PALM OIL MILL EFFLUENT TREATMENT USING AEROBIC SUBMERGED MEMBRANE BIOREACTOR COUPLED WITH BIOFOULING REDUCERS

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To beloved:

My Mother and My Late Father

My wife Retno Adriyani

My Children:

Alif Bagas Adiutomo, Bintang Shafiqa Adiretnani, Cahya Dita Adipramesti

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ASTRACT

The existing palm oil mill effluent (POME) treatment is often still difficult to adhere to the effluent standards. One of the most promising novel technologies in wastewater treatment system is the membrane bioreactor (MBR). The aim of this study is to treat POME using aerobic submerged membrane bioreactor (ASMBR) system to improve the effluent quality before biofouling reducer (BFR) is applied to reduce the membrane fouling. Diluted POME was treated with a 20 L lab-scale ASMBR equipped with a single microfiltration flat sheet membrane module. The ASMBR systems with mixed liquor suspended solids (MLSS) from 3000 to 12,000 mg L^{-1} and solids retention time (SRT) from 20 days and above were used to investigate the best operating condition of the system without BFR. The finding shows ASMBR continuous system operated at MLSS of 9000 mg L^{-1} and SRT of 20 days to produce good quality effluent, less microbial products, and moderate membrane fouling rate. Since membrane fouling is the main obstacle in the membrane system, powdered activated carbon (PAC), granulated activated carbon (GAC) and zeolite (ZEO) were added to the ASMBR as BFR. Batch tests with BFR concentrations from 1 to 10 g L^{-1} were used to determine the best BFR dose. It can be concluded that 4 g L^{-1} of PAC, GAC, and ZEO is the best BFR dose to produce good residual organic contents and colour of final products. Furthermore, the performance of ASMBR without BFR (called BFR_0) and coupled with BFR were compared by assessing the removal efficiencies of organic and colour, the fouling phenomenon propensity, and the critical flux (J_c) enhancement. The systems were subjected to two batches of organic loading rate (OLR), equal to about 1000 and 3000 mg COD L^{-1}. Each system with BFR showed distinct performances by producing higher effluent quality as compared with BFR_0. On both OLR, the ASMBR systems with BFR removed organic constituents with more than 96%, produced effluent with average residual colour of less than 55 ADMI and significantly increased J_c up to 42 L m^{-2} h^{-1}. It can be concluded that PAC is the best BFR for ASMBR system to treat POME by producing the highest quality of effluent, distinct changes in the concentrations of soluble microbial products (SMP) and extracellular polymeric substances (EPS), formed lowest operational trans-membrane pressure (TMP), and produced highest J_c. Finally, the experimental results were verified using activated sludge models no. 1 (ASM1) by also conducting the COD fractionation and respirometric analysis. The stoichiometry and kinetic parameters were determined to describe the bioprocess of the system. The COD fractionation of POME indicated dominant fraction of slowly biodegradable matters (42-56%). Oxygen utilization rate (OUR) of the ASMBR systems was found to fit well with ASM1 results. Compared with BFR_0, the addition of BFR increased the stoichiometry parameter of Y_H up to 0.49 mg cell COD mg^{-1} COD, increased the kinetic parameters of μ_{maxH}, and μ_{maxA} up to 1.6 and 0.48 d^{-1}, respectively, and increased $K_{O,H}$ and $K_{O,A}$ up to 0.59 and 0.82 mg COD L^{-1}, respectively. The value of b_H and K_S were decreased to 0.32 d^{-1} and 0.89 mg COD L^{-1}, respectively. These sets of model parameters were verified describing the enhancement of bioprocess in the ASMBR system coupled with BFR.

ABSTRAK

Rawatan efluen kilang kelapa sawit (POME) yang sedia ada seringkali sukar untuk mematuhi efluen piawai. Salah satu daripada teknologi baru yang berpotensi dalam sistem rawatan air sisa ialah bioreaktor membran (MBR). Kajian ini bertujuan untuk merawat POME menggunakan sistem bioreaktor membran paras tenggelam aerobik (ASMBR) untuk menambah baik kualiti efluen yang kemudiannya menggunakan pengurang kekotoran bio pada membran (BFR) untuk mengurangkan kekotoran membran. POME cair dirawat dengan sebuah ASMBR 20 L pada skala makmal yang dilengkapi dengan satu kepingan rata modul membran penurasan mikro. Sistem ASMBR dengan campuran cecair pepejal terampai (MLSS) daripada 3000 - 12,000 mg L^{-1} dan masa penahanan pepejal (SRT) dari 20 hari dan lebih telah digunakan untuk mengkaji keadaan terbaik bagi operasi ASMBR tanpa BFR. Hasil kajian menunjukkan sebuah sistem ASMBR berterusan yang dijalankan pada MLSS 9000 mg L^{-1} dan SRT 20 hari menghasilkan kualiti efluen yang baik, produk-produk mikrob yang kurang dan kadar kekotoran membran yang sederhana. Oleh sebab kekotoran membran adalah halangan utama bagi sistem membran, serbuk karbon teraktif (PAC), granul karbon teraktif (GAC) dan zeolit (ZEO) ditambahkan kepada ASMBR sebagai BFR. Kajian kelompok dengan kadar BFR daripada 1 - 10 g L^{-1} digunakan untuk menentukan dos terbaik BFR. Kesimpulannya, 4 g L^{-1} PAC, GAC dan ZEO menghasilkan produk akhir dengan kandungan sisa organik dan warna yang baik. Seterusnya, prestasi ASMBR tanpa BFR (disebut BFR_0) dan berganding BFR telah dibandingkan dengan menilai kecekapan penyingkiran organik dan warna, kecenderungan fenomena kekotoran membran, dan peningkatan fluks kritikal (J_c). Sistem-sistem tersebut dijalankan dengan menggunakan dua kelompok kadar beban organik (OLR), masing-masing bersamaan dengan 1000 dan 3000 mg COD L^{-1}. Setiap sistem dengan BFR menunjukkan prestasi yang berbeza dengan menghasilkan kualiti efluen yang lebih tinggi berbanding dengan BFR_0. Pada kedua-dua OLR, sistem ASMBR dengan BFR masing-masing menyingkirkan COD lebih daripada 96%, menghasilkan efluen dengan purata sisa warna kurang daripada 55 ADMI, meningkatkan J_c kepada 42 L m^{-2} h^{-1}. Disimpulkan bahawa PAC adalah BFR terbaik untuk sistem ASMBR yang merawat POME kerana menghasilkan efluen dengan kualiti tertinggi, perubahan nyata dalam kepekatan produk larut mikrob (SMP) dan bahan polimerik luar sel (EPS), membentuk tekanan operasi antara membran (TMP) terendah, dan menghasilkan J_c tertinggi. Akhir sekali, keputusan-keputusan experimen disahkan menggunakan model lumpur teraktif no. 1 (ASM1) dengan menjalankan juga analisis pemecahan COD dan respirometri. Parameter-parameter stoichiometri dan kinetik ditentukan untuk menggambarkan proses bio dalam sistem. Pemecahan COD POME menunjukkan pecahan dominan bahan organik yang terbiodegradasikan secara perlahan (42-56%). Kadar penggunaan oksigen (OUR) bagi sistem ASMBR didapati sepadan dengan keputusan ASM1. Berbanding dengan BFR_0, penambahan BFR meningkatkan parameter stoikiometri Y_H sehingga 0.49 mg sel COD mg^{-1} COD, meningkatkan parameter kinetik μ_{maxH} dan μ_{maxA} masing-masing sehingga 1.6 and 0.48 d^{-1}, dan meningkatkan $K_{O,H}$ dan $K_{O,A}$ masing-masing sehingga 0.59 and 0.82 mg COD L^{-1}. Nilai b_H dan K_S masing-masing berkurang sehingga 0.32 d^{-1} and 0.89 mg COD L^{-1}. Kumpulan parameter model ini mengesahkan adanya peningkatan proses bio pada sistem ASMBR berganding BFR.

