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COMPARISON BETWEEN A CONVENTIONAL MEMBRANE BIOREACTOR (C-MBR) AND A BIOFILM MEMBRANE BIOREACTOR (BF-MBR) FOR DOMESTIC WASTEWATER TREATMENT

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Abstract - In this paper, the influence of biofilm carriers in a MBR on the performance of organic matter and nitrogen removal and the influence on membrane fouling were evaluated. The configurations studied included a Conventional Membrane Bioreactor (C-MBR) and a Biofilm Membrane Bioreactor (BF-MBR) operated in parallel, both fed with domestic wastewater. Regarding organic matter removal, no statistically significant differences were observed between C-MBR and BF-MBR, producing an effluent with a Soluble COD concentration of 27 ± 9.0 mgO_2/L and 26 ±1.0 mgO_2/L and BOD concentration of 6.0 ± 2.5 mgO_2/L and 6.2 ± 2.1 mgO_2/L, respectively. On the other hand, the BF-MBR produced a permeate with lower ammonia and total nitrogen concentrations, which resulted in a removal efficiency of 98% and 73%, respectively. It was also observed that the fouling rate was about 35% higher in the C-MBR than that for the BF-MBR, which also presented a reduction of total membrane resistance, about 29%, and increased operational cycle length around 7 days, compared to C-MBR.

Keywords: Biofilm membrane bioreactor; Fouling; Membrane bioreactor; Wastewater treatment.

INTRODUCTION

Membrane Bioreactors (MBR) were commercialized 30 years ago and their application in wastewater treatment has increased over the past decades. However, the breakthrough for the MBR came in 1989 with the idea to submerge the membranes in the bioreactor (Yamamoto *et al.*, 1989) which resulted in lower Transmembrane Pressure (TMP) and lower operational costs (Le-Clech *et al.*, 2006). This combination made it possible to obtain compact units with small footprints, complete solids removal, operation at higher suspended biomass concentrations, resulting in long sludge retention times, and effluent disinfection, all at once. These intrinsic advantages transformed MBR systems into one of the most promising wastewater treatment technologies up to the present day. As a result, the MBR market value doubled in the five years between 2000 and 2005, reaching $217 million. This number continues to grow as the market was valued at $337 million in 2010 and is expected to grow to $627 million by 2015, with an annual growth rate (CAGR) of 13.2% (Susan, 2011).

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Despite the potential benefits of MBR systems and the role they can play in water conservation and reuse (Subtil *et al.*, 2013), reduction in membrane permeability caused by fouling phenomena, due to a complex membrane/biomass interaction, still remains one of the major drawbacks of MBR. Membrane fouling reduces system performance, mainly because it constrains permeate flow by the accumulation of materials on the membrane surface or inside its pores. As a final result, fouling has a significant economic impact on system operation and, for this reason, it has been under investigation since the early age of MBRs, and still remains one of the most challenging issues regarding their development (Le-Clech *et al.*, 2006; Yang *et al.*, 2006; Anja, 2010). Nowadays, about 30% of all scientific MBR-related literature published deals directly or indirectly with membrane fouling issues (Santos *et al.*, 2011). Although there is no clear agreement regarding the exact phenomena occurring on the membrane interface during activated sludge filtration, membrane fouling in MBRs has been mainly attributed to Extracellular Polymeric Substances (EPS) (Le-Clech *et al.*, 2006), the structural construction material for microbial aggregates. In order to minimize and control the negative effect of membrane bioreactor fouling, different methods have been developed and tested, including the addition of Powdered Activated Carbon (PAC) (Khan *et al.*, 2012; Remya *et al.*, 2010) metal salts (Zhang *et al.*, 2008), organic and inorganic polyelectrolytes (Dizge et a., 2011) and biopolymer (Koseoglu, 2008) in the mixed liquor.

Although chemical additions to the mixed liquor for fouling control in MBR systems generally result in an enhanced filterability, it is important to keep in mind that their use also represents a substantial increase in operational costs. Thus, several studies focused their attention on a hybrid system as an alternative to the conventional MBR (C-MBR), trying to combine the advantages of biofilm and MBR processes in order to overcome some of the limitations of C-MBR. Results from recent research demonstrated that biofilm carriers can reduce the negative effect of suspended solids on the membrane surface and improve its filterability because of a low fouling rate (Leiknes and Ødegaard, 2001; Ivanovic and Leiknes, 2012). Although some studies have been made with Biofilm MBR there is no consensus and some results are controversial. Yang *et al.* (2006) showed that, during long-term experiments, the increasing rate of suction pressure for a Hybrid MBR accounted for 30% of that of a C-MBR, indicating that the degree of membrane fouling for a Hybrid MBR was far lower than that for a C-MBR. Another study developed by Liu *et al.* (2010) showed that the increase of TMP was slowed down in a Hybrid MBR, in which the time to perform a chemical cleaning was 92 days or longer, while in a C-MBR the time was 57-65 days. On the other hand, Yang *et al.* (2009) found worse membrane performance after the addition of carriers, where the rate of membrane fouling in Hybrid MBR was about three times that of Conventional MBR.

