UNIVERSITI PUTRA MALAYSIA

IN-SITU BIOFOULING MITIGATION USING ULTRASONICATION IN MEMBRANE BIOREACTOR

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By

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IN-SITU BIOFOULING MITIGATION USING ULTRASONICATION IN MEMBRANE BIOREACTOR (MBR)

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This thesis investigates the biofouling mitigation in a membrane bioreactor (MBR) using ultrasonication method. Membrane fouling is recognized as a major drawback for the application of wastewater treatment and has remained a critical limiting factor for wide spread application of the technology. Membrane biofouling is characterized as soluble microbial products and extracellular polymeric substances in the form of protein and polysaccharides concentration. Fouling was observed by the increment of the trans-membrane pressure (TMP) and assumed to occur first by pore blockage followed by cake formation over the blocked pores.

Characterization results showed that the concentration of the soluble microbial products (SMP) ranged from 10.76 to 30.72 and 5.97 to 17.05 mg/L for polysaccharides and protein, respectively, and the extracellular polymeric substances (EPS) ranged from 9.87 to 38.70 and 10.56 to 28.85 mg/L for polysaccharides and protein, respectively, at SRT of 30 days. The SMP fraction is considered the main contributor to membrane fouling via adsorption of macromolecules and pore clogging. The evaluation on the performance of membrane bioreactors has been carried out by changing the operating parameters of the system with solids retention time and hydraulic retention time of 30, 15, and 4 days and 12, 8 and 4 hours, respectively. The best removal efficiencies recorded were at SRT 30 days and HRT 12 hours. Removals of COD, BOD, NH_3-N and PO_4^{3-} achieved at 95%, 93%, 98% and 81%, respectively. Results demonstrated that the COD removal efficiency decrease from 95.31% (at HRT 12) to 92.86% (at HRT 8) and further decreased to 92.79% (at HRT 4). The NH_3-N removal efficiency decreased from 97.60% (at HRT 12) to 91.03% (at HRT 8) and remains at 91.25% (at HRT 4). Fouling morphology proves that there were two types of fouling observed which are biofilm and the cake layer formation.

Mitigating membrane biofouling using an in-situ ultrasonication method was carried out at a cleaning frequency of 28 kHz for 10 min contact time with and without chemicals. The best recoveries achieved were 57 and 67% with and without cleaning agents. It should be noted that the best flux recoveries achieved was by using 1.0 M of NaOH and NaOCl, with flux recoveries of 55 and 50%, respectively.

The economic viability of the integrated system showed that it is able to treat effluent with the cost of RM 4.04 per cubic meter with longer operation time, space saving due to in-situ cleaning and the selected sequence could be prolong the treatment process up to three cycle of the normal membrane filtration system. Hence, it can be concluded that this integrated system is cost effective, environmental friendly, space saving and could offer an alternative method in mitigating membrane fouling in a membrane bioreactor.

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IN-SITU PEMBASMIAN SUMBATAN BIO MENGGUNAKAN FREKUENSI SONIK DI DALAM MEMBRAN REAKTOR BIO

Oleh

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Tesis ini mengkaji kaedah pencegahan penyumbatan yang terbentuk secara tindak balas biologi di dalam bioreaktor ber-membran menggunakan kaedah gelombang ultra. Sumbatan pada membran telah dikenalpasti sebagai salah satu punca yang menyekat perkembangan teknologi membran dalam rawatan airsisa dan jalan penyelesian kepada isu ini masih belum terjawab. Sumbatan membran secara tindakbalas biologi boleh di kategorikan sebagai bahan buangan mikrob dan bahan lebihan berpolimer dalam bentuk kepekatan protein dan polisakarida.

Sumbatan membran telah dikesan melalui peningkatan tekanan di dalam membran dan berlaku akibat sumbatan di liang rongga membran diikuti dengan pembentukan lapisan tebal. Keputusan daripada pengkelasan bahan buangan mikrob berada dalam anggaran 10.76 hingga 30.72 mg/L bagi polisakarida dan 5.97 hingga 17.05 mg/L bagi protein. Untuk bahan lebihan berpolimer, kandungan polisakarida didapati dalam anggaran 9.87 hingga 38.70 mg/L dan kandungan protein beranggaran 10.56 hingga 28.85 mg/L pada kadar penyimpanan pepejal selama 30 hari. Pecahan bahan buangan mikrob merupakan penyumbang utama kepada sumbatan membran melalui penyerapan molekul dan penyumbatan liang rongga membran. Keberkesanan bioreactor bermembran diuji melalui pertukaran beberapa parameter dan pembolehubah iaitu pada kadar masa 12, 8 dan 4 jam dan kandungan pepejal tersimpan pada 30, 15 dan 4 hari. Keputusan eksperimen menunjukkan optimum parameter yang terbaik adalah pada kombinasi kadar masa 12 jam dan kandungan pepejal tersimpan pada 30 hari. Kandungan oksigen terlarut kimia, oksigen terlarut organik, ammonia dan fosforus berkurang sebanyak 95%, 93%, 98% dan 81%. Keputusan eksperimen juga menunjukkan pengurangan oksigen terlarut kimia berkurang dari 95.31% (pada kadar 12 jam) kepada 92.86% (pada kadar 8 jam) dan turut berkurang kepada 92.79% (pada kadar 4 jam). Pengurangan kandungan ammonia berkurang dari 97.60% (pada kadar 12 jam) kepada 91.03% (pada kadar 8 jam) dan sekata pada 91.25% (pada kadar 4 jam). Morfologi sumbatan pada permukaan membran membuktikan terdapat dua jenis sumbatan iaitu selaput biologi dan pembentukan lapisan kek.

