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The Effects of Biomass Parameters on the Dissolved Organic Carbon Removal in a Sponge Submerged Membrane Bioreactor

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***Abstract*—**A novel sponge submerged membrane bioreactor (SSMBR) was developed to effectively remove organics and nutrients from wastewater. Sponge is introduced within the SSMBR as a medium for the attached growth of biomass. This paper evaluates the effects of new and acclimatized sponges for dissolved organic carbon (DOC) removal from wastewater at different mixed liquor suspended solids' (MLSS) concentration of the sludge. It was observed in a series of experimental studies that the acclimatized sponge performed better than the new sponge whilst the optimum DOC removal could be achieved at 10g/L of MLSS with the acclimatized sponge. Moreover, the paper analyses the relationships between the $MLSS_{sponge}/MLSS_{sludge}$ and the DOC removal efficiency of SSMBR. The results showed a non-linear relationship between the biomass parameters of the sponge and the sludge, and the DOC removal efficiency of SSMBR. A second-order polynomial function could reasonably represent these relationships.

***Keywords*—**Acclimatization, Dissolved organic carbon, Mathematical model, Sponge submerged membrane bioreactor.

I. Introduction

SUBMERGED membrane bioreactor (SMBR) has been widely applied for the treatment of municipal and industrial wastewater treatment. The performance of an SMBR for water sustainability can be further improved by attached growth systems. An effective support medium can greatly accelerate the attached growth process which eventually results in efficient oxygen transfer, and higher removal efficiency of organic pollutants and nutrients [1]-[3].

A novel sponge submerged membrane bioreactor (SSMBR) [4] provides attached growth system within the SMBR, and it was evaluated by a series of studies [3]-[7] for effective and stable performance. In the SSMBR system, cube sized sponges were introduced as an ideal attached growth medium which could act as well as a mobile carrier for active biomass [4] in a continuously aerated system. The addition of sponges to the SMBR could not only remove over 96% DOC and nutrients but also could significantly reduce membrane fouling, and enhanced sustainable flux [4].

However, the operational conditions may greatly affect the performance of any MBR. There have been a lot of studies on the operational factors such as MLSS [8], food to microorganism ratio [9], sludge retention time SRT [10], hydraulic retention time [11] etc. which may affect the optimum performance of an MBR. Few researchers (inter alia [12], [13]) also investigated the mathematical relationship among the operational conditions and efficiency of the MBR. Ren et al. [13] examined the relation between MLSS and chemical oxygen demand (COD) removal of an SMBR. This paper is specifically aimed at discussing the effects of sponges on the performance of an SSMBR for the removal of DOC. In order to determine the role of sponges for the removal of DOC, some normalized parameters of the MLSS and membrane liquor volatile suspended solids' (MLVSS) concentration of the sponge were used in this paper. The main objective of the work is to identify the condition of the sponge (new or acclimatized), and relationships between the MLSS/MLVSS concentration of the sponge ($MLSS_{sponge}/MLVSS_{sponge}$) and that of the sludge in the bioreactor ($MLSS_{sludge}$) at which the SSMBR performed efficiently for the removal of DOC.

II. Experiments and Methods

A. Materials

The experiments were performed with synthetic wastewater containing glucose, ammonium sulfate, potassium dihydrogen phosphate, and trace nutrients compositions of which are shown in Table I [14]. The synthetic wastewater had DOC of 130-145mg/L, COD of 340-390mg/L, NH_4-N of 15-20mg/L and PO_4-P of 3.5-4.0mg/L. $NaHCO_3$ or H_2SO_4 was used to adjust the pH to 7.

Two different types of sponges were used at each MLSS concentration, new sponge and acclimatized sponge (acclimatized with activated sludge in the laboratory for at least 25 days before commencing the experiments). The sponge specification was reticulated porous polyester-urethane

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sponge (PUS) named S28-30/90R (density of 28-30kg/m^3 with 90 cells per 25mm). Sponge volume fraction of 10% (of bioreactor volume) with size of 1cm×1cm×1cm was used in the study, which was determined according to previous critical flux experiments [5].