In this context the influence of biofilm carriers in a MBR on the performance of organic matter and nitrogen removal and the influence on membrane fouling were evaluated. The configurations studied included a Conventional Membrane Bioreactor (C-MBR), as a control system, and a Biofilm Membrane Bioreactor (BF-MBR) operated in parallel and fed with domestic wastewater.

MATERIAL AND METHODS

Experimental Set-Up and Operating Conditions

The study was carried out using two membrane bioreactor pilot-plants (C-MBR and BF-MBR), working in parallel and gravity fed with domestic wastewater, derived from the student housing and university restroom of University of São Paulo (Figure 1). Prior to the MBR system, wastewater passed through a screening, grit chamber and an oils & grease removal device. Both reactors were made of acrylic, with an effective volume of 100 L, and were operated at a mean Hydraulic Retention Time (HRT) of 10.2 hours and a Solid Retention Time (SRT) of 10 days. The BF-MBR had 40% of its volume occupied by the carriers which were cylindrical polypropylene rings having outer diameters and lengths of 9 mm and 7 mm, respectively, resulting in a specific surface area of 330 $m^2.m^{-3}$. During the evaluation period the total biomass concentration in the C-MBR and BF-MBR (suspended and attached biomass) were kept around 5540 ± 693 mg $MLSS.L^{-1}$ and 5186 ± 435 mg $MLSS.L^{-1}$, respectively.

Aeration was provided continuously by two fine bubble air diffusers (EPDM membrane) in the C-MBR pilot plant, one for aerating the suspension with a mean flow of 10 L $air.min^{-1}$ and another for providing shearing stress on membranes surface for fouling control. In the case of the BF-MBR, the same diffuser was used for circulating carriers and keeping the dissolved oxygen concentration around 1.8 ± 0.6 $mg.L^{-1}$, which was measured daily using an oximeter. Flat sheet membrane modules were used for solid separation, and permeate was continuously withdrawn by a peristaltic pump operating with a cycle of 8 minutes of filtration and 1.6 minutes of relaxation. In the permeate line the temperature, pressure and flow were continuously monitored and recorded with a data logger (Field-Logger 8812010000, from Novus). Membranes were chemically cleaned with a solution of NaOH (4%) when the TMP reached 0.15 bar.

Membrane Module and Characterization

As shown in Figure 1, both reactors were equipped with submerged membranes, which consisted of two Flat Sheet Ultrafiltration membrane modules (FS-UF). Each FS-UF system consisted of 16 plates with a total membrane area of 1.8 m^2. The system was developed in the International Reference Center for Water Reuse of the University of São Paulo with membranes supplied by the AMFOR INC Company. Membrane pore size distribution was performed using Scanning Electron Microscopy (SEM) (Figure 2-(a)) with membrane images analyzed with the ImageJ (NIH) software's "Analyze Particles" function (Figure 2-(b)) as described in Mierzwa *et al*. (2012). The UF membranes used in the study were made of Polyvinylidene Fluoride (PVDF) and had a mean pore size of 22 ± 6 nm (Figure 2-(c)).

