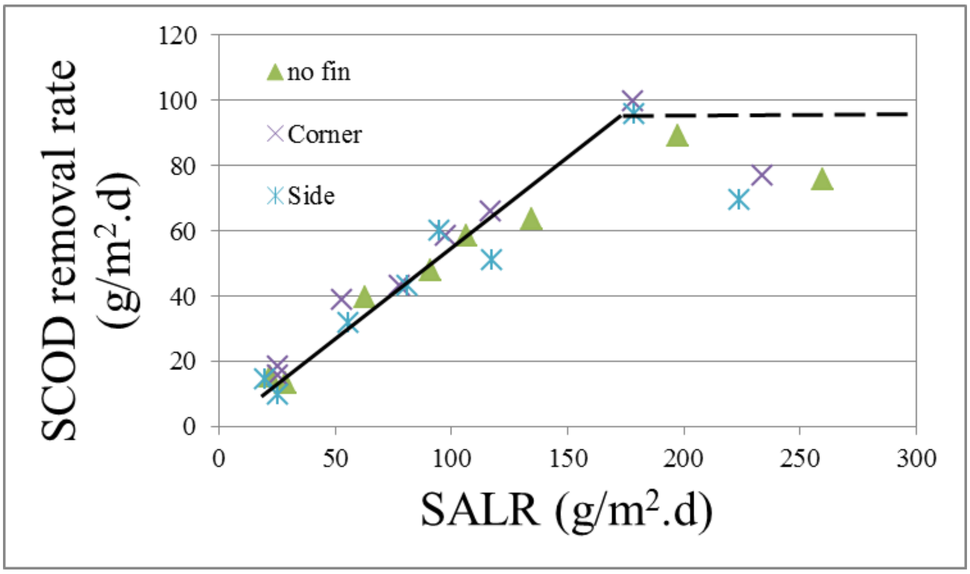


Figure 4: Averaged SCOD removal rates versus surface area organic loading rates

Figure 5 shows the averaged SCOD removal rates of the three carriers at different VLR. The best-fit lines of the three carriers have very similar shape, i.e. the SCOD removal rate varies linearly with the VLR until it reaches a maximum point and then levels off. However, the best-fit lines for the carriers with corner fin and side fin are more or less coincide while the best-fit line for the carrier with no fin is lower than the other two, which most likely attributes to the difference in the carrier surface area. It is in good agreement with Prof. Ødegaard's conclusion [2] and the kinetic theory of biofilm. Both two carriers with fin have comparable specific surface areas (615 m^2/m^3 and 613 m^2/m^3 respectively) which are higher than that of carrier with no fin (547 m^2/m^3). They are proved to have higher treatment capacity. From Figure 5, the carriers with fin can achieve a maximum SCOD removal rate of about 25 kg SCOD/m^3.d at VLR of about 46 kg SCOD/m^3.d (equivalent to about 54% SCOD removal efficiency).

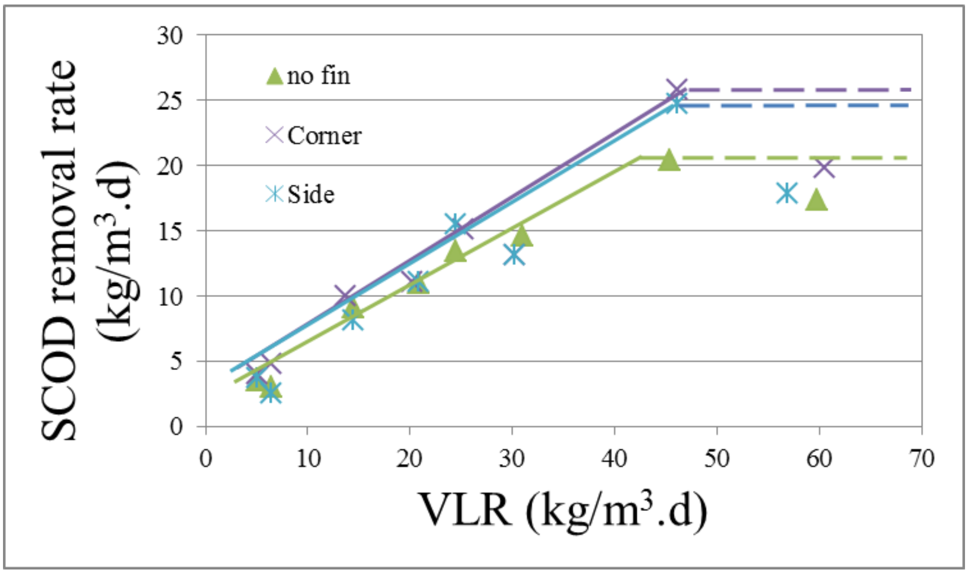


Figure 5: Averaged SCOD removal rates versus volumetric loading rates

Figure 4 and 5 illustrate that MBBR using the carriers with fin can be operated at the high loading range up to a maximum of about 175 g SCOD/m^2.d (equivalent to about 46 kg SCOD/m^3.d) achieving about 54% removal of SCOD.