Penyelesaian isu sumbatan membran menggunakan in-situ gelombang sonik telah di jalankan pada frekuensi 28 kHz untuk 10 minit dengan dan tanpa bahan kimia. Keputusan terbaik diperolehi dengan kadar pembersihan sebanyak 57% tanpa penggunaan bahan kimia dan 67% dengan menggunakan bahan pembersih. Menggunakan NaOH mendapat kadar pembersihan sebanyak 55% dan menggunakan NaOCl mendapat kadar pembersihan sebanyak 50%. Penilaian dari segi praktikal dan

kadar ekonomi, sistem kombinasi ini menunjukkan keupayaan merawat airsisa pada harga RM 4.04 per meter padu dengan tempoh masa operasi yang panjang dan penjimatan ruang kerana proses pembersihan dijalankan di tempat yang sama. Proses penapisan membran dengan kombinasi ini dapat menjimatkan masa kerana satu kitaran bersamaan dengan tiga kali kitaran biasa. Oleh itu, secara kesimpulannya, sistem ini lebih efektif, mesra alam, jimat ruang dan dapat menjadi kaedah alternatif dalam menanggani masalah sumbatan membran.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

θ_h	hydraulic retention time	[h]
TMP	trans-membrane pressure	[kPa/mmHg]
MLSS	mixed liquor suspended solids	[mg/L]
Q	daily volumetric flow rate	[m^3/day]
SMP	soluble microbial products	[mg/L]
EPS	extracellular polymeric substances	[mg/L]
SVI	sludge volume index	-
V	reactor volume at a given time	[m^3]
SRT	sludge retention time	[day]
MBR	membrane bioreactor	-
F/M	food-to-microorganism ratio	-
BOD	biodegradable oxygen demand	[mg/L]
COD	chemical oxygen demand	[mg/L]
RAS	return activated sludge	-
SUVA	specific UV absorbance	-
UAP	utilization-associated products	-
BAP	biomass-associated products	-
PN	protein concentration	[mg/L]
PS	polysaccharide concentration	[mg/L]
PN/PS	ratio protein over polysaccharide	-
TOC	total organic carbon	[mg/L]
J	permeate flux	[LMH]
R	resistance	[m^{-1}]
DO	dissolved oxygen	[mg/L]
DI	deionized water	-
STP	sewage treatment plant	-
ΔP	pressure difference	[kPa/mmHg]

CHAPTER 1

INTRODUCTION

1.1 Background

Membrane bioreactors (MBR) are becoming the-state-of-the-art in wastewater treatment due to their unique advantages and a promising technology for future wastewater treatment. MBR is a combination of bioreactors and membrane filtration for biomass retention, using microbes for biological degradation of pollutants. By improving the biological treatment efficiency, MBR produces high quality effluent, which is difficult to achieve with the conventional activated sludge treatment system.

The success in applications of the submerged hollow fiber membrane modules in MBR has led to rapid expansion of the applications of MBR in municipal wastewater treatment. The global market for membrane bioreactor technology is projected to grow at a compound annual growth rate of 10.5%, increasing in value from $296.0 million in 2008 to $488.0 million by 2013 (Kraume and Drews, 2010). Growth rates of MBR systems are not the same for all world regions and are not increasing from the same base. Municipal or domestic wastewater treatment was the earliest application of MBRs and is still the largest application, accounting for 44% of all systems (Kraume and Drews, 2010). Other influencing factors for driving MBR technology implementation include new and more stringent legislation affecting both sewage treatment and industrial effluent discharge, local water scarcity, the introduction of incentives to encourage improvements in wastewater, decreasing investment costs and the increasing confidence in the acceptance of MBR technology. However, membrane fouling remains as a critical limiting factor for the wide spread applications of MBR.

1.2 Problem statement

Membrane fouling is the most unavoidable challenges which results in reduced performance, severe flux decline, increasing energy consumption and frequent membrane cleaning and/or replacement. Frequent maintenance cleaning (approx. every 2 to 7 days) is needed which leads to environmental hazards through the formation of chemical cleaning by-products such as adsorbable organic halogens (Brepols *et al.*, 2008). Damaging, inefficient or late chemical cleaning might reduce the hollow fiber modules lifespan and result in higher replacement costs.

Fouling is defined as the undesirable deposition and accumulation of microorganisms, colloids, solutes and cell debris within/on the membrane. Major parameters for causing fouling are viscosity of solution, total extracellular polymeric substance (EPS), soluble microbial products (SMP), food to microorganism ratios and the size distribution of sludge flocs and colloids (Jarusutthirak *et al.*, 2006; Jiang *et al.*, 2010). Many authors further dedicated to classifying membrane fouling into three major categories: biofouling, organic fouling and inorganic fouling (Bérubé *et al.*, 2006). All three fouling mechanisms are usually observed simultaneously.

The design, operational conditions, membrane materials, biomass characteristics and feed water characteristics affects fouling of the membrane. Multiple and complex interactions occur between the various operating conditions, biological and ambient conditions which will influence the permeability loss. Since biomass and membrane properties change over time, the nature and location of fouling will vary. Due to its economical impact, fouling has been a major issue in MBR research for more than a decade with a steady increase in published articles (Anja Drews, 2010).

The integration of a MBR system with an in-situ biofouling mitigation process will give an alternative solution to the major drawbacks of membrane fouling and reduce subsequent membrane cleaning and associated cost. This will give advantages in terms of energy reduction and less time consumption in membrane cleaning during operational. The evaluation of performance of a membrane bioreactor in treating high strength wastewater at different loading rates and the control of biofouling development at site will predict the lifespan of the hollow fiber modules.

1.3 Goals and objectives

The goal of this research is to study and evaluate the feasibility of mitigating biofouling in MBR using ultrasonication method locally. This can be achieved through the following specific objectives:

i. to characterize biofouling in terms of soluble microbial products (SMP) and extracellular polymeric substances (EPS) in membrane bioreactor (MBR).
ii. to evaluate the performance of MBR with respect to biofouling formation.
iii. to mitigate biofouling on membrane using ultrasonication method.

