J. Applied Membrane Science & Technology, Vol. 25, No. 3, December 2021, 81–92

The Future Challenges of Anaerobic Membrane Bioreactor (AnMBR) for High Strength Wastewater

S. Salaeh, W. Khongnakorn* & W. Chaipetch

Centre of Excellence in Membrane Science and Technology, Department of Civil and Environmental Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla, 90110, Thailand

Submitted: 1/8/2021. Revised edition: 21/10/2021. Accepted: 21/10/2021. Available online: 15/11/2021

ABSTRACT

This article is to present a review of anaerobic membrane bioreactor (AnMBR), process, operational condition, fouling mechanism and future challenge for high strength wastewater. Since1969s, membrane filtration technology has been used and continuously developed for wastewater treatment and recovery. AnMBR has proposed for the economic feasibility owing to the low footprint, high yield production under the relatively low energy consumption. Continuous stirred tank reactor (CSTR) configuration is the widely used couple with a flat sheet or hollow fibre modules. The various factors of operating condition are influence on the performance such as hydraulic retention time (HRT= 6 – 12 d), solid retention time (SRT > 100 d) and operating temperature (T = 10 - 56ºC). In addition, the increase in temperature is related to high methanogenic activity and high COD removal efficiency (85% - 99%). However, the limitation of this process is fouling that occurs from the soluble microbial product (SMP), exopolymer substance (EPS) and biopolymer cluster (BPC). Almost of appropriate operating conditions for high performance, anti-fouling, the majority of effective microorganisms and energy balance are discussed in detail. For the challenge work, improvement of the prevention membrane fouling and high energy recovery in the hybrid/combination system with forward osmosis (FO), membrane distillation (MD) and powder activated carbon (PAC)-AnMBR.

Keywords: Anaerobic membrane bioreactor (AnMBR), operating condition, removal efficiency, anti-fouling; hybrid process

1.0 INTRODUCTION

Anaerobic membrane bioreactor (AnMBR) is focused and developed for high strength or hardly biodegradable wastewater treatment to obtain the high-water quality and renewable energy as methane-rich biogas from wastewater. Previous researches are studied the application of leachate [1, 2] and industrial wastewater (such as brewery wastewater [3], kraft evaporator condensate [4], etc). The purpose of this article is to present the challenge of the anaerobic membrane bioreactor process, operational condition, fouling mechanism, and hybrid process for the future challenge.

2.0 AnMBR SYSTEMS

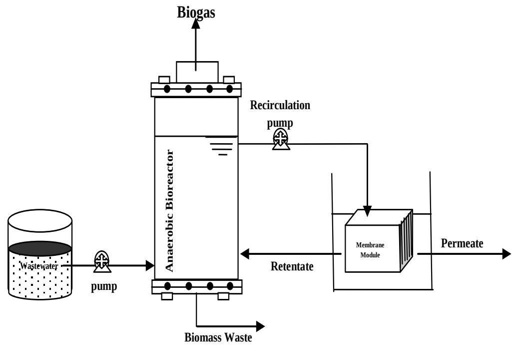
2.1 Membrane Characteristics, Module and Their Configuration

Several authors have explored with the commercial MF and UF polymer membranes which made from polyvinylidene fluoride (PVDF) [5-6],

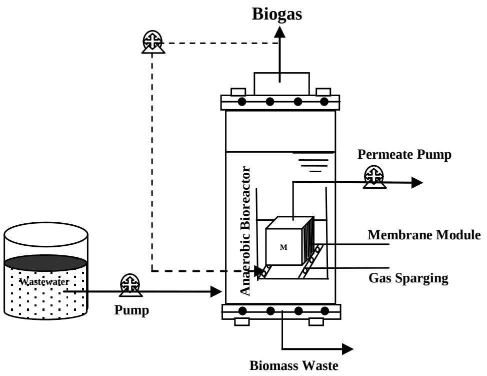
---

* Corresponding to: W. Khongnakorn (email: watsa.k@psu.ac.th)
DOI: https://doi.org/10.11113/amst.v25n3.226