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LIST OF ABBREVIATIONS

APHA	-	American Public Health Association
ASM	-	Activated Sludge Model
ASMBR	-	Aerobic Submerged Bioreactor
ASM1	-	Activated Sludge Model No. 1
ASM2	-	Activated Sludge Model No. 2
ASM2d	-	Activated Sludge Model No. 2d
AMS3	-	Activated Sludge Model No. 3
b_H	-	Decay Coefficient for Heterotrophic Biomass
BAP	-	Biomass-associated Product
BFR	-	Biofouling Reducer
BOD	-	Biological Oxygen Demand
C_0	-	Initial adsorbate concentration
C_e	-	Adsorbate equilibrium concentration after adsorption
CAS	-	Conventional activated sludge
Cell COD	-	Total COD-Soluble COD
CFMF	-	Cross-flow Microfiltration
CO	-	Carbon Monoxide
COD	-	Chemical Oxygen Demand
C_t	-	Oxygen concentration at time

C_s	-	Saturation oxygen concentration
CSTR	-	Continuous stirred Tank Reactor
CT	-	Capillary Tube
DEMF	-	Dead-end Microfiltration
DNA	-	Deoxyribo Nucleic Acid
DO	-	Dissolved Oxygen
DOE	-	Department of Environment
ED	-	Electrodialysis
EPA	-	Environment Protection Agency
EPS	-	Extracellular Polymeric Substance
FESEM-EDX	-	Field Emission Scanning Electron Microscope-Energy Dispersed X-ray
F/M	-	Food to Microorganism Ratio
FS	-	Flat Sheet
g	-	G force
GAC	-	Granular Activated Carbon
HF	-	Hollow Fibre
HRT	-	Hydraulic Retention Time
IMBR	-	Immersed Membrane Bioreactor
J	-	Flux
J_c	-	Critical Flux
K	-	Permeability (LMH/ΔkPa)
K_{La}	-	Oxygen Mass Transfer Coefficient
$K_{O,A}$	-	Oxygen autotrophic half-saturation coefficient
$K_{O,H}$	-	Oxygen heterotrophic half-saturation coefficient
K_S	-	Haft saturation constant

kPa	-	Kilo Pascal
LMH	-	Litre per Meter square per Hour
M	-	Molar
m		Mass of Adsorbent
MBR	-	Membrane Bioreactor
MF	-	Microfiltration
MFR	-	Membrane Fouling Reducer
MLSS	-	Mixed Liquor Suspended Solid
MLVSS	-	Mixed Liquor Volatile Suspended Solid
MT	-	Multi-tubular
NF	-	Nanofiltration
OLR	-	Organic Loading Rate
OUR	-	Oxygen uptake rate
P	-	Pressure
PAC	-	Particulate Activated Carbon
P_{ave}/TMP_{ave}	-	Pressure Average
PE	-	Polyethylene
PEG	-	Polyethylene Glycol
PES	-	Polyethylenesulphone
POME	-	Palm Oil Mill Effluent
PP	-	Polypropylene
PVDF	-	Polyvinylidene Difluroide
Q	-	Influent rate; Langmuir Constant
q_e or $\frac{x}{m}$	-	Adsorbent
Q_{per}	-	Permeate flowrate
Q_r	-	Return activated sludge rate

Q_w	-	Sludge wastage rate
UF	-	Ultrafiltration
RAPD-PCR	-	Random Amplified Polymorphic DNA-PCR
RIS	-	Resistance in Series
R_m	-	Membrane resistance
RO	-	Reverse Osmosis
RPM	-	Revolutions per Minute
R_{tot}	-	Total Resistance
SBR	-	Sequential Batch Reactor
SCOD	-	Soluble COD
S_i	-	Inert Soluble COD
SMBR	-	Side-stream Membrane Biorecator
SMP	-	Soluble Microbial Product
SRT	-	Sludge Retention Time/Solid Retention Time
S_s	-	Readily Biodegradable COD
T	-	Temperature
TCOD	-	Total COD
t_{fil}	-	Filtration time
t_{rel}	-	Relaxation time
TMP	-	Trans-Membrane Pressure
TN	-	Total Nitrogen
TP	-	Total Phosphorus
TSS	-	Total Suspended Solid
μ_{maxH}	-	Maximum specific Autotrophic Growth Rate
μ_H	-	Heterotrophic Grow Rate
μ_{maxH}	-	Maximum specific Heterotrophic Grow Rate

UF	-	Ultrafiltration
USEPA	-	United State Environmental Protection Agency
UV	-	Ultraviolet
V	-	Volume
VSS	-	Volatile Suspended Solid
X_e	-	MLSS in effluent
X_i	-	Inert Particulate COD
X_R	-	MLSS in return sludge of CAS
Y_s	-	Slowly Biodegradable COD
Y_H	-	Heterotrophic Yield
ZEO	-	Zeolite

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CHAPTER 1

INTRODUCTION

1.1 Research Background

The oil palm is the most important agricultural crop in Malaysia, covering more than 5 million hectares, equivalent to almost 75% of total agricultural land and about 12% of the country's total land area (Ahmad *et al.*, 2005; Mukherjee and Sovacool, 2014). In 2009, the production of crude palm oil (CPO) has reached 17.76 million tonnes and increased to 18.5 million tonnes in 2013 (Mukherjee and Sovacool, 2014). This made Malaysia as one of the largest producers, covering about 43% of the world's total palm oil production, and as the largest exporters in the world, accounting about 49% of total palm oil (Ujang *et al.*, 2011). Indigenous from Africa, the oil palm (*Elaeis guineensis Jacq*.) has been domesticated from the wilderness and transformed to become a plantation-based oil industry. The oil palm takes 11-15 months in nursery period. The first harvest carried out after 32-38 months of planting. The oil palm tree takes 5-10 years to reach peak yield. For every hectare of plantation, 10 - 35 tonnes of fresh fruit bunches (FFB) are produced every year. The fleshy mesocarp and the kernel of the fruit are used to obtain oil, yielding about 45-56 % and about 40-50%, respectively. Both mesocarp and fruit kernel produce about 17 tonnes per hectare per year of oil (Rupani *et al.,* 2010). Recently, there are 418 crude palm oil mills, 59 refineries, 57 downstream industries and 18 oleo-chemical plants in Malaysia (Ujang *et al.*, 2011).

However, the oil palm sector also generates an enormous amount of liquid wastewater, known as Palm Oil Mill Effluent (POME) (Borja and Banks, 1995). It has been reported that for every metric tonnes of crude palm oil (CPO) produced, about 0.9 – 1.5 m^3 of POME is generated (Vijayaraghavan *et al.*, 2007). About 0.5 – 0.7 m^3 POME will be discharged from every metric tonnes FFB processed (Yacob *et al.*, 2006). It was recorded since 2004 more than 40 million tonnes of POME annually was generated from 372 mills in Malaysia (Wu *et al.*, 2010; Yacob *et al.*, 2006). This means that nowadays, some 400 palm oil mills will produce more than 44 million metric tonnes of POME annually. The palm oil mill has been identified as the one that produces the largest pollution load into the rivers throughout Malaysia (Wu *et al.*, 2007).

In general, POME is came from three major sources, i.e. sterilizer condensate, wastewater of hydrocyclone and separator sludge. Despite it is non-toxic colloidal suspension, Fresh POME contains high amounts of BOD_5 (25,000 mg/L), COD (50,000 mg/L), total solids (40,500 mg/L), oil and grease (4000 mg/L), and total nitrogen (750 mg/L) (Ahmad *et al.*, 2003; Wu *et al.*, 2010). Typically with very high content of organics and oil, the resulting POME is a thick brownish colour liquid and discharged at a temperature between 80 and 90 ^{o}C. It is also fairly acidic with pH ranging from 4.0 to 5.0. The raw or partially treated POME has an extremely high content of degradable organic matter, which is mostly due to the presence of unrecovered palm oil. This highly polluting wastewater could consequently cause severe pollution of streams due to oxygen depletion and other related effects (Wu *et al.*, 2010).

The regulation of effluent standard stated by the government of Malaysia under the Environmental Quality Act 1974 providing the legal source for environmental management and water pollution control. Since 1978, the regulator has endorsed standards for POME effluent and palm oil mills required to treat their POME prior to discharging it into watercourses. In the latest amendment, the effluent standards are BOD_5 100 mg/L, suspended solids 400 mg/L, oil and grease 50 mg/L, ammonia nitrogen 150 mg/L, total nitrogen 200 mg/L, pH 5-9 and a temperature of 45^{o}C, respectively (DOE, 2010).

Various treatment combinations are currently used to treat POME in Malaysia, including tank digestion and mechanical aeration, tank digestion and facultative ponds, decanter and facultative ponds, physico-chemical and biological treatments (Vijayaraghavan *et al.*, 2007). Prior to biological treatment, POME is treated in physical pre-treatment in order to remove the suspended solids and residual oil using air flotation, coagulation-flocculation, and sedimentation. The application of coagulation and activated carbon as a pre-treatment on POME treatment removed COD, BOD and turbidity by 56%, 71% and 97.9%, respectively. When the pre-treated POME was further treated using membrane ultra-filtration and reverse osmosis, the removal efficiencies COD, BOD, and turbidity were as high as 98.8%, 99.4%, and 100%, respectively (Ahmad *et al.*, 2003). The combination of ponds and sequencing batch reactor (SBR) has also been used to degrade POME, as well as evaporation technology and a clarification system coupled with filtration and aeration (Vijayaraghavan *et al.*, 2007). Today, 85% of POME treatment systems are essentially composed of anaerobic and facultative ponds due to lower capital and operating costs. After the pond system, the effluent is further treated using other biological system, including an open tank digester coupled with extended aeration pond (Abdurahman *et al.*, 2011). Due to the green house related issue, these open types of digesters are currently being converted into closed digesters to contain the biogas. A series of ponds with low maintenance produces a low rate of contaminant degradation. Often, the final discharge does not comply with the effluent standard.