1.4 Scope of work

This thesis aims to improve the performance of MBR in treating sewage effluent and in particular to increase the life-cycle of membrane by reducing membrane fouling. An outline of this research is presented in Figure 1.1. An innovative system using the MBR in combination with activated sludge process and incorporating a cleaning transducer on the MBR system for solving membrane fouling was developed. The performance of this novel system for the removal of organic, nitrogen and phosphorus from wastewater was evaluated. Since membrane fouling is the main obstacle for MBR application, the mechanism of membrane fouling and the major foulants in the MBR sludge were investigated. The soluble microbial products from the sludge were characterized. Based on the new understanding of SMP's role in MBR fouling, some mitigation strategies, including ultrasonication and chemical cleaning were experimented to control membrane fouling in MBR.

1.5 Outline of the thesis

Chapter 1 gives a brief introduction to the background and motivation of the research. This chapter set to point out the aim, objectives and significance of the study. It also gives and outline the scope of the research as well as the overall structure of the thesis.

Chapter 2 provides a detailed literature review on the submerged membrane bioreactor for wastewater treatment. Previous studies on membrane filtration in wastewater treatment and reuse, factors constraining MBR application, characteristics of major foulants in MBR system and the related fouling mechanisms including possible membrane fouling control methods are reviewed extensively.

Chapter 3 describes the methodologies used for the experimental studies on the MBR for organic removal, foulant identification and characterization, the mechanism of membrane fouling and its control strategies, including the experimental setup, materials, laboratory procedures, analytical instruments and measurement of various parameters.

From Chapter 4 to Chapter 6, experimental results are presented. The contents include:

i. characterization of the biofouling in membrane bioreactor,
ii. effects of operating conditions of membrane bioreactor on biofouling formation, mitigating biofouling on membrane.
iii. Chapter 7 summarizes the conclusion(s) drawn from the experimental results.

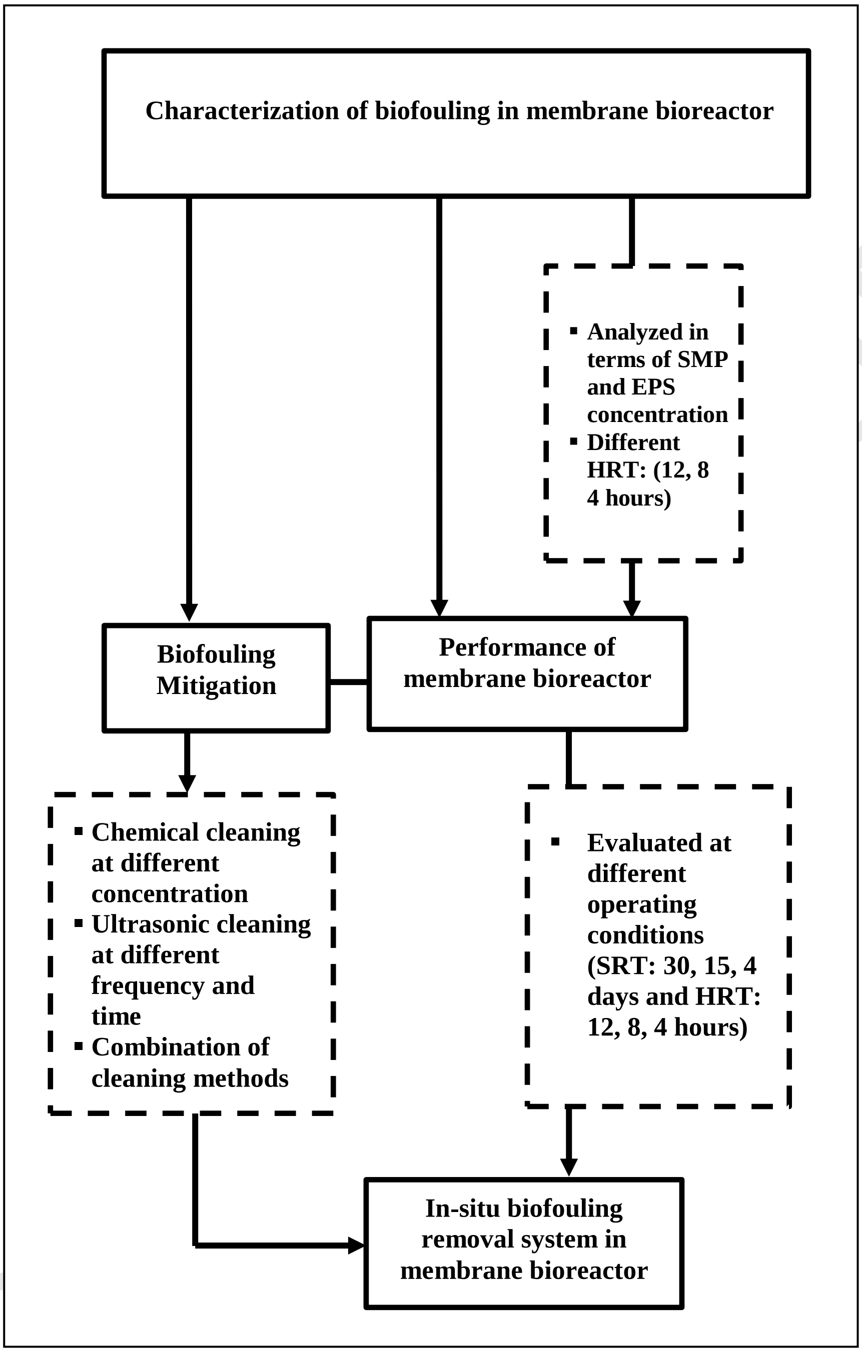

Figure 1.1: Outline of the study

REFERENCES

Adham, S., Chiu, K.-P., Gramith, K., & Oppenheimer, J. (2005). Development of a Microfiltration and Ultrafiltration Knowledge Base. AWWARF, Denver Co.:

Ahmed, Z., Cho, J., Lim, B.-R., Song, K.-G., & Ahn, K.-H. (2007). Effects of sludge retention time on membrane fouling and microbial community structure in a membrane bioreactor. Journal of Membrane Science, 287(2), 211–218. doi:10.1016/j.memsci.2006.10.036

Al-Amoudi, A., & Lovitt, R. W. (2007). Fouling strategies and the cleaning system of NF membranes and factors affecting cleaning efficiency. Journal of Membrane Science, 303(1-2), 4–28. doi:10.1016/j.memsci.2007.06.002

Ardern, E., & Lockett, W. T. (1914). (1914). Experiments on the oxidation of sewage without the aid of filters. Journal of the Society of Chemical Industry, 33(10), 523–539.