polytetrafluoroethylene (PTFE) [7], polysulfone (PS)/ polyethersulfone (PES) family, cellulose acetate (CA) [8], polypropylene (PP) [9] and polyethylene (PE). The modules are often fabricated in flat sheet, hollow fiber, and tubular modules [5, 9, 10]. In addition, ceramic membranes are used and effectively provide for a high resistance for corrosion, anti-fouling, and concentration polarization (CP) control. The ceramic membrane is also tolerant for chemical oxidation and high temperature. The configuration of AnMBR is divided into 2 types: external/side-stream configuration and submerged/ immersed configuration as shown in Figure 1. Almost flat sheet module is employed in submerge configuration. Tubular module is employed in side stream configuration. Nowadays, hollow fiber are developed to operate under high flux because of their high packing density and large pore size [11-12]. Table 1 presents the summary of AnMBR performance under the different membranes. The COD removal in the system is higher than 90% with a high organic loading rate (OLR>10 kg COD/m^3.day) [3-4, 13]. The completely stirred tank reactor (CSTR) configuration is a typical reactor which use for lab-scale at the low loading [14]. Moreover, gas-lift anaerobic membrane bioreactor (Gl-AnMBR), completely mixed digester (CMD), anaerobic dynamic membrane bioreactor (AnDMBR) configurations were conducted to enhance flux and reduce fouling in the systems [3, 15]. The micro-pollutants (such as pharmaceutical products, high strength wastewater, etc) are high removal performance with dynamic technology or submerged anaerobic dynamic membrane bioreactor (AnDMBR) [9].



(a) External cross-flow



(b) Submerged

Figure 1 Configuration of AnMBRs for (a) external and (b) submerged AnMBR (adapted from [16])

2.2 Effects of Operating Condition

Many researches [4, 6, 12, 13] were focused on operating conditions in AnMBR that affect its performance. The performance in AnMBR is focusing on water permeate quality, flux obtained, and methane yield. The mainly significant parameters of operational condition are discussed as follows:

Sludge Retention Time (SRT) and Hydraulic Retention Time (HRT)

SRT is a major important factor that indicates the footprint of the system, biomass concentration, biomass production, and especially the quantity of biopolymer cluster product (BCP) such as soluble microbial product (SMP) and exo-polymer substance (EPS).

Table 1 Summary of AnMBR performance under the different membrane characteristics, membrane module and configuration

Reactor type/module configuration/ membrane configuration	**Type of waste water**	**Membrane type**	**Material**	**Pore size (µm)**	**Filtration area (m^2)**	**Flux (L/m^2 h)**	**TMP (kPa)**	**Reference**
Jet flow anaerobic bioreactor /Cross-flow	Landfill leachate	UF	-	-	1	-	100	[1]
UASB/Flat sheet/AnDMBR	Landfill leachate	-	-	40	-	6	40	[2]
Gas-lift anaerobic membrane bioreactor (Gl-AnMBR)/Tubular	Synthetic sewage, Mimicking household wastewater	UF	PVDF	0.03	0.013	18	-	[5]
UASB/Hollow-fiber	Bamboo industry wastewater	-	PVDF	0.002	0.07	15-35	35-90	[6]
Upflow sludge contact bioreactor /Hollow fiber	Synthetic wastewater	-	PES	0.5	0.2	-	-	[8]
AnHMBR/Anaerobic membrane bioreactor and fixed-bed biofilm reactor	Synthetic wastewater	-	-	0.7	0.022	2.7-6.9	8	[47]
UASB/Completely mixed glass reactor/ Submerged flat sheet/rectangular	High strength wastewaters	-	Polypropylene	10	0.018	2.6	-	[9]
Completely mixed digester (CMD)/Tubular	Dairy manure	UF	PVDF	0.03	0.079	-	-	[12]
CSTR/Submerged Hollow fiber	Textile wastewater	MF	-	0.40	-	1.8–14.4	-	[40]
CSTR/Submerged /Flat sheet	Whey/Sucrose	-	-	0.4	-	2–5	-	[45]
Submerged AnMBR/Hollow-fiber	Pre-screened wastewater from the snacks production	-	PVDF	0.4	2	3.5- 14.4	-	[46]
Submerged/Flat sheet	Synthetic raw sewage	MF	PVDF	0.45	0.05	-	-	[48]