Even though membrane bioreactor (MBR) are still considered as a new technology, the development of this filtration and “clarifier-less” activated sludge system was already initiated in the 1960s. An MBR system can be operated with high concentration of mixed liquor suspended solids (MLSS), and can produce high quality of treated effluent, low quantity of excess sludge, small footprint and can promote water reclamation (Meng *et al.*, 2009). The first generation of MBR was operated with organic or inorganic tubular membranes placed in external recirculation loops. Aerobic submerged membrane bioreactors (ASMBR) specifically for wastewater treatment have been developed at the end of 1980s in order to simplify the use of these systems and to reduce operating costs (Yamamoto *et al.*, 1988). In this configuration, the membranes are directly immersed in the tank containing the biological sludge and the permeate water is extracted. The MBR technology for wastewater treatment experienced rapid development from the early 1990s onwards. The world MBR market is expected to experience sustainable growth as a result of drivers like more stringent legislation, local water scarcity, increased funding, decreasing investment cost and increasing confidence in accepting this technology (Judd, 2006). To date, more than 2200 MBR are installed worldwide. Zenon is the largest installation followed by Kubota and Mitsubishi (Mutamim *et al.*, 2012)

However, in most cases, membrane fouling is considered as the most serious problem affecting system performance of membrane processes, leading to the limitation of extensive application of MBR (Wang *et al.*, 2007). Membrane fouling is the deposition of a layer onto the membrane surface or the blockage or partial blockage of the pores leads to the declining flux and or the increasing of membrane pressure. For decades, researchers conducted various studies to avoid or minimize of these complex phenomena (Zuthi *et al.*, 2012).

The various factors affecting membrane fouling in MBRs have been reviewed (Judd, 2004; Le-Clech *et al.*, 2006). Factors such as the type of wastewater, sludge loading rate, MLSS concentration, mechanical stress, solid retention time (SRT), food-to-microorganism ratio (F/M) and microbial growth phase, are known to affect the concentration of foulant and in turn encouraging the development of membrane fouling (Chang and Judd, 2002; Li *et al.*, 2005). Various techniques have been used to limit membrane fouling, including manipulating bioreactor conditions, modifying hydrodynamics and flux and improving module design (Böhm *et al.*, 2012; Drews, 2010; Field and Pearce, 2011).

In the ASMBR system, air bubble sparking can help to prevent the deposit forming on the membrane surface (Chang and Judd, 2002; Ujang *et al.*, 2005). Periodic backwashing improves membrane permeability and reduces fouling, producing optimal, stable hydraulic operating conditions (Bouhabila *et al.*, 1998; Lim and Bai, 2003). Adding flocculation–coagulation agents limits membrane fouling by aggregation of the colloidal fraction, thus reducing internal clogging of the membranes (Bhatia *et al.*, 2007a; Guo *et al.*, 2010; Iversen *et al.*, 2009). Several materials have been added to the submerged MBR to reduce bio-fouling.

Several studies have shown that the addition of BFR or flux enhancer, which are mostly flocculants or adsorbent, is one of the strategies to lower the fouling propensity in an MBR (Guo *et al.*, 2010; Guo *et al.*, 2008; Koseoglu *et al.*, 2008; Ujang *et al.*, 2002). Meanwhile, the direct addition of activated carbon into the submerged MBR can maintain or improve the organic removal efficiency without the need for the membrane to be cleaned for longer operation time (Munz *et al.*, 2007; Ujang *et al.*, 2002; Ying and Ping, 2006). Akram and Stuckey (2008) concluded that the addition of PAC might improve the flux and organic removal efficiency of a submerged anaerobic MBR. Lee *et al.* (2001) reported that the addition of zeolite to a MBR produced more rigid, stable and strong sludge flocs that can reduce the membrane fouling by forming a less compressible cake layer on the membrane surface.

Recent studies have considered another two important factors to membrane fouling propensity, i.e. bound extracellular polymeric substances (EPS) and soluble microbial products (SMP) (Feng *et al.*, 2012; Jeong *et al.*, 2007; Pan *et al.*, 2010). Studies have also pointed out positive relation between the membrane fouling reducing process and the increase of critical flux and production flux (Le-Clech *et al.*, 2006; Le-Clech *et al.*, 2003). The addition of natural material, i.e. *Moringa oleifera* seed, as a coagulant for pre-treatment has significantly reduced the SS and organic content of POME (Bhatia *et al.*, 2007b). Damayanti *et al.* (2011) reported that *Moringa oleifera* seed has also been proven successful in increasing the critical flux value of a hybrid MBR treating POME, leading to the potential of *Moringa oleifera* as a natural BFR.

1.2 Problem Statement

The extensive production of palm oil produced a huge amount of POME. Treatment of POME, besides of the fulfilling the effluent standard, also offers the potential of water reclamation and reuse. The use of membrane processes in wastewater treatment are considered as a key option of advanced water reclamation and reuse schemes (Pulefou *et al.*, 2008; Wintgens *et al.*, 2005). Therefore, it is necessary to take effort to emphasize on the application of MBR technology in POME treatment and make efforts to enhance the potential for water reclamation and reuse.

The major obstacle on MBR system is membrane fouling. Fouling leads to a decline in permeate flux, requiring more frequent membrane cleaning, which actually increases the operating costs. Finally, membrane fouling leads to the increased total membrane life-cycle cost. Membrane fouling in MBR may be in term of physical, inorganic, organic or biological form. Physical fouling refers to the plugging of membrane pores by colloidal species, such that a certain proportion of the membrane surface is effectively blocked (Judd, 2004). Inorganic and organic fouling usually refer respectively to scalants and macromolecular species (Jiang *et al.*, 2003). Organic fouling in MBR, on the other hand, has been much more widely studied and characterized, as well as biofouling. It has been estimated that almost half of all fouling deposits in membrane systems comprised or involved biofilm (Wang *et al.*, 2007).

Many researchers have been exploring the application of materials which could be used to prevent membrane fouling. As mentioned before, flocculation–coagulation agents, activated carbon, PAC, Zeolite, even natural *Moringa oleifera* has been added to the MBR system and reduce the membrane fouling. Not only for membrane fouling mitigation, several studies stated that the addition of fouling-retarding materials showed improvement on organics removal (Dizge *et al.*, 2011; Li *et al.*, 2011; Ngo and Guo, 2009; Satyawali and Balakrishnan, 2009). Higher quality of final effluent could assist in promoting the water reclamation and reuse in palm oil industry.

The MLSS concentration is a crucial operating factor for MBR system. The use of high concentrations of biomass, which resulting a smaller footprint bioreactor is stated as one of the big advantages of MBR technology. Yet, studies about the influence of MLSS on fouling are sometimes inconsistent (Lousada-Ferreira *et al.*, 2010). Although MBR systems can be operated more effective with higher concentration of biomass (Melin *et al.*, 2006; Meng *et al.*, 2007), several studies concluded that higher biomass population has resulted in higher fouling to the system (Damayanti, *et al.,* 2011; Lousada-Ferreira *et al.*, 2010) . Yet, it is not clear which factors determine the resulting of decreasing flux. The higher MLSS concentration, the higher the production of EPS and SMP (Liu and Fang, 2003). It is widely understood that the EPS generated by micro-organisms are largely responsible for organic fouling of membranes (Jeong *et al.*, 2007), whereas, SMP is considered as the soluble part of EPS release into the solution from substrate metabolism and biomass decay (Judd, 2004; Yuniarto *et al.*, 2013).

1.3 Objectives of the Study

The aim of this study is to study the biotransformation of organic components, mitigation of membrane fouling and enhancement of the flux production of an aerobic submerged membrane bioreactor (ASMBR) for POME treatment.

Specific objectives of this study for achieving the main aim are as follows:

1. To determine the effect of various biomass populations in treating POME on membrane filterability and organic compound concentration using a short term operation of the ASMBR systems;

2. To investigate the best concentration of various BFR in the ASMBR system for treating POME on a batch system;

3. To assess the performance of the ASMBR system with and without the addition of various BFR in treating POME on a long term operational period and various organic loading on the biofouling phenomenon mitigation, biodegradation of organic and residual organic colour;

4. To determine the COD fractionation of POME using respirometry analysis and to estimate biokinetic parameters and coefficients using activated sludge modelling in order to describe the biomass performances in the ASMBR system coupled with and without BFR.

1.4 Scope of the Study

A significant work has been conducted on the application of ASMBR system for treating POME. The research was initiated by conducting a thorough literature review on the generation and characteristic of POME, the application of MBR systems on various types of wastewater, the obstacles in the application of MBR systems, and the various effort has been done to overcome the obstacles and enhancing the performance of MBR systems. Operational factors that affect the process, biomass characterisation, the rate of removal efficiencies, and the membrane fouling phenomenon and its mitigation are some issues have been extracted from literature study. This review found out unanswered questions related to the application of ASMBR for treating POME, as well as the mitigation of possible membrane bio-fouling in the ASMBR system. The following task was setting up and developing a lab scale ASMBR system to conduct the study. The system consisted with a 20 L aerobic reactor with single flat-sheet Kubota MF membrane module and equipped with several supporting systems. Diluted POME of about 1000 and 3000 mg L^{-1} of COD were fed to the ASMBR systems during the course of this study.

The work started with the determination of best concentration of biomass in the ASMBR, since biomass is one of the factors that influence the bioprocess and membrane fouling in MBR system. Moreover, the best SRT, which is a very important role in biomass population, was also determined. The continues system of ASMBR system was subjected with 3,000 to 12,000 mg L^{-1} of MLSS and SRT of 20 days and above, before organic solids removal rate, the concentration of residual colour, the development of biofoulant, and critical flux methods were used as the approach to determine the best biomass concentration and SRT.

To enhance the performance of ASMBR system and mitigate the biofouling, powdered activated (PAC), granulated activated carbon (GAC) and powdered zeolite (ZEO) were used as BFR. Hence, batch adsorption experiments with various concentrations of BFR from 0 – 10 g L^{-1} were used to determine the best concentration of BFR. The adsorption capacity and isotherm of each BFR were also obtained to describe the process occurred in the system.