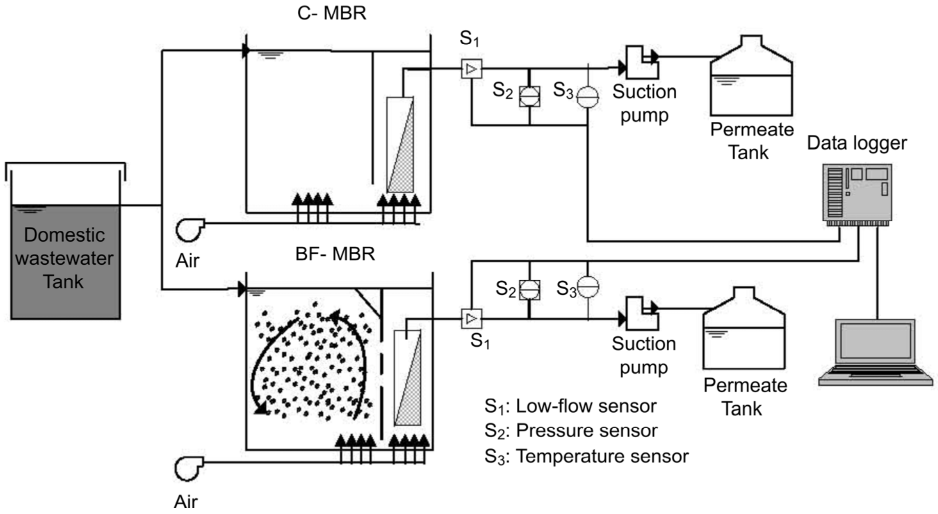
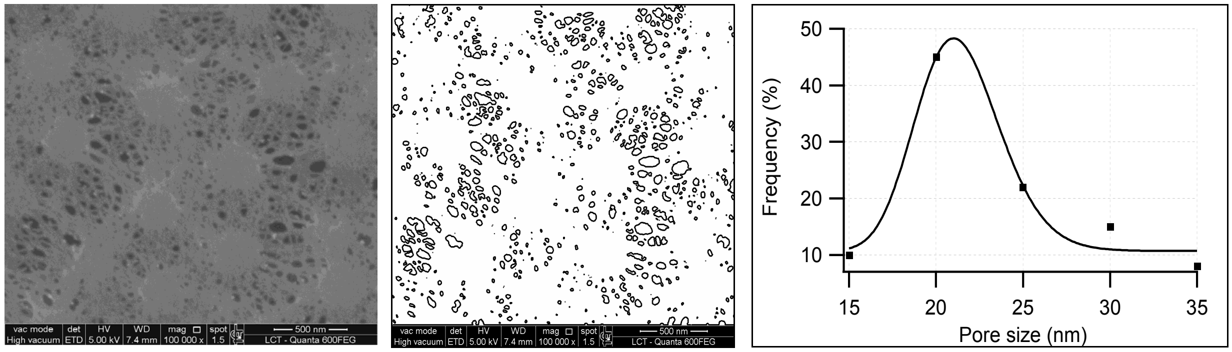


Figure 1: Pilot-plant schemes, where S_1–low-flow sensor (model 8031, Burket); S_2–pressure sensor (model GTP 1000, Gluton); S_3–temperature sensor (model NKTM-2200, NAKA).



(a) (b) (c)

Figure 2: Membrane top surface image (a), after manipulation with ImageJ (b) and membrane pore size distribution (c).

Membrane Fouling Analysis

The degree of membrane fouling between C-MBR and BF-MBR was measured using the series resistance model (Cheryan, 1998; Bae, 2005):

$$J = \frac{Q_p}{A_m} \tag{1}$$

$$R_t = \frac{\Delta P_t}{n_J} \tag{2}$$

$$R_t = R_m + R_f \tag{3}$$

where J is the membrane permeate flux ($m^3.m^{-2}.s^{-1}$), Q_p is the permeate flowrate ($m^3.s^{-1}$), A_m is the membrane surface area (m^2), ΔP_t is the Transmembrane Pressure (TMP) (Pa), n is the viscosity of the permeate (Pa s), R_t is the total filtration resistance (m^{-1}), R_m is the membrane resistance (m^{-1}) and R_f is the total fouling resistance that includes the cake resistance (m^{-1}).

The membrane permeability (J_p) was calculated according to Equation (4).

$$(J_p) = \frac{J}{\Delta P_t} \tag{4}$$

As presented in Figure 3 the fouling rate was estimated during constant flux operation and represents the decrease of permeability per day (L/m^2.h.bar.d).

Analytical Methods

Influent and effluent samples from the C-MBR and BF-MBR were analyzed according to the Standard Methods (APHA, 2005) with a frequency of three times per week for Chemical Oxygen Demand (COD), organic nitrogen ($N_{org.}$-N), ammonium nitrogen (NH_4^+–N), nitrate nitrogen (NO_3^-–N), and nitrite nitrogen (NO_2^-–N). Five day Biochemical Oxygen Demand (BOD_5) was determined using manometric systems from Aqualitic (BOD-System, OxiDirect). Turbidity, pH, and color were measured by a pH meter (model Q400MT, Quimis), turbidimeter (model 2100Q, Hach) and spectrophotometer (model B572, Micronal), respectively. Mixed Liquor Suspended Solids (MLSS) and Mixed Liquor Volatile Suspended Solids (MLVSS) samples from each reactor were analyzed twice in a week according to the Standard Methods (APHA, 2005). Attached Biomass quantification consisted of extracting the biofilm attached to the carriers. The collected carriers (10 units) were put in a flask and kept in a shaker for 10 minutes to pre-release the adhered material. At the end, the remaining material was scraped with a toothbrush and transferred to a beaker, and the resulting volume was measured. Later determinations were performed for concentrations of TSS and VSS.