Practically, long SRT (> 100 d) is an effect on performance and removal efficiency than HRT. The concentration of SMP increases at elevated SRT that causing a decreasing fouling potential [14, 17-20]. The typical HRT is between 6-12 d. Almost of publications conclude that a higher HRT is necessary for biodegradation of complex wastewater and reduction of volatile fatty acids (VFAs) accumulation in the reactor. The accumulation of VFA could reduce the performance efficiency and induce fouling. In the contrast, long SRT makes a larger footprint and lower OLR, and thus induces the reduction of the permeate fluxes [14, 21].

Temperature

The operation under thermophilic conditions (>45 °C) obtained higher methane yields due to the high-rate metabolite. Actually, the limitation of high temperature induces more release of SMP and ESP were caused by the high fouling potential [20]. The operation temperature in the mesophilic range under higher organic loading rates (> 10 g COD/L.d) found no significant different yields when compared with the thermophilic conditions. In the contrast, thermophilic conditions obtain the yields rate more than 5 times in mesophilic conditions especially in the hydrolysis process [22].

Microorganism in the System

Hydrolytic and fermentative bacteria are included *Clostridium spp*, *Peptococcus anaerobes*, *Lactobacillus, Bifidobacterium spp, Desulphovibrio spp, Corynebacterium spp, Actinomyces, Staphylococcus*, and *Escharichia Coli* [22]. Methane yield production depends on the activity of methanogenic populations that are major influenced by temperature. Methanogenic microorganisms identified in mesophilic conditions include the rods (*Methanobacterium, Methanobasillus*) and spheres (*Methanococcus, Methanothrix,* and *Methanocarnia*). Bakonyi *et al.* [21] were concluded that high methanogenic activity and can be diverted when operating under high SRT and high temperature (60 - 65°C).

The summary of operating conditions was the effect on performance is presented in Table 2 and can be concluded as follows:

- The thermophilic temperature increases the biogas production performance according to increasing the microorganism activity.
- The high HRT induced better biodegradation and reduce the VFA accumulation. It will be enhanced methane production.
- The high SRT induces the SMP and EPS production that lower fouling rate in AnMBR.

3.0 FOULING AND PREVENTION

The disadvantage of AnMBR is fouling, especially, biofouling such as soluble microbial product (SMP) and exo-polymer substance (EPS), etc. The operational condition is a main influence to produce biofouling as present above [23-25]. Many researchers studied fouling prevention by increasing cross-flow velocity (CFV), sparging internal recirculation, and vibratory shear process to enhance the shear rate at the membrane surface [26-28]. The ultra-sonication had used to control cake formation and enhance the membrane filtration without the anaerobic bacteria activity inhibition and membrane damage.

Table 2 Summary of AnMBR performance under the different operating condition

Type of waste water	OLR (kg COD/m^3 day)	HRT (d)	SRT (d)	Temp (°C)	COD removal (%)	Reference
Landfill leachate	6.27	7	-	37	90	[1]
Landfill leachate	6.27	7	-	37	90.7	[1]
Landfill leachate	1–6.27	7	-	37	>92	[1]
Landfill leachate	4.87	-	-	-	-	[2]
Brewery wastewater	12	-	-	30	90	[3]
Brewery wastewater	12	-	-	30	99	[3]
Kraft evaporator condensate	22.5	-	-	36-38	93-99	[4]
Kraft evaporator condensate	1-24	-	-	36-38	99	[4]
Synthetic sewage, Mimicking household wastewater	-	-	-	-	98	[5]
Bamboo industry wastewater	4.4	≥5	-	28–30	85-90	[6]
Synthetic wastewater	1.5(±0.20)	0.125	-	37	98 (±0.7)	[8]
Synthetic wastewater	5	1	50	30	96	[10]
High strength wastewaters	2	-	-	35.7- 0.1	99	[9]
Landfill leachate	8-11.8	11-19	30-300	10-35	>95	[13]
Palm oil mill effluent (POME)	7.66±0.40	6	30	45	72-78	[42]
Synthetic raw sewage	-	0.35-0.49	-	30-32	94(±0.5)	[48]
Molasses-based	5–12.2	-	-	27–33	-	[49]
Organic waste mixture	-	2–20	-	35	99	[50]
Organic waste mixture	-	0.083	-	35	99	[50]