The performance of the ASMBR system with and without the addition of various BFR to treat POME on a constant-flux and long term operational period are assessed. The ASMBR systems are subjected to the variation of organic loading rate to study the behaviour of the system. Besides the effect of BFR on reduction of organic compounds, colour, SMP, EPS and the critical flux enhancement are also monitored. During long term operation of the ASMBR systems, respirometric analysis was also done to obtain oxygen uptake rate (OUR) and COD fractionation. International water association's activated sludge models no. 1 (ASM1) is used in calibrating the ASMBR system for estimating biokinetic parameters, describing the effect of BFR on bioprocess in ASMBR system. The whole experiment is conducted in the laboratory of Institut Pengurusan Alam Sekitar dan Sumber-sumber Air (IPASA) Universiti Teknologi Malaysia (UTM). In this study, all analytical measurements are performed according to *Standard Methods for the Examination of Water and Wastewater* (APHA, 1998) and legitimate related standard methods.

1.5 Significance of Research

This study could improve the understanding of optimizing the biotransformation of soluble organics and flux enhancement in the MBR system treating agricultural wastewater. Although the MBR treatment has been proven to have prominent advantages over other conventional treatment system, none of the recent studies have been devoted to the development of ASMBR as a treatment for POME.

Direct treatment of high organic concentration of POME is not viable using ASMBR. Therefore, the treatment of diluted POME is explored by exposing the reactor system with and without BFR using the various organic loading rate and the various types and concentration of BFR. The application of BFR in ASMBR treating POME is new based on the literature review, except the study done by Damayanti *et al.* (2011b) on hybrid MBR. The effect of BFR in the ASMBR system is studied base on their performance to reduce biofouling and enhancing the final effluent quality. Furthermore, the activated sludge model is used to obtain stoichiometry and biokinetic parameters of each process describing the performances of the ASMBR system coupled with and without BFR. The stoichiometry and biokinetic parameters obtained from the models can be used in the design of the similar system in the future.

The operation technique and the maintenance method of ASMBR system coupled with BFR in this study would be a valuable information for rectifying or upgrading similar system. This study may also lead to a new generation of ASMBR application for high strength wastewater, specifically POME, to produce better quality of final effluent, enhancing process capacity, prolonging the membrane maintenance cycle and reducing the operating cost.

1.6 Organization of the Thesis

This thesis consisted of five chapters. First chapter presented an introduction and the research background, as well as research aim and objectives and scope of the study. Chapter 2 covered the literature reviews, including general information on POME namely generation, the amount and the characteristics. Review of the wastewater treatment system existing for treating POME, MBR system and related literature is also presented in this chapter. Chapter 3 consisted of a framework and experimental setup, detailed listing of the material as well as detailed experimental procedures used in this study. Chapter 4 presents the comparative study on four types of BFR used in batch and continuous reactor system, along with the assessment of the ASMBR system's performance using various operating systems and various organic loadings of POME. The latter sections of this chapter discussed the COD fractionation of the wastewater as well as the calibration of activated sludge model on ASMBR without and with BFR for treating POME. Chapter 5 presented the conclusions derived from this study and the recommendations for future studies.

REFERENCES

Abdurahman, N. H., Rosli, Y. M. and Azhari, N. H. (2011). Development of a membrane anaerobic system (MAS) for palm oil mill effluent (POME) treatment. *Desalination*, 266(1-3), 208-212.

Ahmad, A. L., Ismail, S. and Bhatia, S. (2003). Water recycling from palm oil mill effluent (POME) using membrane technology. *Desalination*, 157(1-3), 87-95.

Ahmad, A. L., Ismail, S. and Bhatia, S. (2005a). Membrane treatment for palm oil mill effluent: Effect of transmembrane pressure and crossflow velocity. *Desalination*, 179(1-3), 245-255.

Ahmad, A. L., Ismail, S. and Bhatia, S. (2005b). Ultrafiltration behavior in the treatment of agro-industry effluent: Pilot scale studies. *Chemical Engineering Science*, 60(19), 5385-5394.

Ahmad, A. L., Ismail, S. and Bhatia, S. (2005c). Optimization of coagulation-flocculation process for palm oil mill effluent using response surface methodology. *Environmental Science and Technology*, 39(8), 2828-2834.

Ahmad, A. L., Sumathi, S. and Hameed, B. H. (2005d). Adsorption of residue oil from palm oil mill effluent using powder and flake chitosan: Equilibrium and kinetic studies. *Water Research*, 39(12), 2483-2494.

Ahmad, A. L., Chong, M. F. and Bhatia, S. (2006a). Ultrafiltration modeling of multiple solutes system for continuous cross-flow process. *Chemical Engineering Science*, 61(15), 5057-5069.

Ahmad, A. L., Sumathi, S. and Hameed, B. H. (2006b). Coagulation of residue oil and suspended solid in palm oil mill effluent by chitosan, alum and PAC. *Chemical Engineering Journal*, 118(1-2), 99-105.

Ahmad, A. L., Chong, M. F. and Bhatia, S. (2007). Mathematical modeling of multiple solutes system for reverse osmosis process in palm oil mill effluent (POME) treatment. *Chemical Engineering Journal*, 132(1-3), 183-193.

Ahmad, A. L., Chan, C. Y., Shukor, S. R. A. and Mashitah, M. D. (2008). Recovery of oil and carotenes from palm oil mill effluent (POME). *Chemical Engineering Journal*, 141(1-3), 383-386.

Ahmad, A. L., Chong, M. F. and Bhatia, S. (2009). A comparative study on the membrane based palm oil mill effluent (POME) treatment plant. *Journal of Hazardous Materials*, 171(1–3), 166-174.

Ahmad, Z., Salmiati, Ujang, Z., Damayanti, A. and Olsson, G. (2008) A Novel Approach for Palm Oil Mill Effluent (POME) Treatment And Recovery Using Hybrid Membrane Bioreactor (MBR). Asia Water Conference. Kuala Lumpur. Malaysia

Akram, A. and Stuckey, D. C. (2008). Flux and performance improvement in a submerged anaerobic membrane bioreactor (SAMBR) using powdered activated carbon (PAC). *Process Biochemistry*, 43(1), 93-102.

Al-Malack, M. H. (2006). Determination of biokinetic coefficients of an immersed membrane bioreactor. *Journal of Membrane Science*, 271(1-2), 47-58.

APHA. (1998). *Standart Methods for the Examination of Water and Wastewater* (20 ed.). Washington DC, USA: American Public Health Assocciation, American Water Works Association, Water Environmental Federation.

Arabi, S. and Nakhla, G. (2008). Impact of protein/carbohydrate ratio in the feed wastewater on the membrane fouling in membrane bioreactors. *Journal of Membrane Science*, 324(1–2), 142-150.

Atkinson, S. and Menzefricke, K. (2006). Research studies predict strong growth for MBR markets. *Membrane Technology*, (2), 8-10.

Aziz, S. Q., Aziz, H. A., Yusoff, M. S. and Bashir, M. J. K. (2011). Landfill leachate treatment using powdered activated carbon augmented sequencing batch reactor (SBR) process: Optimization by response surface methodology. *Journal of Hazardous Materials*, 189(1-2), 404-413.

Bacchin, P., Aimar, P. and Field, R. W. (2006). Critical and sustainable fluxes: Theory, experiments and applications. *Journal of Membrane Science*, 281(1-2), 42-69.

Barker, D. J. and Stuckey, D. C. (1999). A review of soluble microbial products (SMP) in wastewater treatment systems. *Water Research*, 33(14), 3063-3082.

Beck, C., Prades, G. and Sadowski, A. G. (2005) Activated sludge wastewater treatment plants optimisation to face pollution overloads during grape harvest periods. *Vol. 51. Water Science and Technology* (pp. 81-88).

Bhatia, S., Othman, Z. and Ahmad, A. L. (2007a). Pretreatment of palm oil mill effluent (POME) using *Moringa oleifera* seeds as natural coagulant. *Journal of Hazardous Materials*, 145(1-2), 120-126.

Bhatia, S., Othman, Z. and Ahmad, A. L. (2007b). Coagulation-flocculation process for POME treatment using *Moringa oleifera* seeds extract: Optimization studies. *Chemical Engineering Journal*, 133(1-3), 205-212.

Böhm, L., Drews, A., Prieske, H., Bérubé, P. R. and Kraume, M. (2012). The importance of fluid dynamics for MBR fouling mitigation. *Bioresource Technology*, 122(0), 50-61.

Borja, R. and Banks, C. J. (1994). Anaerobic digestion of palm oil mill effluent using an up-flow anaerobic sludge blanket reactor. *Biomass and Bioenergy*, 6(5), 381-389.

Borja, R. and Banks, C. J. (1995). Comparison of an Anaerobic Filter and an Anaerobic Fluidized Bed Reactor Treating Palm Oil Mill Effluent. *Process Biochemistry*, 30(6), 511-521.

Borja, R., Banks, C. J. and Sánchez, E. (1996). Anaerobic treatment of palm oil mill effluent in a two-stage up-flow anaerobic sludge blanket (UASB) system. *Journal of Biotechnology*, 45(2), 125-135.

Bottino, A., Capannelli, G., Comite, A. and Mangano, R. (2009). Critical flux in submerged membrane bioreactors for municipal wastewater treatment. *Desalination*, 245(1–3), 748-753.