Arkhangelsky, E., Kuzmenko, D., & Gitis, V. (2007). Impact of chemical cleaning on properties and functioning of polyethersulfone membranes. Journal of Membrane Science, 305(1-2), 176–184. doi:10.1016/j.memsci.2007.08.007

AWWA. (2005a). Microfiltration and Ultrafiltration Membranes in Drinking Water: AWWA Manual of Water Supply Practice M57. Denver Co.: AWWA, 1583213600.

AWWA. (2005b). Microfiltration and Ultrafiltration Membranes in Drinking Water: AWWA Manual of Water Supply Practice M57, Denver Co.: AWWA, 1583213600.

Bae, T.-H., & Tak, T.-M. (2005). Interpretation of fouling characteristics of ultrafiltration membranes during the filtration of membrane bioreactor mixed liquor. Journal of Membrane Science, 264(1-2), 151–160. doi:10.1016/j.memsci.2005.04.037

Barker, D. J., & Stuckey, D. C. (1999). A review of soluble microbial products (SMP) in wastewater treatment systems. Water Research, 33(14), 3063–3082. doi:10.1016/S0043-1354(99)00022-6

Bechhold, H. (1907). Method, Investigation on colloids by filtration. Biochem. Z., (6), p. 397.

Benetti, A. (2000). Composition, fate and transformation of extracellular polymers in wastewater and sludge treatment process, pp. 4–32.

Bérubé, P. R., Afonso, G., Taghipour, F., & Chan, C. C. V. (2006). Quantifying the shear at the surface of submerged hollow fiber membranes. Journal of Membrane Science, 279(1-2), 495–505. doi:10.1016/j.memsci.2005.12.043

Bin, C., Xiaochang, W., & Enrang, W. (2004). (2004). Effects of TMP, MLSS concentration and intermittent membrane permeation on a hybrid submerged MBR

fouling. In Proceedings of the Water Environment-Membrane Technology Conference, Seoul, Korea.
Bouhabila, E. H., Ben Aïm, R., & Buisson, H. (1998). Microfiltration of activated sludge using submerged membrane with air bubbling (application to wastewater treatment). Desalination, 118(1-3), 315–322. doi:10.1016/S0011-9164(98)00156-8

BRANT, J. (2004). Colloidal adhesion to hydrophilic membrane surfaces. Journal of Membrane Science, 241(2), 235–248. doi:10.1016/j.memsci.2004.04.036

Carey, F. A., & Sundberg, R. J. (2007). Advanced Organic Chemistry Part B: Reactions and Synthesis. Ebook (pp. 1–1199). doi:10.1007/b114222

Chang, I. S., le Clech, P., Jefferson, B., & Judd, S. (2002). Membrane Fouling in Membrane Bioreactors for Wastewater Treatment. Journal of Environmental Engineering, 128, 1018–1029.

Chang, I.-S., & Lee, C.-H. (1998). Membrane filtration characteristics in membrane-coupled activated sludge system — the effect of physiological states of activated sludge on membrane fouling. Desalination. doi:10.1016/S0011-9164(98)00220-3

Chang, I.-S., Bag, S.-O., & Lee, C.-H. (2001). Effects of membrane fouling on solute rejection during membrane filtration of activated sludge. Process Biochemistry, 36(8-9), 855–860. doi:10.1016/S0032-9592(00)00284-3

Chang, J. (2002). Continuous process for propylene/propane separation by use of silver nitrate carrier and zirconia porous membrane. Journal of Membrane Science, 205(1-2), 91–102. doi:10.1016/S0376-7388(02)00066-2

Chang, J.-S., Chang, C.-Y., Chen, A.-C., Erdei, L., & Vigneswaran, S. (2006). Long-term operation of submerged membrane bioreactor for the treatment of high strength acrylonitrile-butadiene-styrene (ABS) wastewater: effect of hydraulic retention time. Desalination, 191(1-3), 45–51. doi:10.1016/j.desal.2005.07.020

Chen, D., Weavers, L., Walker, H., & Lenhart, J. (2006). Ultrasonic control of ceramic membrane fouling caused by natural organic matter and silica particles. Journal of Membrane Science, 276(1-2), 135–144. doi:10.1016/j.memsci.2005.09.039

Cheryan, M. (2000). Ultrafiltration and Microfiltration Handbook, 2nd ed., C.

Cho, B. ., & Fane, A. . (2002). Fouling transients in nominally sub-critical flux operation of a membrane bioreactor. Journal of Membrane Science, 209(2), 391–403. doi:10.1016/S0376-7388(02)00321-6

Cho, J. W., Ahn, K. H., Lee, Y. H., Lim, B. R., & Kim, J. Y. (2004). Investigation of biological and fouling characteristics of submerged membrane bioreactor process for wastewater treatment by model sensitivity analysis. In Water Science and Technology (Vol. 49, pp. 245–254). Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-1342305462&partnerID=tZOtx3y1

Cho, J., Song, K.-G., & Ahn, K.-H. (2005). The activated sludge and microbial substances influences on membrane fouling in submerged membrane bioreactor: unstirred batch cell test. Desalination, 183(1-3), 425–429. doi:10.1016/j.desal.2005.05.009

Chudoba, J. (1985). Inhibitory effect of refractory organic compounds produced by activated sludge micro-organisms on microbial activity and flocculation. Water Research, 19(2), 197–200. doi:10.1016/0043-1354(85)90199-X