In addition, Quorum quenching (QQ) was reported for the mitigation and biodegradation of microbial and microbial production which affect fouling [29-30]. Moreover, entrapped cells or/and encapsulation cells had been studied to reduce fouling and enhance the performance of the microbial communities [31-33]. The membrane fabrication and modification with the incorporation by nanoparticles (such as silver (Ag), gold (Au), etc.) were developed for reducing biofouling [34].

4.0 NEW CHALLENGE AND PROSPECTIVE IN HYBRID ANMBR

In the last 10 years, many researchers attempted to develop the system without energy supply or obtain more energy and also less fouling. Many researchers [9, 17, 35] had reported maximum net energy used approximately at 0.04 kWh/m^3 for sulfate-rich urban wastewater removed under high ambient temperature and/or high SRT conditions. The average energy production obtained at 2.02 kWh/kg COD$_{removed}$. Hence, the hybrid/combination system was proposed to reduce energy consumption such as the combine system with forward osmosis (FO) [15, 36], anaerobic membrane bio-electrochemical reactor (AnMBER) [37], granular activated carbon (GAC)-fluidized AnMBR [36], AnMBR-membrane distillation (MD) [39], anaerobic dynamic membrane bioreactor (AnDMBR) [24], entrapped cell- based AnMBR [31], granular or PAC AnMBR [38, 40-42] etc. In addition, adapted microbial fuel cell (MFC) in anaerobic membrane bio-electrochemical reactor (AnMBER) for wastewater treatment with nitrification and denitrification process obtained high performance and less fouling. The energy obtained about 1.16 W/m^3 net cathodic chamber (NCC) [37]. The hybrid technology can be summarized in Table 3. While the couple with FO presented high performance but the external concentration polarization (ECP) by protein was a majority of fouling in this system [36]. Increasing of granule (G-AnMBR) and PAC (PAC-AnMBR) in the system increased performance especially the small particle size due to enhanced hydrodynamic mixing, reduced gas sparging demand [41, 42-44].

Hence, it can be concluded that the development of study is focused as follows:

- Firstly, the study is focused on fouling prevention by hydrodynamic force (i.e. increasing of shear rate at the membrane surface) and biofouling prevention by SMP and EPS limited (i.e. operational condition control).
- Secondly, the study is focused on energy consumption and production by the biogas and methane yield and the biogas recirculation in the system, and,
- The last study is focused on water effluent quality, especially from high strength wastewater (i.e. industrial wastewater or hard biodegradable wastewater).

5.0 CONCLUSION

AnMBR is a well-known process for high-strength wastewater treatment. The efficiency of the system is depending on the membrane properties, design performance, and operational condition. The main advantage is positive net energy obtain and high removal.

Table 3 The summary of energy recovery in hybid AnMBR

Type of hybrid AnMBR	**Membrane**	**Type of wastewater**	**OLR (kg COD/m^3 day)**	**HRT (d)**	**SRT (d)**	**COD removal (%)**	**Energy recovery (kWh/m^3)**	**Reference**
GAC-fluidized AnMBR	PVDF-UF membrane	Domestic Wastewater	1.4±0.5	0.2	11±5	86-90	0.27	[38]
AnMBR-MD	MF PTFE/PP-MD	Synthetic domestic wastewater	-	4	215	98.4 ± 0.4	0.3–0.5 L_{biogas}/g COD_{added}	[39]
MEC-AnMBR	PVDF-UF membrane with	Synthetic wastewater	5	1.5	-	70.6	0.6 V $(DC)_{supply}$	[51]
MFC- AnMBR	MF	Synthetic wastewater	-	-	-	58.7	1.16	[37]