Bouhabila, E. H., Ben Aïm, R. and Buisson, H. (1998). Microfiltration of activated sludge using submerged membrane with air bubbling (application to wastewater treatment). *Desalination*, 118(1–3), 315-322.

Bouhabila, E. H., Ben Aïm, R. and Buisson, H. (2001). Fouling characterisation in membrane bioreactors. *Separation and Purification Technology*, 22–23(0), 123-132.

Broeck, R. v., Dierdonck, J. v., Caerts, B., Bisson, I., Kregersman, B., Nijskens, P., Dotremont, C., Impe, J. F. v. and Smets, I. Y. (2010). The impact of deflocculation-reflocculation on fouling in membrane bioreactors. *Separation and Purification Technology*, 71(3), 279-284.

Canudas, A. G. (2005). *Modelling Biological Organic Matter and Nutrient Removal Processes From Wastewater Using Respirometric and Titrimetric Techniques.* Ph.D, Universitat Autonoma de Barcelona.

Chang, I. S. and Judd, S. (2002). Air sparging of a submerged MBR for municipal wastewater treatment. *Process Biochemistry*, 37(8), 915-920.

Chang, W. S., Hong, S. W. and Park, J. (2002). Effect of zeolite media for the treatment of textile wastewater in a biological aerated filter. *Process Biochemistry*, 37(7), 693-698.

Choi, H., Zhang, K., Dionysiou, D. D., Oerther, D. B. and Sorial, G. A. (2005). Effect of permeate flux and tangential flow on membrane fouling for wastewater treatment. *Separation and Purification Technology*, 45(1), 68-78.

Damayanti, A., Ujang, Z., Salim, M. R., Olsson, G. and Sulaiman, A. Z. (2010). Respirometric analysis of activated sludge models from palm oil mill effluent. *Bioresource Technology*, 101(1), 144-149.

Damayanti, A., Ujang, Z., Salim, M. R. and Olsson, G. (2011a). The effect of mixed liquor suspended solids (MLSS) on biofouling in a hybrid membrane bioreactor for the treatment of high concentration organic wastewater. *Water Science and Technology*, 63(8), 1701-1706.

Damayanti, A., Ujang, Z. and Salim, M. R. (2011b). The influenced of PAC, zeolite, and *Moringa oleifera* as biofouling reducer (BFR) on hybrid membrane bioreactor of palm oil mill effluent (POME). *Bioresource Technology*, 102(6), 4341-4346.

Department of Environmental (DOE). (2010). Environmental Quality Act 1974. Government of Malaysia.

Dialynas, E. and Diamadopoulos, E. (2008). Integration of immersed membrane ultrafiltration with coagulation and activated carbon adsorption for advanced treatment of municipal wastewater. *Desalination*, 230(1-3), 113-127.

Dialynas, E. and Diamadopoulos, E. (2009). Integration of a membrane bioreactor coupled with reverse osmosis for advanced treatment of municipal wastewater. *Desalination*, 238(1-3), 302-311.

Dizge, N., Koseoglu-Imer, D. Y., Karagunduz, A. and Keskinler, B. (2011). Effects of cationic polyelectrolyte on filterability and fouling reduction of submerged membrane bioreactor (MBR). *Journal of Membrane Science*, 377(1-2), 175-181.

Drews, A. (2010). Membrane fouling in membrane bioreactors—Characterisation, contradictions, cause and cures. *Journal of Membrane Science*, 363(1–2), 1-28.

Ekama, G. A., Dold, P. L. and Marais v, G. R. (1986). Procedures for determining influent COD fractions and the maximum specific growth rate of heterotrophs in activated sludge systems. *Water Science and Technology*, 18(6), 91-114.

Fakhru'l-Razi, A. and Noor, M. J. M. M. (1999). Treatment of palm oil mill effluent (POME) with the membrane anaerobic system (MAS). *Water Science and Technology*, 39(10–11), 159-163.

Fan, F., Zhou, H. and Husain, H. (2006). Identification of wastewater sludge characteristics to predict critical flux for membrane bioreactor processes. *Water Research*, 40(2), 205-212.

Fane, A. (2002a). Membrane bioreactors: Design and operational options. *Filtration and Separation*, 39(5), 26-29.

Fane, A. G. (2002b). Membrane bioreactors: design & operational options. *Filtration & Separation*, 39(5), 26-29.

Fane, A. G. (2007). Sustainability and membrane processing of wastewater for reuse. *Desalination*, 202(1–3), 53-58.

Feng, S., Zhang, N., Liu, H., Du, X., Liu, Y. and Lin, H. (2012). The effect of COD/N ratio on process performance and membrane fouling in a submerged bioreactor. *Desalination*, 285(0), 232-238.

Field, R. W., Wu, D., Howell, J. A. and Gupta, B. B. (1995). Critical flux concept for microfiltration fouling. *Journal of Membrane Science*, 100(3), 259-272.

Field, R. W. and Pearce, G. K. (2011). Critical, sustainable and threshold fluxes for membrane filtration with water industry applications. *Advances in Colloid and Interface Science*, 164(1–2), 38-44.

Flemming, H. C. and Leis, A. (2001). Extracellular polymeric substances - the construction material of biofilms - Selected proceedings of the 1st IWA International Conference on Microbial Extracellular Polymeric Substances, held in Mulheim, Germany, 18-20 September 2000 - Preface. *Water Science and Technology*, 43(6), Vii-Ix.

Flemming, H. C. and Wingender, J. (2001). Relevance of microbial extracellular polymeric substances (EPSs) - Part I: Structural and ecological aspects. *Water Science and Technology*, 43(6), 1-8.

Fun, C. W., Haq, M. R. U. and Kutty, S. R. M. (2007). Treatment of palm oil mill effluent using biological sequencing batch reactor system. *WIT Transactions on Ecology and the Environment*, 104, 511-518.

Gujer, W., Henze, M., Mino, T. and Loosdrecht, M. C. M. v. (1999). Activated sludge model No. 3. *Water Science and Technology*, 39(1), 183-193.

Guo, W., Vigneswaran, S., Ngo, H. H., Xing, W. and Goteti, P. (2008a). Comparison of the performance of submerged membrane bioreactor (SMBR) and submerged membrane adsorption bioreactor (SMABR). *Bioresource Technology*, 99(5), 1012-1017.

Guo, W., Vigneswaran, S., Ngo, H. H., Kandasamy, J. and Yoon, S. (2008b). The role of a membrane performance enhancer in a membrane bioreactor: a comparison with other submerged membrane hybrid systems. *Desalination*, 231(1-3), 305-313.

Guo, W., Ngo, H. H., Vigneswaran, S., Dharmawan, F., Nguyen, T. T. and Aryal, R. (2010). Effect of different flocculants on short-term performance of submerged membrane bioreactor. *Separation and Purification Technology*, 70(3), 274-279.

Hai, F. I., Yamamoto, K. and Lee, C. H. (2014). *Membrane Biological Reactors: Theory, Modeling, Design, Management and Applications to Wastewater Reuse*. London. IWA Publishing

He, S. B., Xue, G. and Kong, H. (2006). Zeolite powder addition to improve the performance of submerged gravitation-filtration membrane bioreactor. *Journal of Environmental Science*, 18(2), 242 - 247.

Henze, M., Leslie Grady, C. P., Gujer, W., Maris, G. V. R. and Matsuo, T. (1987). Activated Sludge Process Model No. 1. *Scientific and Technical Report 1*. London, UK: IAWQ.

Henze, M., Gujer, W., Mino, T. and Loosedrecht, M. C.M. v. (2000). *Activated Sludge Models ASM1, ASM2, ASM2d and ASM3* (Science and Technical Report No. 9). London: IWA.

Huang, Z., Ong, S. L. and Ng, H. Y. (2011). Submerged anaerobic membrane bioreactor for low-strength wastewater treatment: Effect of HRT and SRT on treatment performance and membrane fouling. *Water Research*, 45(2), 705-713.

Hussein, M. Z. B., Kuang, D., Zainal, Z. and Teck, T. K. (2001). Kaolin–Carbon Adsorbents for Carotene Removal of Red Palm Oil. *Journal of Colloid and Interface Science*, 235(1), 93-100.

Iversen, V., Mehrez, R., Horng, R. Y., Chen, C. H., Meng, F., Drews, A., Lesjean, B., Ernst, M., Jekel, M. and Kraume, M. (2009). Fouling mitigation through flocculants and adsorbents addition in membrane bioreactors: Comparing lab and pilot studies. *Journal of Membrane Science*, 345(1-2), 21-30.

Jeong, T. Y., Cha, G. C., Yoo, I. K. and Kim, D. J. (2007). Characteristics of bio-fouling in a submerged MBR. *Desalination*, 207(1-3), 107-113.

Jeppsson, U. (1996). *Modelling Aspects of Wastewater Treatment Processes.* Lund Institute of Technology, Sweden.

Jia, Y., Wang, R. and Fane, A. G. (2009). Hybrid PAC-submerged membrane system for trace organics removal: I. Adsorption kinetics study of PAC in a bubbled solution. *Chemical Engineering Journal*, 155(1–2), 155-160.

Jiang, T., Kennedy, M. D., Meer, W. G. J. v., Vanrolleghem, P. A. and Schippers, J. C. (2003). The role of blocking and cake filtration in MBR fouling. *Desalination*, 157(1-3), 335-343.