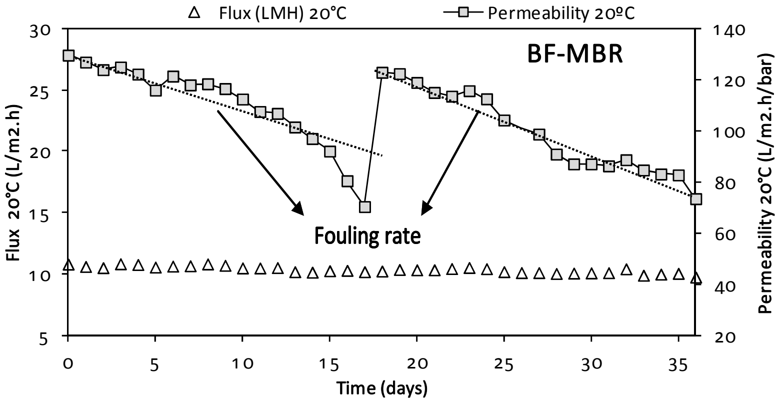


Figure 3: Fouling rate estimation during constant flux operation.

RESULTS AND DISCUSSION

Feed Wastewater Characteristics

Table 1 presents the main characteristics of the wastewater fed into the two membrane treatment systems. The average T-COD and BOD correlation of 2.8 indicates it corresponds to a typical domestic wastewater (Metcalf & Eddy, 2003).

Table 1: Wastewater characteristics fed to both membrane reactors.

Parameter*	Unit	Mean	Maximum	Minimum
pH	-	7.1	7.4	6.1
Temperature	ºC	23.6	26.3	21.0
Turbidity	NTU	412	896	145
Color	Uc	569	973	244
T-COD**	mg $O_2.L^{-1}$	912	1279	512
S-COD***	mg $O_2.L^{-1}$	397	762	145
BOD	mg $O_2.L^{-1}$	289	523	186
NH_4-N	mg $N.L^{-1}$	39.3	58.6	30.8
N_{org}-N	mg $N.L^{-1}$	14.2	26.0	5.8
TN	mg $N.L^{-1}$	53.5	70.3	42.3

*NO_3^- and NO_2^- were always below 0.4 mg N/L.
**Total COD
***Soluble COD

Permeate Quality

Permeate quality obtained during the operation of both membrane bioreactors is presented in Table 2. The use of UF membranes in wastewater treatment has great potential for effluent clarification, which was demonstrated by both systems, resulting in a quite clear effluent, reaching a turbidity removal of 99.9% in both systems (Figure 4). Besides turbidity, color is another parameter related to clarification and it is considered to be one of the most difficult aesthetic parameters for MBR systems (Arévalo *et al.*, 2009). As was expected, in contrast to the results obtained for turbidity, color was present in the effluent from both MBR systems, although better results were obtained by BF-MBR, producing an effluent with statistically significant differences from the C-MBR effluent. Regarding organic matter removal, no statistically significant differences were observed between C-MBR and BF-MBR, with average Soluble COD concentrations of 27 ± 9.0 $mgO_2.L^{-1}$ and 26 ±1.0 $mgO_2.L^{-1}$ and BOD concentrations of 6.0 ± 2.5 $mgO_2.L^{-1}$ and 6.2 ± 2.1 $mgO_2.L^{-1}$, respectively. Liu *et al.* (2010) and Khan *et al.* (2012) reported better COD removal in a biofilm MBR, while Liang *et al.* (2010) and Yang *et al.* (2009) found a worse removal rate in a biofilm MBR (Figure 6). However, in all cases differences in organic matter removal were very small, indicating, as cited by Ivanovic *et al.* (2006), that generally there is no difference in the degree of organic removal between an activated sludge MBR and biofilm MBR when operated at similar HRT and SRT. The authors also reported that both systems can sustainably achieve high COD removal, typically 95 – 99%. Actually, the biomass attached to the carriers has higher activity, making it possible to achieve the same organic matter removal rates with lower biomass concentrations, as was reported by Lee *et al.* (2002). With the biofilm MBR, the same removal of organic matter was achieved as that in the activated sludge MBR, but with almost 1/3 of the biomass.

Besides organic matter removal, another water quality parameter evaluated was nitrogen removal. Different from the results obtained for organic matter, which showed no statistically significant differences in the removal rate, the reactor configuration played an important role in total nitrogen (TN) and ammonia removal. Figure 5 illustrates the temporal variation of TN and NH_4^+ concentrations, as well as their removal efficiencies for both systems (C-MBR and BF-MBR) throughout the whole experiment. The C-MBR reached ammonia and total nitrogen removal efficiencies of 96% and 67%, with final effluent concentrations of 1.7 ± 0.7 mg NH_4-N/L and 17.1 ± 2.6 mg TN-N/L, respectively. On the other hand, the BF-MBR produced a permeate with lower ammonia and total nitrogen concentrations, resulting in removal efficiencies of 98% and 73%, respectively, and an effluent with 0.9 ± 0.5 mg NH_4-N/L and 14 ± 3.1 6 mg TN-N/L.