Figure 6 shows the microscopic observation of the three types of carriers operating under different SALR throughout the experimental period. It's quite obvious that the biofilm grew and got thicker when the SALR was increased from 24 to over 175 g SCOD/m^2.d. No clogging in the void space of the carriers was found.

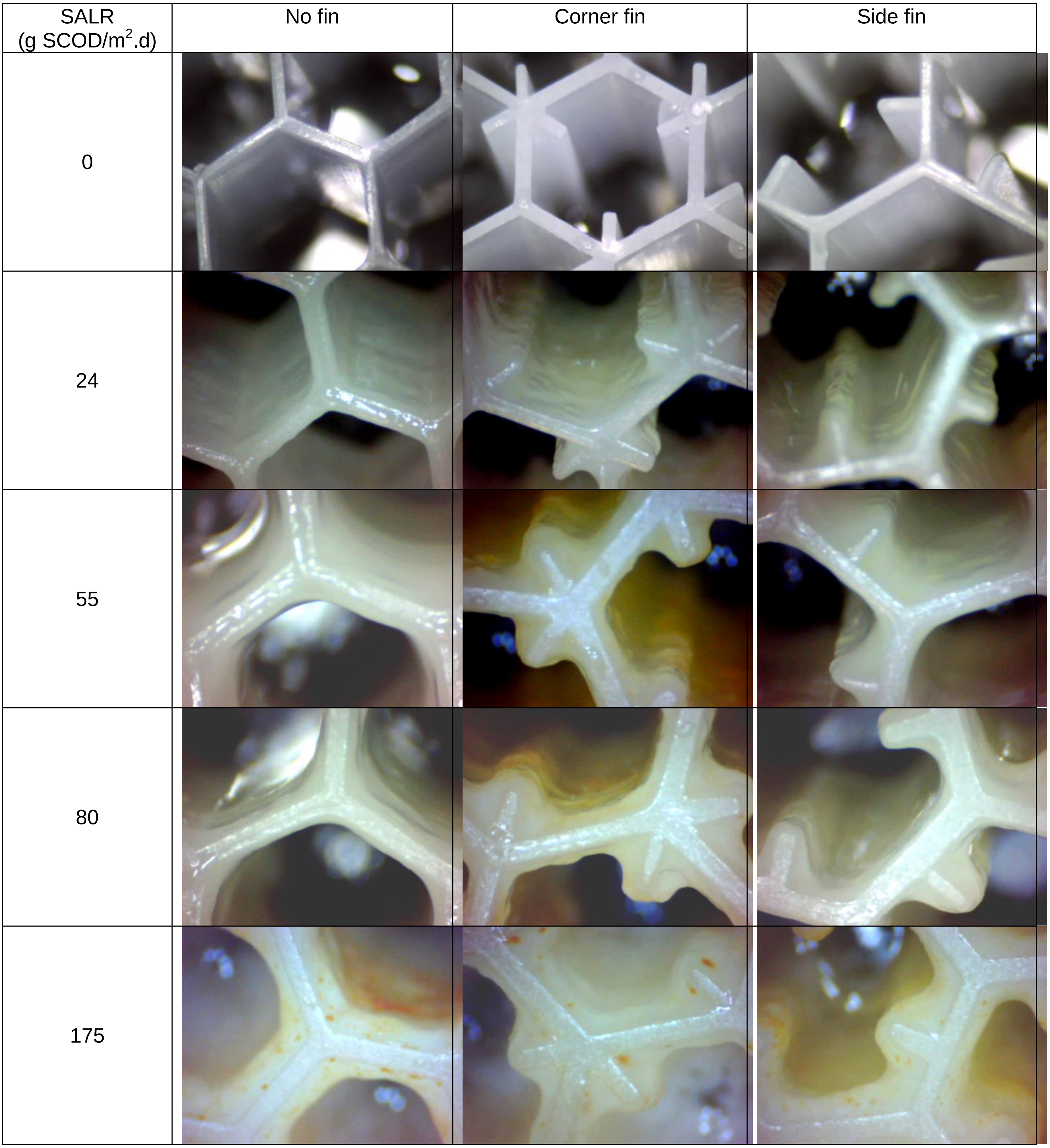


Figure 6. Microscopic observation of the biofilm built up for the carriers with under different SALR