Cicek, N., Winnen, H., Suidan, M. T., Wrenn, B. E., Urbain, V., & Manem, J. (1998). Effectiveness of the membrane bioreactor in the biodegradation of high molecular weight compounds. Water Research, 32(5), 1553–1563. doi:10.1016/S0043-1354(97)00350-3

Comte, S., Guibaud, G., & Baudu, M. (2006). Biosorption properties of extracellular polymeric substances (EPS) resulting from activated sludge according to their type: Soluble or bound. Process Biochemistry, 41(4), 815–823. doi:10.1016/j.procbio.2005.10.014

Defrance, L. (1999). Reversibility of fouling formed in activated sludge filtration. Journal of Membrane Science, 157(1), 73–84. doi:10.1016/S0376-7388(98)00356-1

Dias, F. F., & Bhat, J. V. (1964). MICROBIAL ECOLOGY OF ACTIVATED SLUDGE. I. DOMINANT BACTERIA. Applied Microbiology, 12, 412–417. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0000146235&partnerID=tZOtx3y1

Drews, A. (2010). Membrane fouling in membrane bioreactors—Characterisation, contradictions, cause and cures. Journal of Membrane Science, 363(1-2), 1–28. doi:10.1016/j.memsci.2010.06.046

Drews, A., Lee, C.-H., & Kraume, M. (2006). Membrane fouling - a review on the role of EPS. Desalination, 200(1-3), 186–188. doi:10.1016/j.desal.2006.03.290

Drews, A., Vocks, M., Bracklow, U., Iversen, V., & Kraume, M. (2008). Does fouling in MBRs depend on SMP? Desalination, 231(1-3), 141–149. doi:10.1016/j.desal.2007.11.042

Faust, S. D., & Aly, O. (1998). Chemistry of Water Treatment. CRC Press Taylor and Francis, Florida, USA.

Ferrando, M., Rrzek, A., Zator, M., Lopez, F., & Guell, C. (2005). An approach to membrane fouling characterization by confocal scanning laser microscopy. Journal of Membrane Science, 250(1-2), 283–293. doi:10.1016/j.memsci.2004.10.043

Flemming, H. C., & Wingender, J. (2001). Relevance of microbial extracellular polymeric substances (EPSs) - Part I: Structural and ecological aspects. In Water Science and Technology (Vol. 43, pp. 1–8). Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0035023483&partnerID=tZOtx3y1

Frølund, B., Palmgren, R., Keiding, K., & Nielsen, P. H. (1996). Extraction of extracellular polymers from activated sludge using a cation exchange resin. Water Research, 30(8), 1749–1758. doi:10.1016/0043-1354(95)00323-1

Geng, Z., & Hall, E. R. (2007). A comparative study of fouling-related properties of sludge from conventional and membrane enhanced biological phosphorus removal processes. Water Research, 41(19), 4329–38. doi:10.1016/j.watres.2007.07.007

Günder, B. (2001). The Membrane-coupled Activated Sludge Process in Municipal Wastewater Treatment.

Hamachi, M., & Mietton-Peuchot, M. (2002). Analysis of deposit behaviour in crossflow microfiltration by means of thickness measurement. Chemical Engineering Journal, 86(3), 251–257. doi:10.1016/S1385-8947(01)00184-X

Han, S.-S., Bae, T.-H., Jang, G.-G., & Tak, T.-M. (2005). Influence of sludge retention time on membrane fouling and bioactivities in membrane bioreactor system. Process Biochemistry, 40(7), 2393–2400. doi:10.1016/j.procbio.2004.09.017

Han, Y., Liu, J., Guo, X., & Li, L. (2012). Micro-environment characteristics and microbial communities in activated sludge flocs of different particle size. Bioresource Technology, 124, 252–8. doi:10.1016/j.biortech.2012.08.008

Hilal, N., Bowen, W. R., Alkhatib, L., & Ogunbiyi, O. (2006). A Review of Atomic Force Microscopy Applied to Cell Interactions with Membranes. Chemical Engineering Research and Design, 84(4), 282–292. doi:10.1205/cherd05053

Hong, S., & Elimelech, M. (1997). Chemical and physical aspects of natural organic matter (NOM) fouling of nanofiltration membranes. Journal of Membrane Science, 132(2), 159–181. doi:10.1016/S0376-7388(97)00060-4

Huang, H., Lee, N., Young, T., Gary, A., Lozier, J. C., & Jacangelo, J. G. (2007). Natural organic matter fouling of low-pressure, hollow-fiber membranes: Effects of NOM source and hydrodynamic conditions. Water Research, 41(17), 3823–32. doi:10.1016/j.watres.2007.05.036

Iritani, E., Katagiri, N., Sengoku, T., Yoo, K. M., Kawasaki, K., & Matsuda, A. (2007). Flux decline behaviors in dead-end microfiltration of activated sludge and its supernatant. Journal of Membrane Science, 300(1-2), 36–44. doi:10.1016/j.memsci.2007.04.041

Itonaga, T., Kimura, K., & Watanabe, Y. (2004). Influence of suspension viscosity and colloidal particles on permeability of membrane used in membrane bioreactor (MBR). Water Science and Technology, 50(12), 301–309. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-13444283376&partnerID=tZOtx3y1

Jenkins, D., Richard, M., & Daigger, G. (1993). Manual on the Causes and Control of Activated Sludge Bulking and Foaming.