TABLE I
CONSTITUENTS OF BIODEGRADABLE SYNTHETIC WASTEWATER

Compounds	Molecular weight (g/mol)	Concentration (mg/L)
Organics and nutrients		
Glucose ($C_6H_{12}O_6$)	180.0	280
Ammonium sulfate ($(NH_4)_2SO_4$)	132.1	72
Potassium phosphate (KH_2PO_4)	136.1	13.2
Trace nutrients:		
Calcium chloride ($CaCl_2{\cdot}2H_2O$)	147.0	0.368
Magnesium sulfate ($MgSO_4{\cdot}7H_2O$)	246.5	5.07
Magnesium sulfate ($MgSO_4{\cdot}7H_2O$)	197.9	0.275
Zinc sulfate ($ZnSO_4{\cdot}7H_2O$)	287.5	0.44
Ferric chloride anhydrous ($FeCl_3$)	162.2	1.45
Cupric sulfate ($CuSO_4{\cdot}5H_2O$)	249.7	0.391
Cobalt chloride ($CoCl_2{\cdot}6H_2O$)	237.9	0.42
Sodium molybdate dihydrate ($Na_2MoO_4{\cdot}2H_2O$)	242.0	1.26
Yeast extract		30

B. Experimental Setup and Analysis

The membrane module used in the study was polyethylene hollow fibre with the pore size of 0.1μm and the surface area of 0.05m^2 (Mitsubishi-Rayon, Japan). The effective volume of the bioreactor was 6L and the filtration rate was maintained at 10L/m^2/h. The influent 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. A pressure gauge was used to measure the trans-membrane pressure (TMP), and a soaker hose air diffuser was used to maintain the air flow rate. Physical cleaning was done twice a day by backwashing with the filtrate at a rate of 30L/m^2/h.

The sludge used in the study was taken from a local wastewater treatment plant and was acclimatized with synthetic wastewater. The performance of the SSMBR was assessed at three different initial MLSS concentrations of 5, 10, and 15g/L. DOC of the influent and effluent was measured using the AnalytikJena Multi N/C 3100. SOUR was measured using the YSI 5300 biological oxygen monitor. The analysis of MLSS and MLVSS were done according to standard methods [15].

III. RESULTS AND DISCUSSION

A. DOC Removal Efficiency of the SSMBR

The experiments were conducted for two variations of the sponge conditions: new and acclimatized. For the acclimatized condition, sponges were kept immersed in wastewater for approximately 25 days before introducing them into the SSMBR. Figs. 1, 2, and 3 compare the DOC removal efficiencies of the SSMBR at different initial $MLSS_{sludge}$ concentrations of 5, 10, and 15g/L.

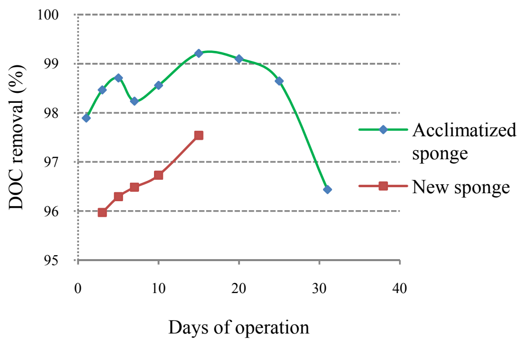

Fig. 1 DOC removal (%) vs. days of operation of SSMBR (initial $MLSS_{sludge}$ of 5g/L)

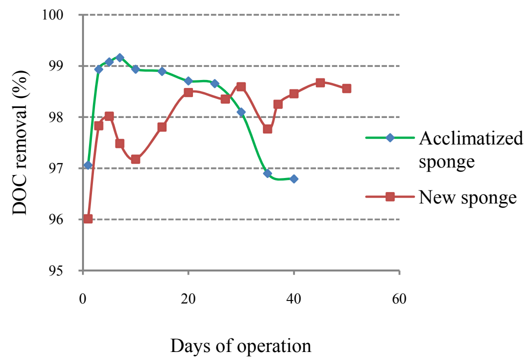

Fig. 2 DOC removal (%) vs. days of operation of SSMBR (initial $MLSS_{sludge}$ of 10g/L)