However, the limitation of AnMBR is fouling. Hence, the hybrid process such as dynamics process (AnDMBR), osmotic pressure process (FO-AnMBR), porous material addition (PAC-AnMBR; G-AnMBR), electrochemical process (AnMBER), and microorganism improvement have been proposed and developed to achieve high performance and high energy recovery.

ACKNOWLEDGEMENT

The research was financially supported by the Thailand Research Fund (TRF) through a Research and Researcher for industries (RRi) under contract number "PHD58I0056" and the budget revenue of Prince of Songkla University under contract number "ENG6302157S". The authors would like to thank Center of Excellence in Membrane Science and Technology, Prince of Songkla University for partial support of this study.

REFERENCES

[1] A. Zayen, S. Mnif, F. Aloui, F. Fki, S. Loukil, M. Bouaziz, and S. Sayadi. 2010. Anaerobic Membrane Bioreactor for the Treatment of Leachates from Jebel Chakir Discharge in Tunisia. *J. Hazard. Mater.* 177: 918-923.

[2] Z. Xie, Z. Wang, Q. Wang, C. Zhu, and Z. Wu. 2014. An Anaerobic Dynamic Membrane Bioreactor (AnDMBR) for Landfill Leachate Treatment: Performance and Microbial Community Identification. *Bioresour. Technol.* 161: 29-39.

[3] A. Torres, A. Hemmelmann, C. Vergara, and D. Jeison. 2011. Application of Two-phase Slug-Flow Regime to Control Flux Reduction on Anaerobic Membrane Bioreactors Treating Wastewaters with High Suspended Solids Concentration. *Sep. Purif. Technol.* 79: 20-25.

[4] K. Xie, H. J. Lin, B. Mahendran, D. M. Bagle, K. T. Leung, S. N. Liss, and B. Q. Liao. 2010. Performance and Fouling Characteristics of a Submerged Anaerobic Membrane Bioreactor for Kraft Evaporator Condensate Treatment. *Environ. Technol.* 31(5): 511-521.

[5] A. Lucia Prieto, H. Futselaar, P. N. L. Lens, R. Bair, and D. H. Yeh. 2013. Development and Startup of a Gas-lift Anaerobic Membrane Bioreactor (Gl-AnMBR) for Conversion of Sewage to Energy, Water and Nutrients. *J. Memb Sci.* 44: 1158-167.

[6] W. Wang, Q. Yang, S. Zheng, and D. Wu. 2013. Anaerobic Membrane Bioreactor (AnMBR) for Bamboo Industry Wastewater Treatment. *Bioresour. Technol.* 149: 292-300.

[7] J. Ho, and S. Sung. 2010. Methanogenic Activities in Anaerobic Membrane Bioreactors (AnMBR) Treating Synthetic Municipal Wastewater. *Bioresour. Technol.* 101: 2191-2196.

[8] A. Yuzir, N. Abdullah, S. Chelliapan, and P. Sallis. 2013. Effect of Mecoprop (RS)-MCPP on the Biological Treatment of Synthetic Wastewater in an Anaerobic Membrane Bioreactor. *Bioresour. Technol.* 133: 158-165.

[9] M. E. Ersahin, H. Ozgun, Y. Tao, B. Jules, and V. Lier. 2014. Applicability of Dynamic Membrane Technology in Anaerobic Membrane

Bioreactors. *Water Res.* 48: 420-429.

[10] D. W. Gao, T. Zhang, C. Y. Y Tang, W. M. Wu, C. Y. Wong, Y. H. Lee, D. H. Yeh, and C. S. Criddle. 2010. Membrane Fouling in an Anaerobic Membrane Bioreactor: Differences in Relative Abundance of Bacterial Species in the Membrane Foulant Layer and in Suspension. *J. Memb Sci.* 364: 331–338.