Jeong, T.-Y., Cha, G.-C., Yoo, I.-K., & Kim, D.-J. (2007). Characteristics of bio-fouling in a submerged MBR. Desalination, 207(1-3), 107–113. doi:10.1016/j.desal.2006.07.006

Ji, L., & Zhou, J. (2006). Influence of aeration on microbial polymers and membrane fouling in submerged membrane bioreactors. Journal of Membrane Science, 276(1-2), 168–177. doi:10.1016/j.memsci.2005.09.045

Kim, I. S., & Jang, N. (2006). The effect of calcium on the membrane biofouling in the membrane bioreactor (MBR). Water Research, 40(14), 2756–64. doi:10.1016/j.watres.2006.03.036

Koh, L., Ahn, W., & Clark, M. (2006). Selective adsorption of natural organic foulants by polysulfone colloids: Effect on ultrafiltration fouling. Journal of Membrane Science, 281(1-2), 472–479. doi:10.1016/j.memsci.2006.04.030

Laspidou, C., & Rittmann, B. E. (2002). A unified theory for extracellular polymeric substances, soluble microbial products, and active and inert biomass. Water Research, 36(11), 2711–2720. doi:10.1016/S0043-1354(01)00413-4

Le Clech, P., Jefferson, B., Chang, I. S., & Judd, S. J. (2003). Critical flux determination by the flux-step method in a submerged membrane bioreactor. Journal of Membrane Science, 227(1-2), 81–93. doi:10.1016/j.memsci.2003.07.021

Le-Clech, P., Chen, V., & Fane, T. A. G. (2006a). Fouling in membrane bioreactors used in wastewater treatment. Journal of Membrane Science. doi:10.1016/j.memsci.2006.08.019

Le-Clech, P., Chen, V., & Fane, T. A. G. (2006b). Fouling in membrane bioreactors used in wastewater treatment. Journal of Membrane Science, 284(1-2), 17–53. doi:10.1016/j.memsci.2006.08.019

Le-Clech, P., Jefferson, B., & Judd, S. . (2003). Impact of aeration, solids concentration and membrane characteristics on the hydraulic performance of a membrane bioreactor. Journal of Membrane Science, 218(1-2), 117–129. doi:10.1016/S0376-7388(03)00164-9

Lee, E. K., Chen, V., & Fane, A. G. (2008). Natural organic matter (NOM) fouling in low pressure membrane filtration — effect of membranes and operation modes. Desalination, 218(1-3), 257–270. doi:10.1016/j.desal.2007.02.021

Lee, H.-J., Kim, D. H., Cho, J., & Moon, S.-H. (2003). Characterization of anion exchange membranes with natural organic matter (NOM) during electrodialysis. Desalination, 151(1), 43–52. doi:10.1016/S0011-9164(02)00971-2

Lesjean, B., Rosenberger, S., Schrotter, J.-C., & Recherche, A. (2004). Membrane-aided biological wastewater treatment — an overview of applied systems. Membrane Technology, 2004(8), 5–10. doi:10.1016/S0958-2118(04)00200-9

Li, J., Hallbauer, D. K., & Sanderson, R. D. (2003). Direct monitoring of membrane fouling and cleaning during ultrafiltration using a non-invasive ultrasonic technique. Journal of Membrane Science, 215, 33–52. doi:10.1016/S0376-7388(02)00600-2

Li, X., & Wang, X. (2006). Modelling of membrane fouling in a submerged membrane bioreactor. Journal of Membrane Science, 278(1-2), 151–161. doi:10.1016/j.memsci.2005.10.051

Liang, S., Liu, C., & Song, L. (2007). Soluble microbial products in membrane bioreactor operation: Behaviors, characteristics, and fouling potential. Water Research, 41(1), 95–101. doi:10.1016/j.watres.2006.10.008

Liikanen, R., Yli-Kuivila, J., & Laukkanen, R. (2002). Efficiency of various chemical cleanings for nanofiltration membrane fouled by conventionally-treated surface water. Journal of Membrane Science, 195(2), 265–276. doi:10.1016/S0376-7388(01)00569-5

Liu, C., & Caothien, S.J. Hayes, T. C. (2001). Membrane chemical cleaning: from art to Science,. Proc. AWWA 2000 Water Quality Technology Conference, Denver Co.

Liu, R., Huang, X., Sun, Y. F., & Qian, Y. (2003). Hydrodynamic effect on sludge accumulation over membrane surfaces in a submerged membrane bioreactor. Process Biochemistry, 39(2), 157–163. doi:10.1016/S0032-9592(03)00022-0

Lonsdale, H. K. (1981). Membrane Separation Processes 1979, Report No. 5-79. Journal of Membrane Science, 8(2), 222. doi:10.1016/S0376-7388(00)82092-X

Lyko, S., Al-Halbouni, D., Wintgens, T., Janot, A., Hollender, J., Dott, W., & Melin, T. (2007). Polymeric compounds in activated sludge supernatant -- Characterisation and retention mechanisms at a full-scale municipal membrane bioreactor. Water Research, 41(17), 3894–902. doi:10.1016/j.watres.2007.06.012

Mallevialle, J., & Odendaal, P. (1996). Water treatment Membrane Processes,. Denver Co.: AWWA McGraw Hill, USA.

McAdam, E. J., & Judd, S. J. (2006). A review of membrane bioreactor potential for nitrate removal from drinking water. Desalination, 196(1-3), 135–148. doi:10.1016/j.desal.2006.03.008

Meng, F., Chae, S.-R., Drews, A., Kraume, M., Shin, H.-S., & Yang, F. (2009). Recent advances in membrane bioreactors (MBRs): membrane fouling and membrane material. Water Research, 43(6), 1489–512. doi:10.1016/j.watres.2008.12.044

Meng, F., Liao, B., Liang, S., Yang, F., Zhang, H., & Song, L. (2010). Morphological visualization, componential characterization and microbiological identification of membrane fouling in membrane bioreactors (MBRs). Journal of Membrane Science, 361(1-2), 1–14. doi:10.1016/j.memsci.2010.06.006

Meng, F., Yang, F., Xiao, J., Zhang, H., & Gong, Z. (2006). A new insight into membrane fouling mechanism during membrane filtration of bulking and normal sludge suspension. Journal of Membrane Science, 285(1-2), 159–165. doi:10.1016/j.memsci.2006.08.020