3.3 Effects of Surface Modification for New MBBR Carriers

The surface of the carrier samples was modified in order to test the effects of surface modification on the carrier's performance. The new carrier with fin at corners (corner fin) was selected based on its greatest specific surface area and the highest SCOD removal rate as discussed in Section 3.2. Three methods were tried to modify the carrier surface properties, i.e. addition of foam or calcium carbonate into the base material (HDPE) for improvement of carrier surface roughness as well as plasma surface treatment of the carrier surface for improvement of the surface hydrophilicity.

Table 2 shows the changes of the carrier surface properties after the modifications as compared to the original unmodified carrier. The sample having plasma surface treatment has a reduced surface roughness of 270 nm but a small contact angle of 49.2° (very hydrophilic).The sample with foam addition has the surface roughness greatly increased from 336 nm to 1360 nm while the contact angle has slightly changed from 73.1° to 76.4° (less hydrophilic). As for the carrier sample with $CaCO_3$ addition, the surface roughness is slightly increased to 526 nm but the contact angle has greatly increased to 99.0° (very hydrophobic).

Table2: Surface properties of the carriers with surface modification

No.	Modification method	Surface roughness (nm)	Contact angle (°)
	Unmodified carrier	336	73.1°
1	Plasma treatment	270	49.2°
2	Foam addition	1360	76.4°
3	$CaCO_3$ addition	526	99.0°

Roughness is well proven to enhance microbe cell adhesion whereas it is a rather complex issue for the effect of hydrophilicity on the cell adhesion which would also depend on the cell type, culture medium, adsorption protein and roughness etc. It could be linear or parabolic relationship. The general trend is that more hydrophilic surface tends to promote cell adhesion.

To evaluate the performance of the carriers with different modification, the amounts of biomass grown on the carrier samples during the initial biofilm build-up period (i.e. 2 days after seeding) were measured and compared. Figure 7 shows that the carrier with foam addition has the greatest surface roughness (1360nm) and thus has the maximum amount of biomass of 7.73 mg/carrier on the surface (34% increase as compared with the unmodified one). On the other hand, Figure 8 illustrates another phenomenon that the carrier with $CaCO_3$ addition has the highest contact angle (99.0°). That means it is rather hydrophobic. It has got the minimum amount of biomass of 4.61 mg/carrier on the surface (20% less than that on the unmodified one). Lastly, the sample with plasma surface treatment seems to illustrate the counter effect of the reduced surface roughness and the higher hydrophilicity. Although it has the smallest contact angle, the amount of biomass grown on the surface is quite similar to the unmodified one. From Figures 7 & 8, surface roughness is considered more effective for enhancing the biofilm build-up as compared with surface hydrophilicity.