Jiang, T., Myngheer, S., De Pauw, D. J. W., Spanjers, H., Nopens, I., Kennedy, M. D., Amy, G. and Vanrolleghem, P. A. (2008). Modelling the production and degradation of soluble microbial products (SMP) in membrane bioreactors (MBR). *Water Research*, 42(20), 4955-4964.

Jiang, Y., Wang, Z. and Fu, J. (1997). Measurement of water solubility in membrane phase containing surfactants and carriers in liquid surfactant membranes by gas chromatography. *Beijing Huagong Daxue Xuebao(Ziran*

Kexueban)/Journal of Beijing University of Chemical Technology, 24(3), X1-4.

Judd, S. (2002). Submerged membrane bioreactors: flat plate or hollow fibre? *Filtration & Separation*, 39(5), 30-31.

Judd, S. (2004). A review of fouling of membrane bioreactors in sewage treatment. *Water Science and Technology*, 49, 229-235.

Judd, S. (2005) Fouling control in submerged membrane bioreactors. *Vol. 51. Water Science and Technology* (pp. 27-34).

Judd, S. (2006). *The MBR Book: Principles and Applications of Membrane Bioreactors in Water and Wastewater Treatment* (First ed.): Elsevier Ltd.

Judd, S. (2008). The status of membrane bioreactor technology. *Trends in Biotechnology*, 26(2), 109-116.

Karahan, O., Dogruel, S., Dulekgurgen, E. and Orhon, D. (2008). COD fractionation of tannery wastewaters-Particle size distribution, biodegradability and modeling. *Water Research*, 42(4-5), 1083-1092.

Khan, M. M. T., Takizawa, S., Lewandowski, Z., Jones, W. L., Camper, A. K., Katayama, H., Kurisu, F. and Ohgaki, S. (2011). Membrane fouling due to dynamic particle size changes in the aerated hybrid PAC-MF system. *Journal of Membrane Science*, 371(1-2), 99-107.

Kim, J. S. and Lee, C. H. (2003). Effect of powdered activated carbon on the performance of an aerobic membrane bioreactor: Comparison between cross-flow and submerged membrane systems. *Water Environment Research*, 75(4), 300-307.

Kimura, K., Miyoshi, T., Naruse, T., Yamato, N., Ogyu, R. and Watanabe, Y. (2008). The difference in characteristics of foulants in submerged MBRs caused by the difference in the membrane flux. *Desalination*, 231(1-3), 268-275.

Koch, G., Kühni, M., Gujer, W. and Siegrist, H. (2000). Calibration and validation of activated sludge model no. 3 for Swiss municipal wastewater. *Water Research*, 34(14), 3580-3590.

Koseoglu, H., Yigit, N. O., Iversen, V., Drews, A., Kitis, M., Lesjean, B. and Kraume, M. (2008). Effects of several different flux enhancing chemicals on filterability and fouling reduction of membrane bioreactor (MBR) mixed liquors. *Journal of Membrane Science*, 320(1-2), 57-64.

Le-Clech, P., Alvarez-Vazquez, H., Jefferson, B. and Judd, S. (2003a). Fluid hydrodynamics in submerged and sidestream membrane bioreactors. *Water Science and Technology*, 48(3), 113-119.

Le-Clech, P., Jefferson, B., Chang, I. S. and Judd, S. (2003b). Critical flux determination by the flux-step method in a submerged membrane bioreactor. *Journal of Membrane Science*, 227(1-2), 81-93.

Le-Clech, P., Jefferson, B. and Judd, S. (2003c). 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.

Le-Clech, P., Fane, A., Leslie, G. and Childress, A. (2005). MBR focus: the operators' perspective. *Filtration & Separation*, 42(5), 20-23.

Le-Clech, P., Chen, V. and Fane, T. A. G. (2006). Fouling in membrane bioreactors used in wastewater treatment. *Journal of Membrane Science*, 284(1–2), 17-53.

Lee, J. C., Kim, J. S., Kang, I. J., Cho, M. H., Park, P. K. and Lee, C. H. (2001). Potential and limitations of alum or zeolite addition to improve the performance of a submerged membrane bioreactor. *Water Science and Technology*, 43(11), 59-66.

Lee, K. T. and Boateng, C. O. (2013) Economic sustainability assessment of biofuels production from oil palm biomass. *Vol. 138. Green Energy and Technology* (pp. 189-215).

Lee, W., Kang, S. and Shin, H. (2003). Sludge characteristics and their contribution to microfiltration in submerged membrane bioreactors. *Journal of Membrane Science*, 216(1-2), 217-227.

Lesjean, B. and Huisjes, E. H. (2008). Survey of the European MBR market: trends and perspectives. *Desalination*, 231(1–3), 71-81.

Lesouef, A., Payraudeau, M., Rogalla, F. and Kleiber, B. (1992). Optimizing nitrogen removal reactor configurations by onsite calibration of the IAWPRC activated sludge model. *Water Science and Technology*, 25(6), 105-123.

Li, H., Yang, M., Zhang, Y., Liu, X., Gao, M. and Kamagata, Y. (2005a) Comparison of nitrification performance and microbial community between submerged membrane bioreactor and conventional activated sludge system. *Vol. 51. Water Science and Technology* (pp. 193-200).

Li, N. N., Fane, A. G., Ho, W. S. W. and Matsuura, T. (2008). *Advanced Membrane Technology and Applications*. New Jersey: John Wiley & Sons, Inc.

Li, X., Hai, F. I. and Nghiem, L. D. (2011). Simultaneous activated carbon adsorption within a membrane bioreactor for an enhanced micropollutant removal. *Bioresource Technology*, 102(9), 5319-5324.

Li, Y. Z., He, Y. L., Liu, Y. H., Yang, S. C. and Zhang, G. J. (2005b). Comparison of the filtration characteristics between biological powdered activated carbon sludge and activated sludge in submerged membrane bioreactors. *Desalination*, 174(3), 305-314.

Liang, S., Liu, C. and Song, L. (2007). Soluble microbial products in membrane bioreactor operation: Behaviors, characteristics, and fouling potential. *Water Research*, 41(1), 95-101.

Lim, A. L. and Bai, R. (2003). Membrane fouling and cleaning in microfiltration of activated sludge wastewater. *Journal of Membrane Science*, 216(1–2), 279-290.

Liu, Y. and Fang, H. H. P. (2003). Influences of extracellular polymeric substances (EPS) on flocculation, settling, and dewatering of activated sludge. *Critical Reviews in Environmental Science and Technology*, 33(3), 237-273.

Liu, Y., Wang, L., Wang, B., Cui, H. and Zhang, J. (2005) Performance improvement of hybrid membrane bioreactor with PAC addition for water reuse. *Vol. 52. Water Science and Technology* (pp. 383-391).

Lousada-Ferreira, M., Geilvoet, S., Moreau, A., Atasoy, E., Krzeminski, P., van Nieuwenhuijzen, A. and van der Graaf, J. (2010). MLSS concentration: Still a poorly understood parameter in MBR filterability. *Desalination*, 250(2), 618-622.

Ma, A. N., Cheah, S. C. and Chow, M. C. (1993). Current status of palm oil processing wastes management. In Yeoh, B. G., Chee, K. S., Phang, S. M., Isa, Z., Idris, A. & Mohamed, M. (Eds.), *Waste Management in Malaysia: Current Status and Prospects for Bioremediation.* (pp. 111-136): Ministry of Science, Technology and the Environment, Malaysia.

Maartens, A., Jacobs, E. P. and Swart, P. (2002). UF of pulp and paper effluent: Membrane fouling-prevention and cleaning. *Journal of Membrane Science*, 209(1), 81-92.

Madaeni, S. S. (2001). Effect of large particles on microfiltration of small particles. *Journal of Porous Materials*, 8(2), 143-148.

Makinia, J. (2010). *Mathematical Modelling and Computer Simulation of Activated Sludge Systems*: IWA Publishing.

Meinel, F., Ruhl, A. S., Sperlich, A., Zietzschmann, F. and Jekel, M. (2015). Pilot-scale investigation of micropollutant removal with granular and powdered activated carbon. *Water, Air, and Soil Pollution*, 226(1).

Melin, T., Jefferson, B., Bixio, D., Thoeye, C., De Wilde, W., De Koning, J., Graaf, J. v. and Wintgens, T. (2006). Membrane bioreactor technology for wastewater treatment and reuse. *Desalination*, 187(1-3), 271-282.

Meng, F., Shi, B., Yang, F. and Zhang, H. (2007). New insights into membrane fouling in submerged membrane bioreactor based on rheology and hydrodynamics concepts. *Journal of Membrane Science*, 302(1-2), 87-94.

Meng, F., Chae, S. R., Drews, A., Kraume, M., Shin, H.-S. and Yang, F. (2009). Recent advances in membrane bioreactors (MBRs): Membrane fouling and membrane material. *Water Research*, 43(6), 1489-1512.

Meshko, V., Markovska, L., Mincheva, M. and Rodrigues, A. E. (2001). Adsorption of basic dyes on granular acivated carbon and natural zeolite. *Water Research*, 35(14), 3357-3366.

Metcalf & Eddy. (2004). *Wastewater Engineering, Treatment and Reuse* (4 ed.): McGraw-Hill.