Meng, F., Zhang, H., Li, Y., Zhang, X., & Yang, F. (2005). Application of fractal permeation model to investigate membrane fouling in membrane bioreactor. Journal of Membrane Science, 262(1-2), 107–116. doi:10.1016/j.memsci.2005.04.013

Metcalf, E., & Eddy, H. (2003). Wastewater engineering: treatment and reuse. Wastewater Engineering, Treatment, Disposal and Reuse. Techobanoglous G, Burton FL, Stensel HD (eds). Tata McGraw-Hill Publishing Company Limited, 4th edition. New Delhi, India (p. 1819). Retrieved from http://www.lavoisier.fr/notice/fr097556.html

Mulder, M. (1996). Basic Principles of Membrane Technology Second Edition (p. 564). Springer. Retrieved from http://books.google.com/books?hl=en&lr=&id=tSlUcdPqnScC&pgis=1

Nagaoka, H. (1999). Nitrogen removal by submerged membrane separation activated sludge process. Water Science and Technology, 39(8), 107–114. doi:10.1016/S0273-1223(99)00192-4

Nagaoka, H., Kurosaka, M., Shibata, N., & Kobayashi, M. (2006). Effect of bubble flow velocity on drag-force and shear stress working on submerged hollow fibre membrane. Water Science & Technology, 54(10), 185. doi:10.2166/wst.2006.818

Nagaoka, H., Ueda, S., & Miya, A. (1996). Influence of bacterial extracellular polymers on the membrane separation activated sludge process. Water Science and Technology, 34(9), 165–172. doi:10.1016/S0273-1223(96)00800-1

Namkung, E., & Rittmann, B. E. (1988). Effects of SMP on biofilm-reactor performance. Journal of Environmental Engineering, 114(1). Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0023966216&partnerID=tZOtx3y1

Ng, H. Y., Tan, T. W., & Ong, S. L. (2006). Membrane fouling of submerged membrane bioreactors: impact of mean cell residence time and the contributing factors. Environmental Science & Technology, 40, 2706–2713. doi:10.1021/es0516155

Ni, B.-J., Rittmann, B. E., & Yu, H.-Q. (2011). Soluble microbial products and their implications in mixed culture biotechnology. Trends in Biotechnology, 29(9), 454–63. doi:10.1016/j.tibtech.2011.04.006

Nuengjamnong, C., Kweon, J. H., Cho, J., Polprasert, C., & Ahn, K.-H. (2005). Membrane fouling caused by extracellular polymeric substances during microfiltration processes. Desalination, 179(1-3), 117–124. doi:10.1016/j.desal.2004.11.060

Owen, G., Bandi, M., Howell, J. A., & Churchouse, S. J. (1995). Economic assessment of membrane processes for water and waste water treatment. Journal of Membrane Science, 102, 77–91. doi:10.1016/0376-7388(94)00261-V

Paul, P., & Hartung, C. (2008). Modelling of biological fouling propensity by inference in a side stream membrane bioreactor. Desalination, 224(1-3), 154–159. doi:10.1016/j.desal.2007.02.087

Pike, E. B., Carrington, E. G., & Ashburner, P. A. (1972). An evaluation of procedures for enumerating bacteria in activated sludge. Journal of Applied Bacteriology, 35(2), 309–321. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0015355868&partnerID=tZOtx3y1

Pirog, T. P., Grinberg, T. A., & Malashenko, R. Y. (1997). Protective functions of exopolysaccharides produced by an acinetobacter sp. Microbiology, 66(3), 279–283. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-27644560352&partnerID=tZOtx3y1

Porcelli, N., & Judd, S. J. (n.d.). Impact of cleaning protocol on membrane permeability recovery: a sensitivity analysis, J. Am. Water Works Assoc. (in Press).

Porcelli, N., Hillis, P., & Judd, S. (2009). Microfiltration membrane plant start up: a case study with autopsy and permeability recovery analysis. Environmental Technology, 30(6), 629–39. doi:10.1080/09593330902849467

Presdee, J., Veerapaneni, S., Shorney-Darby, H., & Clement, J. (n.d.). Integration of Membrane Filtration into Water Treatment System. AWWA.

Psoch, C., & Schiewer, S. (2005). Critical flux aspect of air sparging and backflushing on membrane bioreactors. Desalination, 175(1), 61–71. doi:10.1016/j.desal.2004.09.023

Qin, J., Oo, M., Tao, G., & Kekre, K. (2007). Feasibility study on petrochemical wastewater treatment and reuse using submerged MBR. Journal of Membrane Science, 293(1-2), 161–166. doi:10.1016/j.memsci.2007.02.012

Ramesh, A., Lee, D. J., Wang, M. L., Hsu, J. P., Juang, R. S., Hwang, K. J., … Tseng, S. J. (2006). Biofouling in Membrane Bioreactor. Separation Science and Technology. doi:10.1080/01496390600633782

Ripperger, S., & Altmann, J. (2002). Crossflow microfiltration – state of the art. Separation and Purification Technology, 26(1), 19–31. doi:10.1016/S1383-5866(01)00113-7

Rosenberger, S., & Kraume, M. (2003). Filterability of activated sludge in membrane bioreactors. Desalination, 151(2), 195–200. doi:10.1016/S0011-9164(02)00998-0

Rosenberger, S., Evenblij, H., Tepoele, S., Wintgens, T., & Laabs, C. (2005). The importance of liquid phase analyses to understand fouling in membrane assisted activated sludge processes—six case studies of different European research groups. Journal of Membrane Science, 263(1-2), 113–126. doi:10.1016/j.memsci.2005.04.010

Rosenberger, S., Laabs, C., Lesjean, B., Gnirss, R., Amy, G., Jekel, M., & Schrotter, J.-C. (2006). Impact of colloidal and soluble organic material on membrane performance in membrane bioreactors for municipal wastewater treatment. Water Research, 40(4), 710–20. doi:10.1016/j.watres.2005.11.028

S., J. (2004). Membrane Treatment Technical Guidance Document (UKWIR),. UK Water Industry Research Ltd.(DW/14A).