Table 2: Results for the main parameters utilized to characterize the effluent quality for C-MBR and BF-MBR (N=24).

Parameter	C-MBR				BF-MBR				
	Min	Mean	Max.	S.D.	Min.	Mean	Max.	S.D.	*p-value*
Color (uC)	12	30	72	15	9.0	23	50	10	0.0465
Turbidity (NTU)	0.10	0.36	0.85	0.21	0.09	0.22	0.65	0.14	0.0064
BOD (mg O_2/L)	2.0	6.0	10.0	2.5	2.0	6.2	9	2.1	0.8191
S-COD (mg O_2/L)	16	27	50	9.0	14	26	51	10	0.5847
NH_4(mg N/L)	0.8	1.7	3.4	0.7	0.3	0.9	2.1	0.5	0.00012
NO_3(mg N/L)	8.2	13.3	18.5	2.8	8.1	11.9	17.9	2.7	0.0261
TN (mg N/L)	12.9	17.1	22.3	2.6	10.5	14.4	20.5	3.1	0.00184

Higher TN removal in BF-MBR can mostly be attributed to multifunctional microbial reactions that take place in the developed biofilm, especially simultaneous nitrification and denitrification (SND), which play an important role in nitrogen removal. Yang *et al.* (2009) evaluated carbon and nitrogen removals under different COD/TN ratios in a moving bed membrane bioreactor (MBMBR) and demonstrated that simultaneous nitrification and denitrification were the main processes in the TN removal, where up to 89.1% was removed by SND while, for the same period, the TN removal by SND in the activated sludge MBR was only 42.5%. A comparison with other studies is presented in Figure 5.

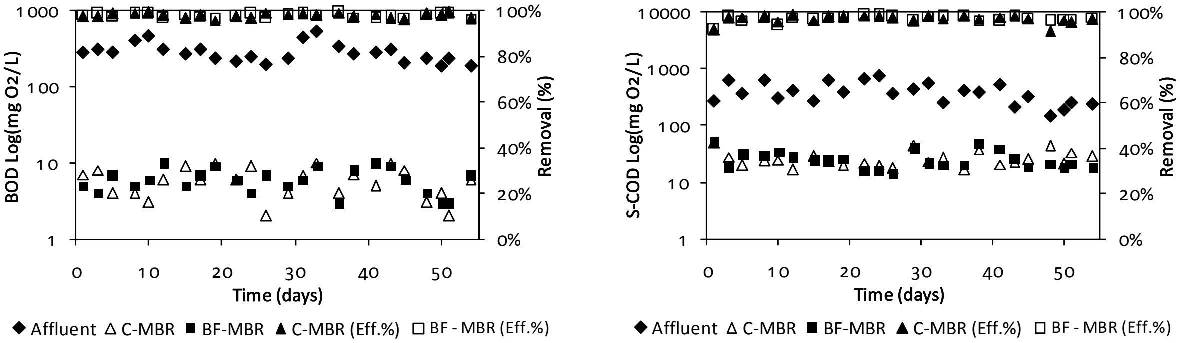


Figure 4: BOD and S-COD profiles in C-MBR and BF-MBR during the experimental evaluation period.

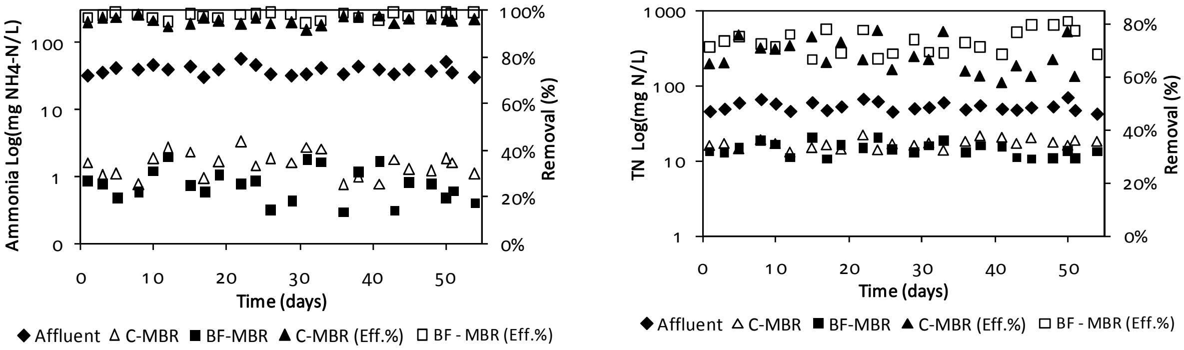


Figure 5: Ammonia and TN profiles in the C-MBR and BF-MBR during the experimental evaluation period.