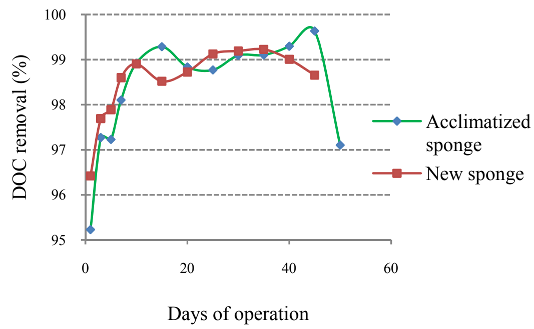

Fig. 3 DOC removal (%) vs. days of operation of SSMBR (initial $MLSS_{sludge}$ of 15g/L)

It is observed from the comparisons shown in Figs. 1, 2, and 3 that the performance of the acclimatized sponges was generally better for the removal of DOC. When the new sponges were introduced into the SSMBR with initial $MLSS_{sludge}$ concentration of 5g/L, the system became quickly unstable by a rapid rise of TMP before the optimum DOC removal could be achieved. At the initial $MLSS_{sludge}$ concentration of 15g/L, the DOC removal efficiencies peaked twice but with drops in between the peaks (Fig. 3). It appears that the SSMBR performed best for the DOC removal with the acclimatized sponges in the SSMBR when the initial $MLSS_{sludge}$ concentration was maintained at 10g/L (Fig. 2). The SSMBR quickly achieved the maximum DOC removal efficiency (>99%) followed by a slow and steady drop in the removal efficiency. The desired DOC removal efficiency, therefore, could be maintained for a longer time.

B. Effects of Biomass Parameters on the DOC Removal

The effects of sponges on the DOC removal can be compared among the different experiments by comparing the DOC removal efficiency (%) against the ratio of the $MLSS_{sponge}/MLVSS_{sponge}$ to the corresponding $MLSS_{sludge}$ concentration. Figs. 4 and 5 compare the DOC removal efficiencies of the acclimatized sponges in the $MLSS_{sludge}$ concentrations of 10g/L and 15g/L respectively.

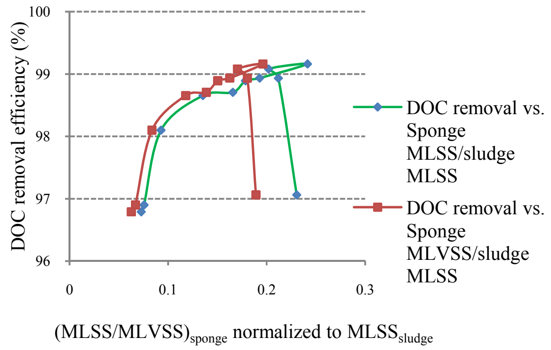

Fig. 4 DOC removal vs. $(MLSS/MLVSS)_{sponge}/MLSS_{sludge}$ (for the acclimatized sponge and initial $MLSS_{sludge}$ of 10g/L)

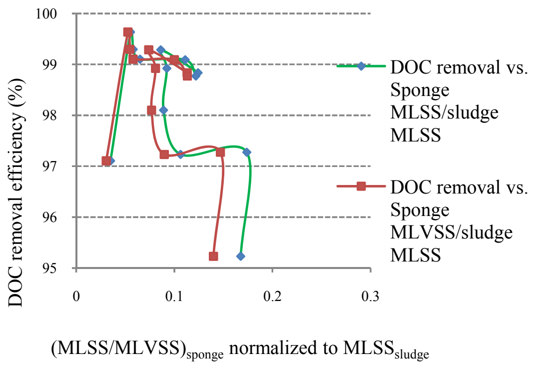

Fig. 5 DOC removal vs. $(MLSS/MLVSS)_{sponge}/MLSS_{sludge}$ (for the acclimatized sponge and initial $MLSS_{sludge}$ of 15g/L)