[11] A. Santos, and S. Judd. 2010. The Commercial Status of Membrane Bioreactors for Municipal Wastewater. *Sep Sci Technol*. 45: 850-857.

[12] J. M. Wallace, and S. I. Safferman. 2014. Anaerobic Membrane Bioreactors and the Influence of Space Velocity and Biomass Concentration on Methane Production for Liquid Dairy Manure. *Biomass Bioenergy.* 66: 143-150.

[13] A. P. Trzcinski, and D. C. Stuckey. 2010. Treatment of Municipal Solid Waste Leachate using a Submerged Anaerobic Membrane Bioreactor at Mesophilic and Psychrophilic Temperatures: Analysis of Recalcitrants in the Permeate using GC–MS. *Water Res*. 44: 671-680.

[14] H. Lin, W. Peng, M. Zhang, J. Chen, H. Hong, and Y. Zhang. 2013. A Review on Anaerobic Membrane Bioreactors: Applications, Membrane Fouling and Future Perspectives. *Desalination.* 314: 169-188.

[15] Y. Liu, and B. Mi. 2012. Combined Fouling of Forward Osmosis Membranes: Synergistic Foulant Interaction and Direct Observation of Fouling Layer Formation. *J. Memb Sci.* 407: 136-144.

[16] W. Khongnakorna,b, L. P. Vaursa, W. Bootluckb, and W. J. Lauc. Chapter Book in Synthetic Polymeric Membranes for Advanced Water Treatment, Gas Separation, and Energy Sustainability.

[17] Y. Shen, W. Zhao, K. Xiao, and X. Huang. 2010. A Systematic Insight into Fouling Propensity of Soluble Microbial Products in Membrane Bioreactors based on Hydrophobic Interaction and Size Exclusion. *J. Memb Sci.* 346: 187-193.

[18] R. K. Dereli, M. E. Ersahin, H. Ozgun, I. Ozturk, D. Jeison, F. van der Zee, and J. B. van Lier. 2012. Potentials of Anaerobic Membrane Bioreactors to Overcome Treatment Limitations Induced by Industrial Wastewaters. *Bioresour. Technol.* 122: 160-170.

[19] R. K. Dereli, B. Heffernan, A. Grelot, P. Frank, Zee van der and B.van Lier Jules. 2015. Influence of High Lipid Containing Wastewater on Filtration Performance and Fouling in AnMBRs Operated at Different Solids Retention Times. *Sep. Purif. Technol*. 139: 43-52.

[20] H. Ozgun, R. K. Dereli, M. E. Ersahin, C. Kinaci, H. Spanjers, and J. B. van Lier. 2013. A Review of Anaerobic Membrane Bioreactors for Municipal Wastewater Treatment: Integration Options, Limitations and Expectations. *Sep. Purif. Technol.* 118: 89-104.

[21] P. Bakonyi, N. Nemestóthy, V. Simon, and K. Bélafi-Bakó. 2014. Fermentative Hydrogen Production in Anaerobic Membrane Bioreactors: A Review. *Bioresour. Technol.* 156: 357-363.

[22] C. Visvanathan, and A. Abeynayaka. 2012. Developments and Future Potentials of Anaerobic Membrane Bioreactors (AnMBRs). *Membr. Water Treat.* 3(1): 1-23.

[23] M. Xu, X. Wen, Z. Yu, Y. Li, and X. Huang. 2011. A Hybrid Anaerobic Membrane Bioreactor Coupled with Online Ultrasonic Equipment for Digestion of Waste Activated Sludge. *Bioresour. Technol.* 102: 5617-5625.

[24] X. Y. Zhang, Z. W. Wang, Z. C. Wu, T. Y. Wei, F. H. Lu, J. Tong, and S. H. Mai. 2011. Membrane Fouling in an Anaerobic Dynamic Membrane Bioreactor (AnDMBR) for Municipal Wastewater Treatment: Characteristics of Membrane Foulants and Bulk Sludge. *Process Biochem.* 46: 1538-1544

[25] M. Dagnew, W. Parker, and P. Seto. 2012. Anaerobic Membrane Bioreactors for Treating Waste Activated Sludge: Short Term Membrane Fouling Characterization and Control Tests. *J. Memb Sci.* 421-422: 103-110.