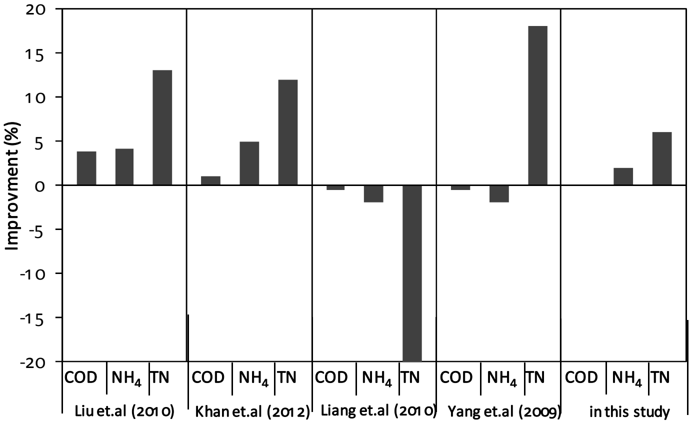


Figure 6: Efficiency improvement of organic matter and nitrogen removal in a BF-MBR compared to C-MBR.

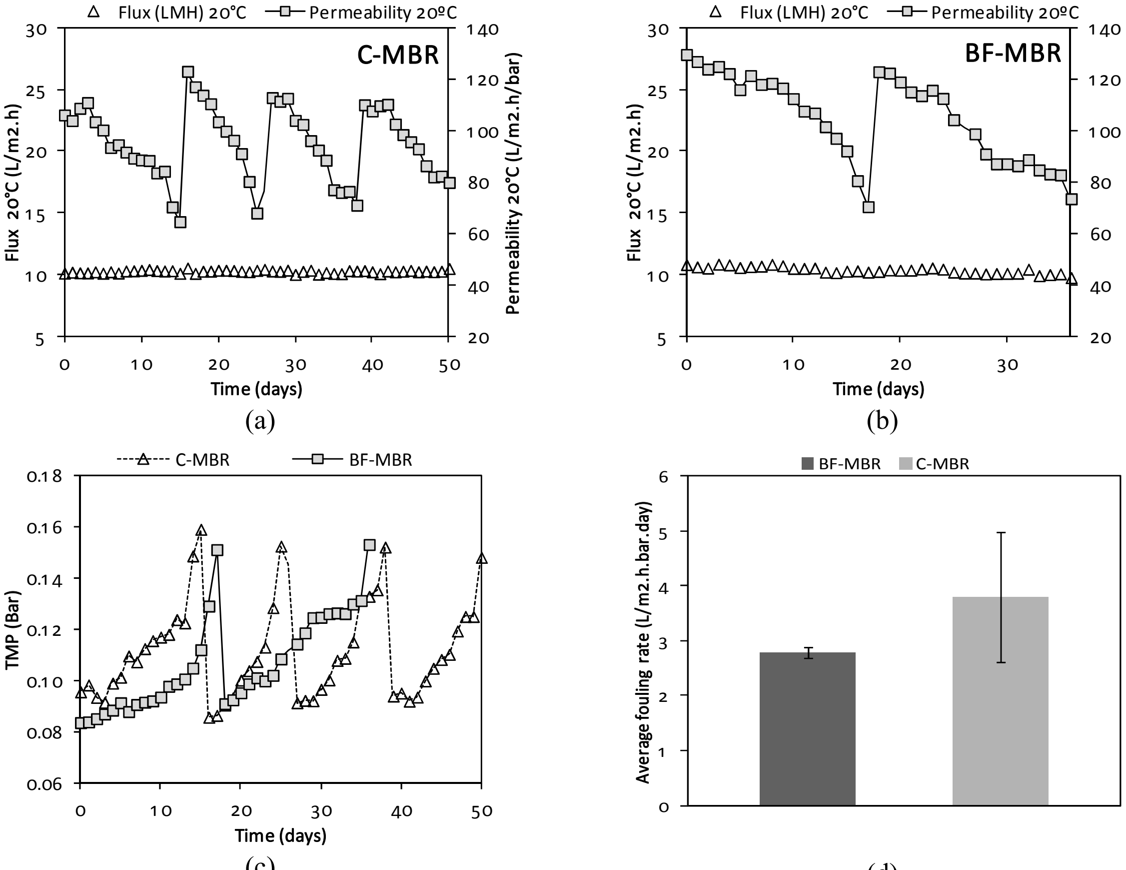
Filtration Characteristics

The transmembrane pressure (TMP) profile is an important parameter to evaluate membrane performance in submerged membrane bioreactors since it is directly influenced by the membrane fouling rate. TMP was monitored at a constant flux condition of 10.2 ± 0.2 LMH for the C-MBR and 10.4 ± 0.3 LMH for the BF-MBR. Figure 7 illustrates the TMP profile and fouling rate throughout the whole experiment. It can be observed in Figure 7 that the TMP rate for C-MBR was higher than that for the biofilm membrane bioreactor, resulting in a mean fouling rate for C-MBR and BF-MBR of 3.8 ± 1.2 L/m2.h.bar.d and 2.8 ± 0.1 L/m2.h.bar.d, respectively. As a result, the mean length of operational cycles increased by 7 days in the BF-MBR compared to the C-MBR. The resistance analysis results are presented in Table 3 and represent the mean values during the entire experimental period. Total resistance was reduced in the BF-MBR by about 29%. The fouling resistance (R_f), which included the resistance due to cake formation, pore blocking, and adsorption on the membrane surface, was found to be the predominant resistance fraction in the C-MBR, representing 58%. On the other hand in the BF-MBR the fouling resistance represented only 40%. Several studies found lower fouling rates and improved filterability when attached biomass was applied with a membrane bioreactor.

Table 3: Resistance analysis, fouling rate and permeability for C-MBR and BF-MBR during the operational period.

Process	R_t (m^{-1})	R_m (m^{-1})	R_f (m^{-1})	R_m/R_t	R_f/R_t	Permeability ($L/h.m^2.bar$)
C-MBR	5.8×10^{12}	2.5×10^{12}	3.4×10^{12}	0.42	0.58	94 ± 14
BF-MBR	4.1×10^{12}	2.5×10^{12}	1.6×10^{11}	0.60	0.40	105 ± 37

R_t is the total resistance, R_m is the membrane resistance; R_f is the fouling resistance.



(a) (b)

(c) (d)

Figure 7: Membrane filterability during the experimental period, where: (a) and (b) permeability; (c) Transmembrane pressure profile and (d) mean fouling rate.

Wang *et al*. (2010) reported a reduction of 48% in total resistance by introducing biofilm carriers into the mixed liquor, which increased the operational cycles three times. Li and Yang (2007) indicated that attached biomass can absorb some soluble organic polymers from the mixed liquor, and therefore can decrease their effect on membrane fouling.