From the comparison shown in Figs. 4 and 5, it appears that the effects of acclimatized sponges on the removal of DOC was more stable when it was introduced in the bioreactor with initial $MLSS_{sludge}$ of 10g/L. The SSMBR (with initial $MLSS_{sludge}$ of 10g/L) had the maximum DOC removal efficiency achieved at or near the point where the normalized $MLSS_{sponge}/MLSS_{sludge}$ was approximately 0.24. The $MLSS_{sponge}$ /$MLSS_{sludge}$ at the first day of the operation of the SSMBR was about 0.23 which was close to 0.24. As a result, the effects of sponges might have been quickly stabilized to the system's operation and a steady operational efficiency was maintained by the system for a longer time. The similar trend line of $MLVSS_{sponge}/MLSS_{sludge}$ (Fig. 4) indicates that the sponges might also have positive influence on the biomass viability by accumulating volatile suspended solids within its pores or on the surface. On the other hand, the system behaved in an unstable manner when the SSMBR was operated with initial $MLSS_{sludge}$ of 15g/L (Fig. 5). The maximum removal of DOC occurred at $MLSS_{sponge}/MLSS_{sludge} \approx 0.05$ whereas the system started operating on the first day with $MLSS_{sponge}/MLSS_{sludge} \approx 0.15$.

C. Mathematical Functions for the Effects of Biomass Parameters of Sponge and Sludge on the DOC Removal

It has been discussed in the previous section that the SSMBR performed best for the DOC removal when the SSMBR was operated at the initial $MLSS_{sludge}$ concentration of 10g/L using acclimatized sponges as the attached growth medium. The maximum DOC removal efficiency was achieved when the $MLSS_{sponge}/MLSS_{sludge}$ was approximately 0.24. The test results indicate that for this SSMBR with acclimatized sponges, the $MLSS_{sponge}/MLSS_{sludge}$ was 0.23 on the first day and in the following 20 days, the $MLSS_{sponge}/MLSS_{sludge}$ were more or less stable around 0.2.

From the critical analyses of experimental results, a general mathematical function for the correlation of different characteristic biomass parameters with the DOC removal efficiency has been developed. The general representation of the mathematical relation is shown in (1).

$$D_i = a_i S_i^2 + b_i S_i + \Delta d_i \qquad (1)$$

Here D_i is the DOC removal (%) and S_i is representative for the effects of different characteristic biomass parameters of the sponge and the sludge that could be correlated well with the DOC removal efficiencies. a_i and b_i in (1) are the coefficients values of which are shown in Table II, and in Figs. 6, 7, 8 and 9 for each of the representative cases of S_i. Δd_i is the constant which has a value even when the value of S_i is zero.

TABLE II
MATHEMATICAL FUNCTIONS FOR THE EFFECTS OF DIFFERENT BIOMASS PARAMETERS ON THE DOC REMOVAL OF SSMBR

Parameters (S_i)	Mathematical equation of D_i (%)	Δd_i (%)	Coefficients		R^2
			a_i	b_i	
S_1 ($MLSS_{sponge}$/ $MLSS_{sludge}$)	$D_1 = -a_1S_1^2 + b_1S_1 + \Delta d_1$	94.27	-108.34	45.63	0.928
S_2 ($MLVSS_{sponge}$/ $MLSS_{sludge}$)	$D_2 = -a_2S_2^2 + b_2S_2 + \Delta d_2$	93.82	-174.52	60.50	0.949
S_3 ($Biomass_{sponge}$)	$D_3 = -a_3S_3^2 + b_3S_3 + \Delta d_3$	90.09	-10.44	19.08	0.918
S_4 ($MLSS_{sludge}$)	$D_4 = -a_4S_4^2 + b_4S_4 + \Delta d_4$	84.21	-0.11	2.57	0.936

Following are the main biomass parameters (S_i) that were found affecting significantly the DOC removal of SSMBR:

i. $MLSS_{sponge}/MLSS_{sludge}$ (for the effects of sponge)
ii. $MLVSS_{sponge}/MLSS_{sludge}$ (for the effects of sponge)
iii. $Biomass_{sponge}$ (biomass on sponge, g Biomass/g sponge)
iv. $MLSS_{sludge}$ (MLSS concentration of the sludge)

All the analyses show a nonlinear relationship (Figs. 6 to 9) between the DOC removal (%) and the characteristic biomass parameters (S_i). Neglecting the initial values of the experimental results, a 2nd order polynomial in (1) describes reasonably well the effects of sponge on the DOC removal.