[26] A. Kola, Y. Ye, P. Le-Clech, and V. Chen. 2014. Transverse Vibration as Novel Membrane Fouling Mitigation Strategy in Anaerobic Membrane Bioreactor Applications. *J. Membr. Sci.* 455: 320-329.

[27] I. Ruigómez, L. Vera, E. González, G. González, and J. Rodríguez-sevilla. 2016a. A Novel Rotating HF Membrane to Control Fouling on Anaerobic Membrane Bioreactors Treating Wastewater. *J. Membr. Sci.* 501: 45-52.

[28] I. Ruigómez, L. Vera, E. González, and J. Rodríguez-Sevilla. 2016b. Pilot Plant Study of a New Rotating Hollow Fibre Membrane Module for Improved Performance of an Anaerobic Submerged MBR. *J. Membr. Sci.* 514: 105-113.

[29] B. Xu, T. Ng, S. Huang, and H. Ng. 2020. Effect of Quorum Quenching on EPS and Size-Fractioned Particles and Organics in Anaerobic Membrane Bioreactor for Domestic Wastewater Treatment. *Water Res.* 179: 115850.

[30] H. Elnaz. 2021. Fouling Challenges in Membrane Bioreactor. *J. Appl. Membr. Sci. Technol*. 25(1): 73-76.

[31] C. Juntawang, C. Rongsayamanont, E. Khan. 2017. Entrapped Cells-based-anaerobic Membrane Bioreactor Treating Domestic Wastewater: Performances, Fouling, and Bacterial Community Structure. *Chemosphere*. 187: 147-155.

[32] K. K. Ng, X. Shi, M. K. Y. Tang, and H. Y. Ng. 2014. A Novel Application of Anaerobic Bio-entrapped Membrane Reactor for the Treatment of Chemical Synthesis-based Pharmaceutical Wastewater. *Sep. Purif. Technol.* 132: 634-643.

[33] M. T. Do, and D. C. Stuckey. 2019. Fate and Removal of Ciprofloxacin in an Anaerobic Membrane Bioreactor (AnMBR). *Bioresour. Technol.* 289: 121683.

[34] S. Sujithra, and G. Arthanareeswaran. 2021. Incorporation of Antifouling Based Nanoparticles in Ultrafiltration Membrane for Improving Water Permeability and Mitigate Microbial Fouling.

J. Appl. Membr. Sci. Technol. 25(1): 21-33.

[35] R. Pretel, A. Robles, M.V. Ruano, A. Seco, and J. Ferrer. 2014. The Operating Cost of an Anaerobic Membrane Bioreactor (AnMBR) Treating Sulphate-rich Urban Wastewater. *Sep. Purif. Technol*. 126: 30-38.

[36] Y. Ding, T. Yu, L. Zhipeng, L. Feng, Y. Hong. 2014. Characterization of Organic Membrane Foulants in a Forward Osmosis Membrane Bioreactor Treating Anaerobic Membrane Bioreactor Effluent. *Bioresour. Technol*. 167: 137-143.

[37] Y. Tian, C. Ji, K. Wang, and P. L. Clech. 2014. Assessment of an Anaerobic Membrane Bio-electrochemical Reactor (AnMBER) for Wastewater Treatment and Energy Recovery. *J. Membr. Sci.* 450: 242-248.

[38] P. J. Evans, P. Parameswaran, K. Lim, J. Bae, C. Shin, J. Ho, and P. L. McCarty 2019. A Comparative Pilot-scale Evaluation of Gas-sparged and Granular Activated Carbon-fluidized Anaerobic Membrane Bioreactors for Domestic Wastewater Treatment. *Bioresour. Technol*. 288: 120949.