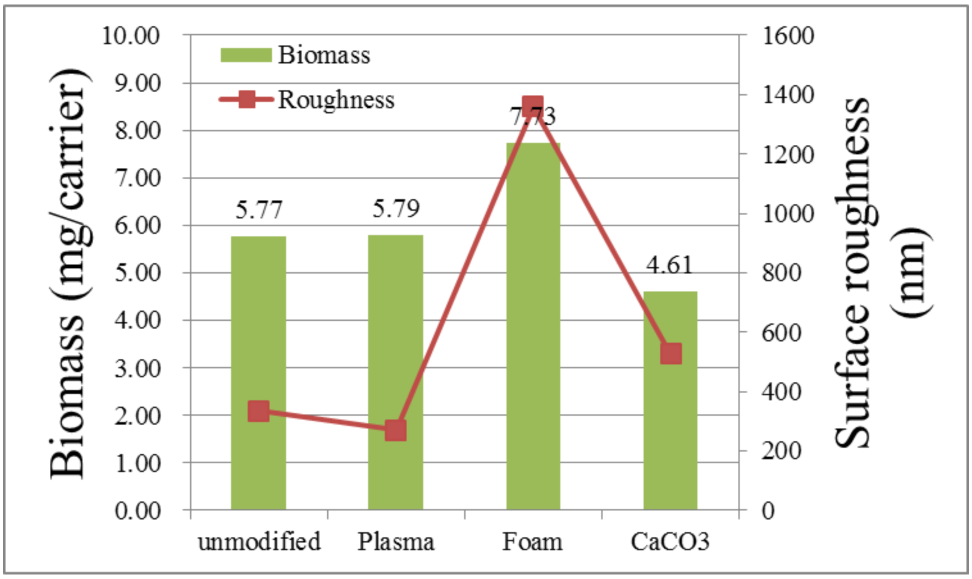


Figure 7: Biofilm build-up versus surface roughness

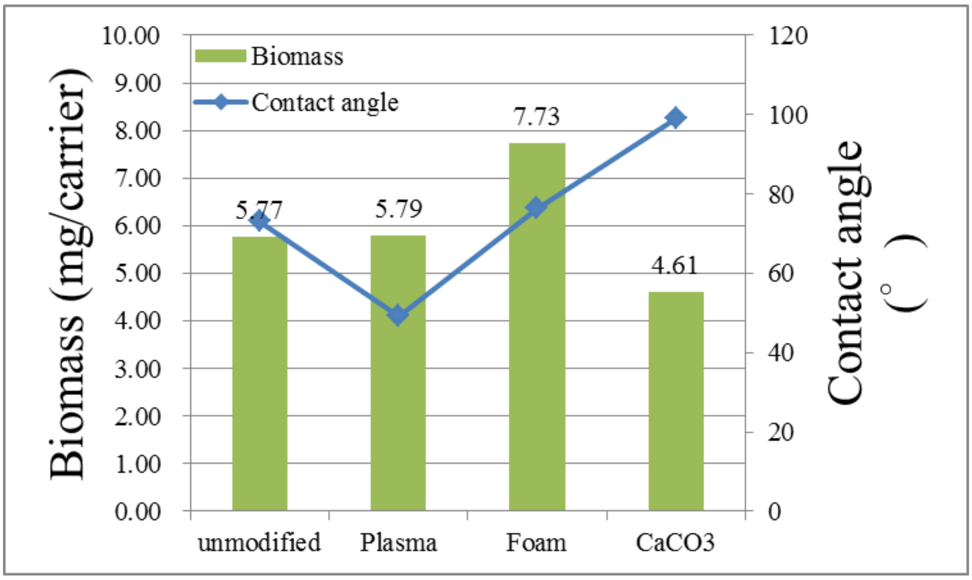


Figure 8: Biofilm build-up versus surface contact angle

Figure 9 shows the biomass growth on the four types of carriers during the initial biofilm build-up period. The amounts of biomass grown on the carrier samples after 2 days and 15 days of seeding respectively were measured and compared. It could be seen that biofilm grows faster on the carrier with rougher surface (the one with foam addition). The observation may give some clues that quicker start-up of MBBR may be achieved with carrier of rougher surface.

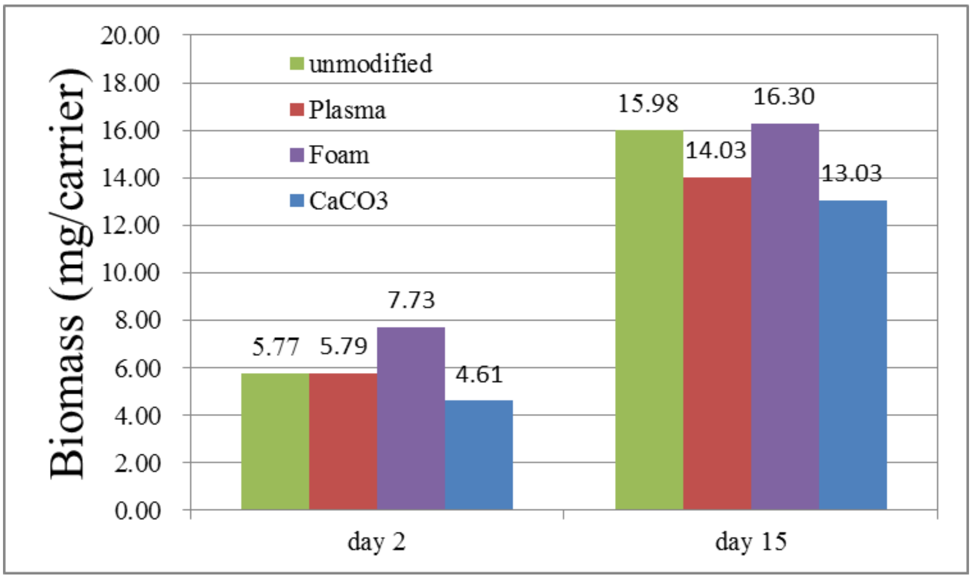


Figure 9: Biofilm growth during the initial biofilm build-up period

3.4 Potential High Loading Application of MBBR

In order to illustrate the merits of MBBR using the new carrier developed (with corner fin) in treating high strength organic wastewater, a scenario of treating diluted soymilk of SCOD 3,000 mg/L at the maximum loading conditions identified in the above experiments is shown in Table 3.