Mukherjee, I. and Sovacool, B. K. (2014). Palm oil-based biofuels and sustainability in southeast Asia: A review of Indonesia, Malaysia, and Thailand. *Renewable and Sustainable Energy Reviews*, 37(0), 1-12.

Mulas, M. (2006). *Modelling and Control of Activated Sludge Processes.* PhD Thesis, University of Cagliari, Italy.

Munz, G., Gori, R., Mori, G. and Lubello, C. (2007). Powdered activated carbon and membrane bioreactors (MBRPAC) for tannery wastewater treatment: long term effect on biological and filtration process performances. *Desalination*, 207(1-3), 349-360.

Mutamim, N. S. A., Noor, Z. Z., Hassan, M. A. A. and Olsson, G. (2012). Application of membrane bioreactor technology in treating high strength industrial wastewater: a performance review. *Desalination*, 305, 1-11.

Najafpour, G., Yieng, H. A., Younesi, H. and Zinatizadeh, A. (2005). Effect of organic loading on performance of rotating biological contactors using Palm Oil Mill effluents. *Process Biochemistry*, 40(8), 2879-2884.

Ng, C. A., Sun, D. and Fane, A. G. (2006). Operation of membrane bioreactor with powdered activated carbon addition. *Separation Science and Technology*, 41(7), 1447-1466.

Ng, W. J., Goh, A. C. C. and Tay, J. H. (1987). Palm oil mill effluent (POME) treatment : an assessment of coagulants used to aid liquid-solid separation. *Biological Wastes*, 21, 237-248.

Ng, W. J., Goh, A. C. C. and Tay, J. H. (1988). Palm oil mill effluent treatment liquid- solid separation with dissolved air flotation. *Biological Wastes*, 25, 257-268.

Ngo, H. H. and Guo, W. S. (2009). Membrane fouling control and enhanced phosphorus removal in an aerated submerged membrane bioreactor using modified green bioflocculant. *Bioresource Technology*, 100(18), 4289-4291.

Nielsen, S. S. (2010). *Food Analysis Laboratory Manual* (Second Edition ed.). Texas: Springer.

Orhon, D., Ateş, E., Sözen, S. and Çokgör, E. U. (1997). Characterization and COD fractionation of domestic wastewaters. *Environmental Pollution*, 95(2), 191-204.

Ostuni, E., Chapman, R. G., Liang, M. N., Meluleni, G., Pier, G., Ingber, D. E. and Whitesides, G. M. (2001). Self-assembled monolayers that resist the adsorption of proteins and the adhesion of bacterial and mammalian cells. *Langmuir*, 17(20), 6336-6343.

Pan, J. R., Su, Y. and Huang, C. (2010). Characteristics of soluble microbial products in membrane bioreactor and its effect on membrane fouling. *Desalination*, 250(2), 778-780.

Petersen, B., Gernaey, K., Henze, M. and Vanrolleghem, P. A. (2003). Calibration of Activated Sludge Models: A Critical Review of Experimental Designs. In Agathos, S. & Reineke, W. (Eds.), *Biotechnology for the Environment: Wastewater Treatment and Modeling, Waste Gas Handling* (Vol. 3C, pp. 101-186): Springer Netherlands.

Pollice, A., Brookes, A., Jefferson, B. and Judd, S. (2005). Sub-critical flux fouling in membrane bioreactors — a review of recent literature. *Desalination*, 174(3), 221-230.

Pollice, A. and Laera, G. (2005) Effects of complete sludge retention on biomass build-up in a membrane bioreactor. *Vol. 52. Water Science and Technology* (pp. 369-375).

Pollice, A., Giordano, C., Laera, G., Saturno, D. and Mininni, G. (2007). Physical characteristics of the sludge in a complete retention membrane bioreactor. *Water Research*, 41(8), 1832-1840.

Pulefou, T., Jegatheesan, V., Steicke, C. and Kim, S.-H. (2008). Application of submerged membrane bioreactor for aquaculture effluent reuse. *Desalination*, 221(1-3), 534-542.

Rai, P., Rai, C., Majumdar, G. C., DasGupta, S. and De, S. (2006). Resistance in series model for ultrafiltration of mosambi (Citrus sinensis (L.) Osbeck) juice in a stirred continuous mode. *Journal of Membrane Science*, 283(1–2), 116-122.

Remy, M., van der Marel, P., Zwijnenburg, A., Rulkens, W. and Temmink, H. (2009). Low dose powdered activated carbon addition at high sludge retention times to reduce fouling in membrane bioreactors. *Water Research*, 43(2), 345-350.

Remy, M., Potier, V., Temmink, H. and Rulkens, W. (2010). Why low powdered activated carbon addition reduces membrane fouling in MBRs. *Water Research*, 44(3), 861-867.

Rosa, M. and De Pinho, M. (1997). Membrane surface characterisation by contact angle measurements using the immersed method. *Journal of membrane science*, 131(1), 167-180.

Rosenberger, S., Witzig, R., Manz, W., Szewzyk, U. and Kraume, M. (2000). Operation of different membrane bioreactors: experimental results and physiological state of the micro-organisms. *Water Science and Technology*, 41(10-11), 269-277.

Rosenberger, S. and Kraume, M. (2002). Filterability of activated sludge in membrane bioreactors. *Desalination*, 146(1-3), 373-379.

Rosenberger, S., Evenblij, H., Poele, S. T., Wintgens, T. and 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.

Royan, F. (2012). Membrane Multiplier: MBR set for Global Growth. Retrieved Januari 15, 2015, from http://www.waterworld.com

Rübbelke, D. T. G. (2011). International support of climate change policies in developing countries: Strategic, moral and fairness aspects. *Ecological Economics*, 70(8), 1470-1480.

Rupani, P. F., Singh, R. P., Ibrahim, M. H. and Esa, N. (2010). Review of Current Palm Oil Mill Effluent (POME) Treatment Methods: Vermicomposting as a Sustainable Practice. *World Applied Sciences Journal* 11(1), 70-81.

Salmiati. (2008). *Intracellular Biopolymer Production From Fermented Palm Oil Mill Effluent Using Mixed Microbial Cultures.* PhD Thesis, Universiti Teknologi Malaysia, Johor, Malaysia.

Salmiati, Salim, M. R., Ujang, Z. and Osson, G. (2010). Cod Fractionation of Palm Oil Mill Effluent : Typical Treatment, Biodegradability and Modeling. *Sustainable Environment Research*, 20(6), 7.

Santos, A. and Judd, S. (2010). The commercial status of membrane bioreactors for municipal wastewater. *Separation Science and Technology*, 45(7), 850-857.

Santos, A., Ma, W. and Judd, S. (2011). Membrane bioreactors: Two decades of research and implementation. *Desalination*, 273(1), 148-154.

Satyawali, Y. and Balakrishnan, M. (2009a). Performance enhancement with powdered activated carbon (PAC) addition in a membrane bioreactor (MBR) treating distillery effluent. *Journal of Hazardous Materials*, 170(1), 457-465.

Satyawali, Y. and Balakrishnan, M. (2009b). Effect of PAC addition on sludge properties in an MBR treating high strength wastewater. *Water Research*, 43(6), 1577-1588.

Seo, G. T., Moon, C. D., Chang, S. W. and Lee, S. H. (2004) Long term operation of high concentration powdered activated carbon membrane bio-reactor for advanced water treatment. *Vol. 50. Water Science and Technology* (pp. 81-87).

Setiadi, T., Husaini and Djajadiningrat, A. (1996). Palm oil mill effluent treatment by anaerobic baffled reactors: recycle effects and biokinetic parameters. . *Water Science & Technology*, 34(11), 59-66.

Shin, H. S. and Kang, S. T. (2003). Characteristics and fates of soluble microbial products in ceramic membrane bioreactor at various sludge retention times. *Water Research*, 37(1), 121-127.

Spanjers, H., Olsson, G. and Klapwijk, A. (1994). Determining short-term biochemical oxygen demand and respiration rate in an aeration tank by using respirometry and estimation. *Water Research*, 28(7), 1571-1583.

Spanjers, H. and Vanrolleghem, P. (1995). Respirometry as a tool for rapid characterization of wastewater and activated sludge. *Water Science and Technology*, 31(2), 105-114.

Stephenson, T., Judd, S., Jefferson, B. and Brindle, K. (2000). *Membrane Bioreactors for Wastewater Treatment*. London: IWA Publishing.

Sulaiman, N. M. N. and Ling, C. K. (2004). Membrane ultrafiltration of treated palm oil mill effluent (POME). *Jurnal Teknologi*, 41(F), 113-120

Sun, F. Y., Wang, X. M. and Li, X. Y. (2008). Visualisation and characterisation of biopolymer clusters in a submerged membrane bioreactor. *Journal of Membrane Science*, 325(2), 691-697.

Suwandi, M. S. (1993). Determination of optimized membrane area from long-term flux decline data. *Desalination*, 90, 379-388.

Syafalni, S., Abustan, I., Dahlan, I., Wah, C. K. and Umar, G. (2012). Treatment of dye wastewater using granular activated carbon and zeolite filter. *Modern Applied Science*, 6(2), 37-51.

Tajuddin, M. T. (2006) *Development of hollow fiber ultrafiltration membrane reactor for palm oil mill effluent tertiary treatment.* PhD Thesis. Universiti Teknologi Malaysia.