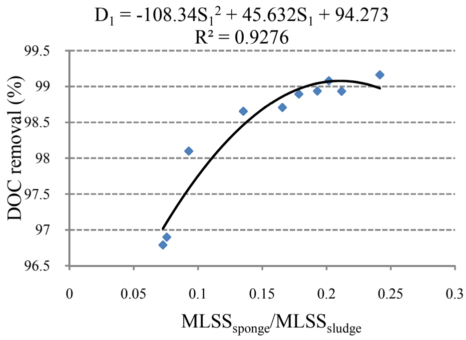

Fig. 6 Effects of $MLSS_{sponge}$ (normalized to $MLSS_{sludge}$≈10 g/L) on the DOC removal

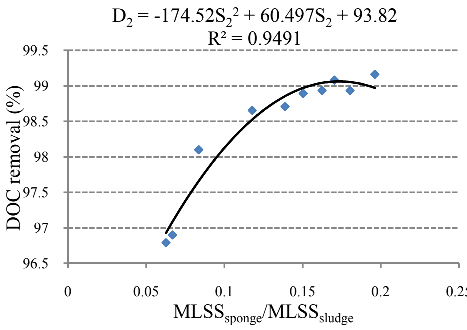

Fig. 7 Effects of $MLVSS_{sponge}$ (normalized to $MLSS_{sludge}$≈10 g/L) on the DOC removal

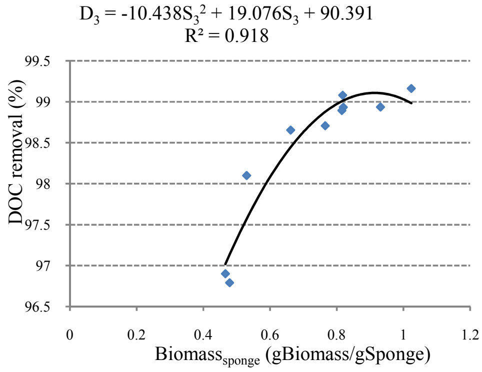

Fig. 8 Effects of biomass of sponge on the DOC removal

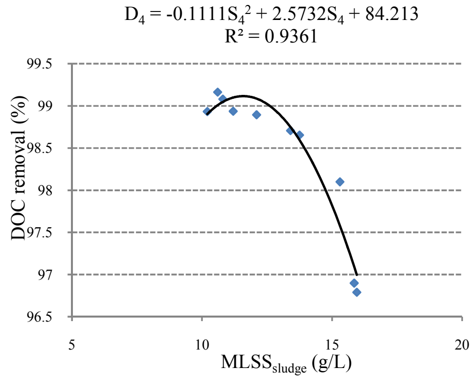

Fig. 9 Effects of MLSS concentration of the sludge on DOC removal

IV. CONCLUSIONS

This paper presents different experimental results and analyzes them to evaluate the performance of sponges for the organic pollutants' removal in a novel SSMBR system. As compared to new sponge, the acclimatized sponge was found to perform better as an attached growth support medium and mobile carrier of biomass. However, the optimum DOC removal by SSMBR could be achieved when the MLSS concentration of the acclimatized sponge is at an optimum with respect to the MLSS concentration of the sludge. Among the different combinations of the experiments done with the SSMBR, it was found that the performance of the SSMBR was optimum for the DOC removal (>99%) when it was operated with an initial MLSS concentration of the sludge of 10g/L and when the ratio of the MLSS concentration of the sponge to that of the sludge was at or around 0.2. At this ratio, the activities of the sponge in the SSMBR might have been quickly stabilized and remained steady for a longer time. This suggests that for the optimum performance of an SSMBR, acclimatization of the sponge should be done in a way to keep the ratio close to experimentally observed optimum value. At a stable state of the activities of the sponge within the bioreactor, the DOC removal efficiency of the SSMBR can be given as 2nd-order polynomial functions of the characteristic biomass parameters of the sponge and that of the bioreactor sludge.

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