Table 3: Removal efficiency in the scenario of maximum loading for MBBR system

VLR (kg SCOD/m^3.d)	SCOD Removal (kg COD/m^3.d)	HRT (hr)	Effluent SCOD (mg/L)	Media fill ratio (%)	SCOD removal efficiency (%)
46	25	1.6	1,370	42	54%

When the MBBR operates at the maximum loading conditions (i.e. VLR of 46 kg SCOD/m^3.d and SALR of 175 g SCOD/m^2.d), the hydraulic retention time (HRT) can be as short as 1.6 hrs. and the SCOD removal were about 54%. The soluble organic in the wastewater, which cannot be removed by chemical coagulation, can be assimilated into the bacteria cells quickly in the MBBR reactor. As a result, the SCOD was removed in a short HRT and the biomass grows fast at short SRT. The sloughed off biomass from the carrier can be removed by chemical enhanced sedimentation or dissolved air flotation (DAF). The conceptual treatment process is shown in Figure 10.

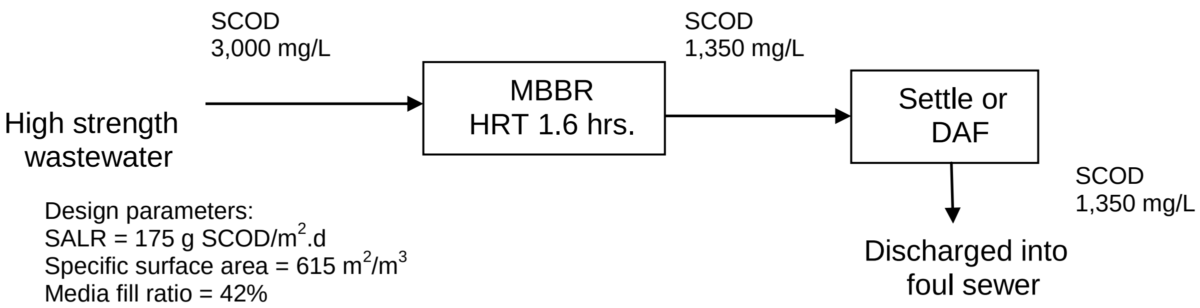


Figure 10: Treatment process using the new MBBR carrier

As a comparison, conceptual treatment processes based on conventional activated sludge (AS) and membrane bioreactor (MBR) are designed. Since the treated effluent SCOD of AS and MBR are much lower than the required level, only a portion of the wastewater is treated and then blended with the remaining untreated portion to give a combined SCOD of about 1,350 mg/L.