Tsai, H. H., Ravindran, V. and Pirbazari, M. (2005). Model for predicting the performance of membrane bioadsorber reactor process in water treatment applications. *Chemical Engineering Science*, 60(20), 5620-5636.

Ujang, Z., Au, Y. L. and Nagaoka, H. (2002). Comparative study on microbial removal in immersed membrane filtration (IMF) with and without powdered activated carbon (PAC). *Water Science and Technology*, 46(9), 109-115.

Ujang, Z. and Lim, L. P. (2005) Critical flux of membrabe bioreactor for digested palm oil mill effluent (POME) treatment. Water Environment – Membrane Technology (WEMT), Seoul, South Korea.

Ujang, Z., Ng, S. S. and Nagaoka, H. (2005). Package plant of extended aeration membrane bioreactors: a study on aeration intensity and biofouling control. *Water Science and Technology*, 51(10), 335-342.

Ujang, Z., Salmiati and Salim, M. R. (2011). Microbial Biopolimerization Production from Palm Oil Mill Effluent (POME). In Elnashar, M. (Ed.), *Biopolymers* (pp. 473-494): Sciyo.

Vanrolleghem, P. A., Spanjers, H., Petersen, B., Ginestet, P. and Takacs, I. (1999). Estimating (combinations of) Activated Sludge Model No. 1 parameters and components by respirometry. *Water Science and Technology*, 39(1), 195-214.

Vanrolleghem, P. A., Insel, G., Petersen, B., Sin, G., De Pauw, D., Nopens, I., Dovermann, H., Weijers, S. and Gernaey, K. (2003). A comprehensive model calibration procedure for activated sludge models. *Proceedings of the Water Environment Federation*, 2003(9), 210-237.

Vigneswaran, S., Guo, W. S., Smith, P. and Ngo, H. H. (2007). Submerged membrane adsorption hybrid system (SMAHS): process control and optimization of operating parameters. *Desalination*, 202(1-3), 392-399.

Vijayaraghavan, K., Ahmad, D. and Aziz, M. E. A (2007). Aerobic treatment of palm oil mill effluent. *Journal of Environmental Management*, 82(1), 24-31.

Visvanathan, C., Yang, B. S., Muttamara, S. and Maythanukhraw, R. (1997). Application of air backflushing technique in membrane bioreactor. *Water Science and Technology*, 36(12), 259-266.

Wang, S. and Zhu, Z. H. (2006). Characterisation and environmental application of an Australian natural zeolite for basic dye removal from aqueous solution. *Journal of Hazardous Materials*, 136(3), 946-952.

Wang, S. and Peng, Y. (2010). Natural zeolites as effective adsorbents in water and wastewater treatment. *Chemical Engineering Journal*, 156(1), 11-24.

Wang, X. M., Li, X. Y. and Huang, X. (2007). Membrane fouling in a submerged membrane bioreactor (SMBR): Characterisation of the sludge cake and its high filtration resistance. *Separation and Purification Technology*, 52(3), 439-445.

Wang, Z. W., Wu, Z. C. and Tang, S. J. (2009). Extracellular polymeric substances (EPS) properties and their effects on membrane fouling in a submerged membrane bioreactor. *Water Research*, 43(9), 2504-2512.

Wen, D., Ho, Y. S., Xie, S. and Tang, X. (2006). Mechanism of the adsorption of ammonium ions from aqueous solution by a Chinese natural zeolite. *Separation Science and Technology*, 41(15), 3485-3498.

Widjaja, T., Soeprijanto and Altway, A. (2010). Effect of Powdered Activated Carbon Addition on a Submerged Membrane Adsorption Hybrid Bioreactor with Shock Loading of a Toxic Compound. *Journal of Mathematics and Technology*, 139-146.

Wintgens, T., Melin, T., Schäfer, A., Khan, S., Muston, M., Bixio, D. and Thoeye, C. (2005). The role of membrane processes in municipal wastewater reclamation and reuse. *Desalination*, 178(1–3), 1-11.

Wong, Y. S., Kadir, M. O. A. B. and Teng, T. T. (2009). Biological kinetics evaluation of anaerobic stabilization pond treatment of palm oil mill effluent. *Bioresource Technology*, 100(21), 4969-4975.

Wu, T. Y., Mohammad, A. W., Jahim, J. M. and Anuar, N. (2007a). Palm oil mill effluent (POME) treatment and bioresources recovery using ultrafiltration membrane: Effect of pressure on membrane fouling. *Biochemical Engineering Journal*, 35(3), 309-317.

Wu, Z., Wang, Z., Zhou, Z., Yu, G. and Gu, G. (2007b). Sludge rheological and physiological characteristics in a pilot-scale submerged membrane bioreactor. *Desalination*, 212(1-3), 152-164.

Wu, T. Y., Mohammad, A. W., Jahim, J. M. and Anuar, N. (2009). A holistic approach to managing palm oil mill effluent (POME): Biotechnological advances in the sustainable reuse of POME. *Biotechnology Advances*, 27(1), 40-52.

Wu, T. Y., Mohammad, A. W., Jahim, J. M. and Anuar, N. (2010). Pollution control technologies for the treatment of palm oil mill effluent (POME) through end-of-pipe processes. *Journal of Environmental Management*, 91(7), 1467-1490.

Xing, W., Ngo, H. H., Kim, S. H., Guo, W. S. and Hagare, P. (2008). Adsorption and bioadsorption of granular activated carbon (GAC) for dissolved organic carbon (DOC) removal in wastewater. *Bioresource Technology*, 99(18), 8674-8678.

Xu, Z., Nakhla, G. and Patel, J. (2006). Characterization and modeling of nutrient-deficient tomato processing wastewater treatment using an anaerobic/aerobic system. *Chemosphere*, 65(7), 1171-1181.

Yacob, S., Ali Hassan, M., Shirai, Y., Wakisaka, M. and Subash, S. (2006a). Baseline study of methane emission from anaerobic ponds of palm oil mill effluent treatment. *Science of The Total Environment*, 366(1), 187-196.

Yacob, S., Shirai, Y., Hassan, M. A., Wakisaka, M. and Subash, S. (2006b). Start-up operation of semi-commercial closed anaerobic digester for palm oil mill effluent treatment. *Process Biochemistry*, 41(4), 962-964.

Yamamoto, K., Hiasa, M., Mahmood, T. and Matsuo, T. (1988). Direct Solid-Liquid Separation Using Hollow Fiber Membrane in an Activated Sludge Aeration Tank. In Lijklema, L., Imhoff, K. R., Ives, K. J., Jenkins, D., Ludwig, R. G., Suzuki, M., Toerien, D. F., Wheatland, A. B., Milburn, A. & Izod, E. J. (Eds.), *Water Pollution Research and Control Brighton* (pp. 43-54): Pergamon.

Yang, W., Cicek, N. and Ilg, J. (2006). State-of-the-art of membrane bioreactors: Worldwide research and commercial applications in North America. *Journal of Membrane Science*, 270(1–2), 201-211.

Ying, Z. and Ping, G. (2006). Effect of powdered activated carbon dosage on retarding membrane fouling in MBR. *Separation and Purification Technology*, 52(1), 154-160.

Yuniarto, A., Noor, Z. Z., Ujang, Z., Olsson, G., Aris, A. and Hadibarata, T. (2013). Bio-fouling reducers for improving the performance of an aerobic submerged membrane bioreactor treating palm oil mill effluent. *Desalination*, 316(0), 146-153.

Zhang, J., Chua, H. C., Zhou, J. and Fane, A. G. (2006). Factors affecting the membrane performance in submerged membrane bioreactors. *Journal of Membrane Science*, 284(1–2), 54-66.

Zhao, W. T., Huang, X., Lee, D. J., Wang, X. H. and Shen, Y. X. (2009). Use of submerged anaerobic-anoxic-oxic membrane bioreactor to treat highly toxic coke wastewater with complete sludge retention. *Journal of Membrane Science*, 330(1-2), 57-64.

Zhao, X., Hickey, R. F. and Voice, T. C. (1999). Long-term evaluation of adsorption capacity in a biological activated carbon fluidized bed reactor system. *Water Research*, 33(13), 2983-2991.

Zheng, X., Zhou, Y., Chen, S., Zheng, H. and Zhou, C. (2010). Survey of MBR market: Trends and perspectives in China. *Desalination*, 250(2), 609-612.

Zinatizadeh, A. A. L., Mohamed, A. R., Abdullah, A. Z., Mashitah, M. D., Isa, M. H. and Najafpour, G. D. (2006). Process modeling and analysis of palm oil mill effluent treatment in an up-flow anaerobic sludge fixed film bioreactor using response surface methodology (RSM). *Water Research*, 40(17), 3193-3208.

Zinatizadeh, A. A. L., Mohamed, A. R., Mashitah, M. D., Abdullah, A. Z. and Isa, M. H. (2007). Optimization of pre-treated palm oil mill effluent digestion in an up-flow anaerobic sludge fixed film bioreactor: A comparative study. *Biochemical Engineering Journal*, 35(2), 226-237.

Zuthi, M. F. R., Ngo, H. H. and Guo, W. S. (2012). Modelling bioprocesses and membrane fouling in membrane bioreactor (MBR): A review towards finding an integrated model framework. *Bioresource Technology*, 122(0), 119-129.