[39] X. Song, W. Luo, J. McDonald, S. J. Khan, F. Hai, W. E. Price, and L. D. Nghiem. 2018. An Anaerobic Membrane Bioreactor – Membrane Distillation Hybrid System for Energy Recovery and Water Reuse: Removal Performance of Organic Carbon, Nutrients, and Trace Organic. *Sci. Total Environ.* 628-629: 358-365.

[40] B. E. L. Baeta, R. L. Ramos, D. R. S. Lima, and S. F. Aquino. 2012. Use of Submerged Anaerobic Membrane Bioreactor (SAMBR) Containing Powdered Activated Carbon (PAC) for the Treatment of Textile Effluents. *Water Sci. Technol.* 65: 1540-1547.

[41] Y. Xiao, H. Yaohari, C. D. Araujo, C. Chau, and D. C. Stuckey. 2017. Removal of Selected Pharmaceuticals in an Anaerobic Membrane Bioreactor (AnMBR) with/without Powdered Activated Carbon (PAC). *Chem. Eng. J.* 321: 335-345.

[42] C. A. Ng, L. Y. Wong, C. H. Yee, M. J. K. Bashir, C. HO, H. Nisar, and P. K. Lo. 2017. Investigation on the Performance of Hybrid Anaerobic Membrane Bioreactors for Fouling Control and Biogas Production in Palm Oil Mill Effluent Treatment. *Water Sci. Technol.* 76(6): 1389-1398.

[43] L. Chen, P. Cheng, L. Ye, H. Chen, X. Xu, and L. Zhu. 2020. Biological Performance and Fouling Mitigation in the Biochar-amended Anaerobic Membrane Bioreactor (AnMBR) Treating Pharmaceutical. *Bioresource Technology.* 302: 122805.

[44] C. Chen, W. Guo, and H. H. Ngo. 2016. Advances in Granular Growth Anaerobic Membrane Bioreactor (G-AnMBR) for Low Strength Wastewater Treatment. *Environ. Prog. Sustain*. 1: 77-83.

[45] A. Spagni, S. Casu, N. A. Crispino, R. Farina, and D. Mattioli. 2010. Filterability in a Submerged Anaerobic Membrane Bioreactor. *Desalination.* 250: 787-792.

[46] C. Ramos, F. Zecchino, D. Ezquerra, and V. Diez. 2014. Chemical Cleaning of Membranes from an Anaerobic

Membrane Bioreactor Treating Food Industry Wastewater. *J. Membr. Sci*. 45: 8179-8188.

[47] Y. K. Wang, X. R. Pan, G. P. Sheng, W. W. Li, B. J. Shi, and H. Q. Yu. 2014. Development of an Energy-Saving Anaerobic Hybrid Membrane Bioreactors for 2-chlorophenol-contained Wastewater Treatment. *Chemosphere*. 140: 79-84.

[48] C. W. Teo, and P. C. Y. Wong. 2014. Enzyme Augmentation of an Anaerobic Membrane Bioreactor Treating Sewage Containing Organic Particulates. *Water Research*. 48: 335-344.

[49] K. C. Wijekoon, C. Visvanathan, and A. Abeynayaka. 2011. Effect of Organic Loading Rate on VFA Production, Organic Matter Removal and Microbial Activity of a Two-stage Thermophilic Anaerobic Membrane Bioreactor. *Bioresour. Technol.* 102: 5353-5360.

[50] E. Jeong, H. W. Kim, J. Y. Nam, and H. S. Shin. 2010. Enhancement of Bioenergy Production and Effluent Quality by Integrating Optimized Acidification with Submerged Anaerobic Membrane Bioreactor. *Bioresour. Technol.* 101: 7-12.

[51] A. Ding, Q. Fan, R. Cheng, G. Sun, M. Zhang, and D. Wu. 2018. Impacts of Applied Voltage on Microbial Electrolysis Cell-anaerobic Membrane Bioreactor (MEC-AnMBR) and its Membrane Fouling Mitigation. *Chem. Eng. J.* 333: 630-635.