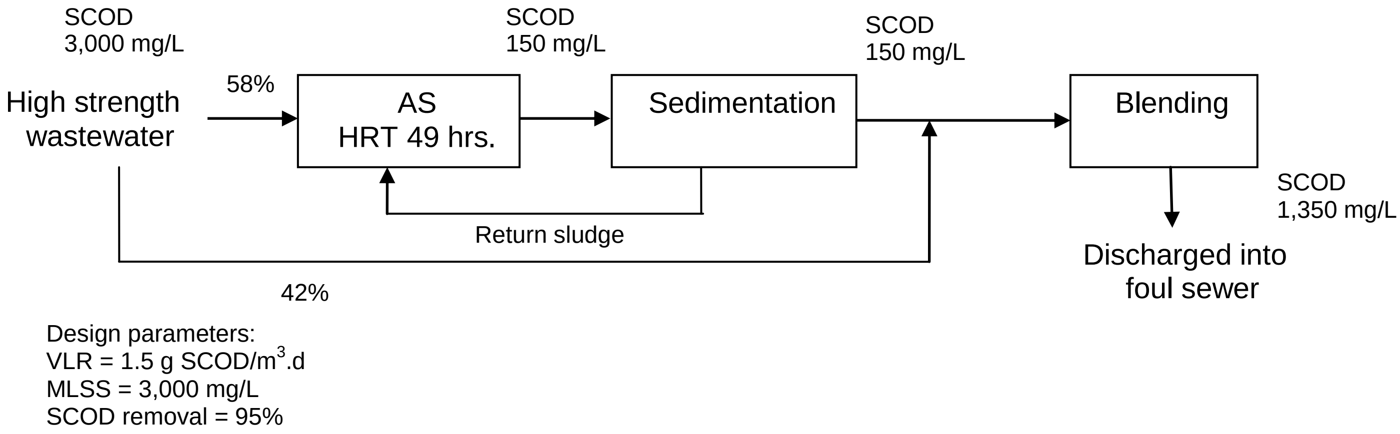


Figure 11: Treatment process based on activated sludge

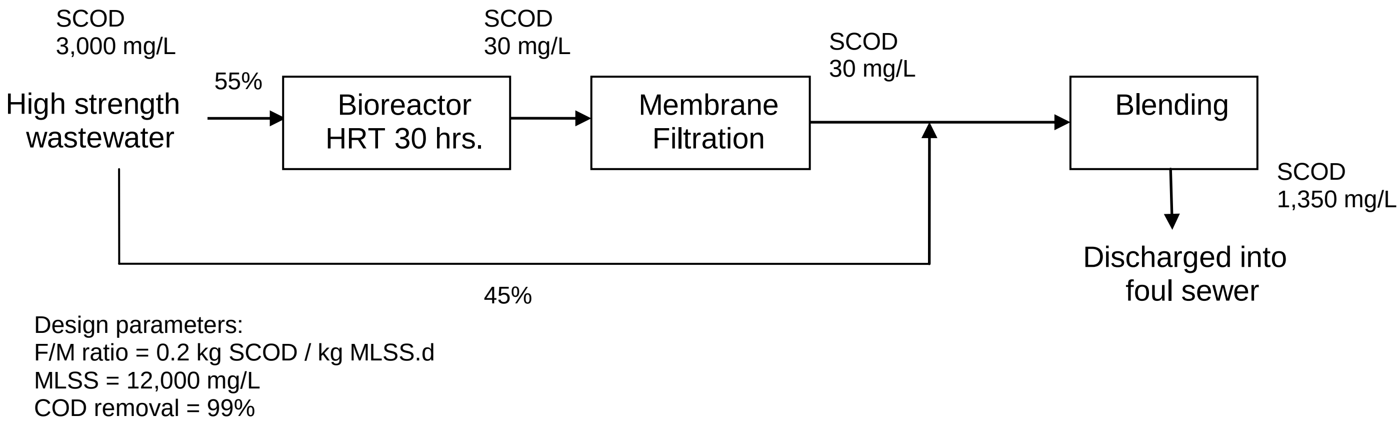


Figure 12: Treatment process based on MBR technology

The three treatment processes are summarized in Table 4 for comparison.

Table 4: Comparison of HRT of different treatment processes

Treatment	Portion of wastewater for biological treatment	HRT of biological reactor for treated stream (hr)	HRT of biological reactor for total wastewater (hr)
MBBR	100%	1.6	1.6
AS	58%	49	28.4
MBR	55%	30	16.5

From the above scenarios, it is shown that the HRT of MBBR process and so the space requirements are much less than those of other biological treatment processes, especially for partial treatment of high strength organic wastewater for discharge into the foul sewer. Combining with highly efficient solid separation techniques such as chemical enhanced sedimentation or DAF, the MBBR system will be extremely compact. Since most large food and beverage factories are located in industrial areas where public sewers are available but with very limited space, the MBBR have great potential on helping the industry to meet the discharge standards.

4 CONCLUSION

Three new carrier designs have been developed and tested. Laboratory studies show that all the three carriers have the same SCOD removal based on SALR. Whereas, based on VLR, both two carriers with fin have higher SCOD removal than the carrier with no fin because of the greater specific surface areas. The experimental results have demonstrated that the new carriers can be operated at very high loading up to a maximum of about 175 g SCOD/m^2.d (equivalent to about 46 kg SCOD/m^3.d) achieving about 54% SCOD removal.

This study also shows how the surface roughness and hydrophilicity affect the biofilm build-up on the carrier surface, which suggests a faster start-up of MBBR by providing rougher carrier surface. Addition of foam into the base material for the carrier is proved to be a possible method to increase the carrier surface roughness. Further study is required to identify the most cost-effective method for this.

From the comparison among the MBBR using the new carrier, AS and MBR, MBBR is demonstrated to be the most compact process for partial treatment of the high strength organic wastewater for discharge into the foul sewer. This offers a viable solution to assist the local food and beverage industry to achieve the compliance in the Hong Kong context.

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