CONCLUSIONS

This study evaluated the influence in overall performance of an attached biomass membrane bioreactor compared to a suspended biomass membrane bioreactor. The following conclusions can be drawn:

1 - No significant differences were observed regarding organic matter removal. Both systems produced an effluent with low COD concentration and about 96% COD removal;

2 - The biofilm membrane bioreactor improved the total nitrogen removal. Average TN removal in the BF-MBR was enhanced by 6%, compared with that in the C-MBR;

3 - The attached biomass in the membrane bioreactor improved the permeability and significantly reduced the fouling rate. As a result, the operational cycle length increased around 7 days in the BF-MBR compared to the C-MBR.

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REFERENCES

Anja, D., Membrane fouling in membrane bioreactors–characterisation, contradictions, cause and cures. Journal of Membrane Science, 363, p. 1-28 (2010).

Arévalo, J., Garralón, G., Plaza, F., Moreno, B., Pérez, J. and Goméz, M. A., Wastewater reuse after treatment by tertiary ultrafiltration and a membrane bioreactor (MBR): A comparative study. Desalination, 243, p. 32-41 (2009).

APHA, Standard Methots for the Examination of Water and Wastewater. 21st Ed. (2005).

Bae, T. and Tak, T., Interpretation of fouling characteristics of ultrafiltration membranes during the filtration of membrane bioreactor mixed liquor. Journal of Membrane Science, 267, p. 151-160 (2005).

Cheryan, M., Ultrafiltration and Microfiltration Handbook. Florida, CRC PRESS (1998).

Dizge, N., Koseoglu-Imer, D. Y., Karagunduz, A. and Keskinler, B., Effects of cationic polyelectrolyte on filterability and fouling reduction of submerged membrane bioreactor (MBR). Journal of Membrane Science, 377, p. 175-181 (2011).

Guo, W., Ngo, H., Palmer, C. G., Xing, W., Hu, A. Y. and Listowski A., Roles of sponge sizes and membrane types in a single stage sponge-submerged membrane bioreactor for improving nutrient removal from wastewater for reuse. Desalination, 249, p. 672-676 (2009).

Ivanovic, I., Leiknes, T. O. and Ødegaard H., Influence of loading rates on production and characteristics of retentate from a biofilm membrane bioreactor. Desalination, 199, p. 490-492 (2006).