Sezgin, M., Jenkins, D., & Parker, D. S. A unified theory of filamentous activated sludge bulking, 50 Journal of the Water Pollution Control Federation 362–381 (1978). Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0017930141&partnerID=tZOtx3y1

Shen, Y., Zhao, W., Xiao, K., & Huang, X. (2010). A systematic insight into fouling propensity of soluble microbial products in membrane bioreactors based on hydrophobic interaction and size exclusion. Journal of Membrane Science, 346(1), 187–193. doi:10.1016/j.memsci.2009.09.040

Shimizu, Y., Okuno, Y.-I., Uryu, K., Ohtsubo, S., & Watanabe, A. (1996). Filtration characteristics of hollow fiber microfiltration membranes used in membrane bioreactor for domestic wastewater treatment. Water Research, 30(10), 2385–2392. doi:10.1016/0043-1354(96)00153-4

Shorrock, C. J., & Bird, M. R. (1998). Membrane Cleaning: Chemically Enhanced Removal of Deposits Formed During Yeast Cell Harvesting. Food and Bioproducts Processing, 76(1), 30–38. doi:10.1205/096030898531729

Song, L., & Elimelech, M. (1995). Particle Deposition onto a Permeable Surface in Laminar Flow. Journal of Colloid and Interface Science, 173(1), 165–180. doi:10.1006/jcis.1995.1310

Strugholtz, S., Sundaramoorthy, K., Panglisch, S., Lerch, A., Brügger, A., & Gimbel, R. (2005). Evaluation of the performance of different chemicals for cleaning capillary membranes. Desalination, 179(1-3), 191–202. doi:10.1016/j.desal.2004.11.067

Tabor, W. A. (1976). Wastewater microbiology. Annual Reviews in Microbiology, 30(1), 263–278.

Thurman, E. M. (2013). Organic geochemistry of natural waters. S.l.: Springer.

Trägårdh, G. (1989). Membrane cleaning. Desalination, 71(3), 325–335. doi:10.1016/0011-9164(89)85033-7

Väisänen, P., Bird, M. R., & Nyström, M. (2002). Treatment of UF Membranes with Simple and Formulated Cleaning Agents. Food and Bioproducts Processing, 80(2), 98–108. doi:10.1205/09603080252938735

Van de Graaf, A. A., Mulder, A., De Bruijn, P., Jetten, M. S. M., Robertson, L. A., & Kuenen, J. G. (1995). Anaerobic oxidation of ammonium is a biologically mediated process. Applied and Environmental Microbiology, 61(4), 1246–1251. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0028935825&partnerID=tZOtx3y1

Wang, Y.-Q., Su, Y.-L., Ma, X.-L., Sun, Q., & Jiang, Z.-Y. (2006). Pluronic polymers and polyethersulfone blend membranes with improved fouling-resistant ability and ultrafiltration performance. Journal of Membrane Science, 283(1-2), 440–447. doi:10.1016/j.memsci.2006.07.021

Wang, Z., Wu, Z., Yin, X., & Tian, L. (2008). Membrane fouling in a submerged membrane bioreactor (MBR) under sub-critical flux operation: Membrane foulant and gel layer characterization. Journal of Membrane Science, 325(1), 238–244. doi:10.1016/j.memsci.2008.07.035

Wang, Z.-P., & Zhang, T. (2010). Characterization of soluble microbial products (SMP) under stressful conditions. Water Research, 44(18), 5499–509. doi:10.1016/j.watres.2010.06.067

Wisniewski, C., Persin, F., Cherif, T., Sandeaux, R., Grasmick, A., & Gavach, C. (2001). Denitrification of drinking water by the association of an electrodialysis process and a membrane bioreactor: feasibility and application. Desalination, 139(1-3), 199–205. doi:10.1016/S0011-9164(01)00311-3

Yamato, N., Kimura, K., Miyoshi, T., & Watanabe, Y. (2006). Difference in membrane fouling in membrane bioreactors (MBRs) caused by membrane polymer materials. Journal of Membrane Science, 280(1-2), 911–919. doi:10.1016/j.memsci.2006.03.009

Yang, Q., Chen, J., & Zhang, F. (2006). Membrane fouling control in a submerged membrane bioreactor with porous, flexible suspended carriers. Desalination, 189(1-3), 292–302. doi:10.1016/j.desal.2005.07.011

Yigit, N. O., Harman, I., Civelekoglu, G., Koseoglu, H., Cicek, N., & Kitis, M. (2008). Membrane fouling in a pilot-scale submerged membrane bioreactor operated under various conditions. Desalination, 231(1-3), 124–132. doi:10.1016/j.desal.2007.11.041

Yu, H., Xie, Y., Hu, M., Wang, J., Wang, S., & Xu, Z. (2005). Surface modification of polypropylene microporous membrane to improve its antifouling property in MBR: CO plasma treatment. Journal of Membrane Science, 254(1-2), 219–227. doi:10.1016/j.memsci.2005.01.010

Zeman, L. J., & Zydney, A. L. (1996). Microfiltration and Ultrafiltration: Principles and Applications, (1st ed.)N.

Zhang, L.-Z., Wang, Y.-Y., Wang, C.-L., & Xiang, H. (2008). Synthesis and characterization of a PVA/LiCl blend membrane for air dehumidification. Journal of Membrane Science, 308(1-2), 198–206. doi:10.1016/j.memsci.2007.09.056

Zhang, Y., Fane, A., & Law, A. (2006). Critical flux and particle deposition of bidisperse suspensions during crossflow microfiltration. Journal of Membrane Science, 282(1-2), 189–197. doi:10.1016/j.memsci.2006.05.022

Zondervan, E., & Roffel, B. (2007). Evaluation of different cleaning agents used for cleaning ultra filtration membranes fouled by surface water. Journal of Membrane Science, 304(1-2), 40–49. doi:10.1016/j.memsci.2007.06.041