Ivanovic I. and Leiknes T. O., The biofilm membrane bioreactor (BF-MBR) - a review. Desalination and Water Treatment, 37, p. 288-295 (2012).

Khan, S. J., Visvanathan, C. and Jegatheesan, V., Effect of powdered activated carbon (PAC) and cationic polymer on biofouling mitigation in hybrid MBRs. Bioresource Technology, 113, p. 165-168 (2012).

Koseoglu, H., Yigit, N. O., Iversen, V., Drews, A., Kitis, M., Lesjean, B. and Kraume, M., Effects of several different flux enhancing chemicals on filterability and fouling reduction of membrane bioreactor (MBR) mixed liquors. Journal of Membrane Science, 320, p. 57-64 (2008).

Le-Clech, P., Chen, V. and Fane, T. A. G., Fouling in membrane bioreactors used in wastewater treatment. Journal of Membrane Science, 284, p. 17-53 (2006).

Lee, J., Ahn, W. Y. and Lee C. H., Comparison of the filtration characteristics between attached and suspended growth microorganisms in submerged membrane bioreactor. Water Research, 35, p. 2435-2445 (2002).

Leiknes, T. O. and Ødegaard, H., The development of a biofilm membrane bioreactor. Desalination, 202, p. 135-143 (2001).

Liang, Z., Das, A., Beerman, D. and Hu, Z., Biomass characteristics of two types of submerged membrane bioreactors for nitrogen removal from wastewater. Water Research, 44, p. 3313-3320 (2010).

Li, X. Y. and Yang S. F., Influence of loosely bound extracellular polymeric substances (EPS) on the flocculation, sedimentation and dewaterability of activated sludge. Water Research, 41, p. 1022-1030 (2007).

Liu, Q., Wang, X., Liu, Y., Yuan, H. and Yujiao, D., Performance of a hybrid membrane bioreactor in municipal wastewater treatment. Desalination, 258, p. 143-147 (2010).

Metcalf, L., Eddy, H. P. and Tchobanoglous, G., Wastewater Engineering: Treatment, Disposal, Reuse. EUA, McGraw-Hill, 4th Ed. (2003).

Mierzwa, J. C., Vecitis, C. D., Carvalho, J., Arieta, V. and Verlage M., Anion dopant effects on the structure and performance of polyethersulfone membranes. Journal of Membrane Science, 421, p. 91-102 (2012).

Remya, M., Potiera, V., Temminka, H., Rulkensb, W., Why low powdered activated carbon addition reduces membrane fouling in MBRs. Water Research, 44, p. 861-867 (2010).

Santos, A., Ma, W. and Judd, S. J., Membrane bioreactors: Two decades of research and implementation. Desalination, 273, p. 148-154 (2011).

Subtil, E. L., Hespanhol, I., Mierzwa, J. C., Biorreatores com membranas submersas (BRMs): Alternativa promissora para o tratamento de esgotos sanitários para reúso. Rev. Ambient. Água, 8(3), p. 129-142 (2013). (In Portuguese).

Susan, H., Membrane Bioreactors: Global Markets (Report MST047C). BCC Research (2011).

Wang, X. C., Liu, Q. and Liu, Y. J., Membrane fouling control of hybrid membrane bioreactor. Effect of extracellular polymeric substance. Separation Science and Technology, 45, p. 928-934 (2010).

Yamamoto, K., Hiasa, M., Mahmood, T. and Matsuo, T., Direct solid–liquid separation using hollow fiber membrane in an activated-sludge aeration tank. Water Science and Technology, 21, p. 43-54 (1989).

Yang, W., Cicek, N. and Ilg, J., State-of-the-art of membrane bioreactors: Worldwide research and commercial applications in North America. Journal of Membrane Science 207, p. 201-211 (2006).

Yang, Q., Chen, J. and Zhang, F., Membrane fouling control in a submerged membrane bioreactor with porous, flexible suspended carriers. Desalination, 189, p. 292-302 (2006).

Yang, S., Yang, F., Fu, Z. and Lei, R., Comparison between a moving bed membrane bioreactor and a conventional membrane bioreactor on organic carbon and nitrogen removal. Bioresource Technology, 100, p. 2369-2374 (2009).

Yang, S., Yang, F., Fu, Z. and Lei, R., Comparison between a moving bed membrane bioreactor and a conventional membrane bioreactor on membrane fouling. Bioresource Technology, 100, p. 6655-6657 (2009).

Zhang, H., Sun, B., Zhao, X. and Gao, Z., Effect of ferric chloride on fouling in membrane bioreactor. Separation and Purification Technology, 63, p. 341-347 (2008).