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

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

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A thesis submitted in fulfilment of the requirements for the award of the degree of Doctor of Philosophy (Chemical Engineering)

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To beloved:
My Mother and My Late Father
My wife Retno Adiyani
My Children:
Alif Bagas Adiutomo, Bintang Shafiq Adiretnani, Cahya Dita Adipramesti
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ABSTRACT

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 BFR0) 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 BFR0. 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 BFR0, 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 $\mu_{\text{max}H}$ and $\mu_{\text{max}A}$ 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 kilap 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 dilengkap dengan satu kepingan modul membran penurasan mikro. Sistem ASMBR dengan campuran ceai pepejal terampil (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 BFR0) dan berganding BFR telah dibandingkan dengan penilaian kepekaran penyekapan organik dan warna, kecenderungan fenomena kekotoran membran, dan peningkatan flus kritikal (Jc). 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 BFR0. Pada kedua-dua OLR, sistem ASMBR dengan BFR masing-masing menyegarkan COD lebih daripada 96%, menghasilkan efluen dengan purata sisa warna kurang daripada 55 ADMI, meningkatkan Jc 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 Jc tertinggi. Akhir sekali, keputusan-keputusan eksperimen 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 BFR0, penambahan BFR meningkatkan parameter stoikiometri YH sehingga 0.49 mg sel COD mg^{-1} COD, meningkatkan parameter kinetik μ_{max}H dan μ_{max}A 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 bH dan KS 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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<td>ASM</td>
<td>Activated Sludge Model</td>
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<td>ASMBR</td>
<td>Aerobic Submerged Bioreactor</td>
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<td>ASM1</td>
<td>Activated Sludge Model No. 1</td>
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<td>bH</td>
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<td>BAP</td>
<td>Biomass-associated Product</td>
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<td>BFR</td>
<td>Biofouling Reducer</td>
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<td>BOD</td>
<td>Biological Oxygen Demand</td>
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<td>C0</td>
<td>Initial adsorbate concentration</td>
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<td>Adsorbate equilibrium concentration after adsorption</td>
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<td>CAS</td>
<td>Conventional activated sludge</td>
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<td>Cell COD</td>
<td>Total COD-Soluble COD</td>
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<td>CFMF</td>
<td>Cross-flow Microfiltration</td>
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<td>CO</td>
<td>Carbon Monoxide</td>
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Cs - 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
Jc - Critical Flux
K - Permeability (LMH/ΔkPa)
KLa - Oxygen Mass Transfer Coefficient
KO,A - Oxygen autotrophic half-saturation coefficient
KO,H - Oxygen heterotrophic half-saturation coefficient
KS - 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
$P_{\text{ave/TMPave}}$ - Pressure Average
PE - Polyethylene
PEG - Polyethylene Glycol
PES - Polyethylene sulphone
POME - Palm Oil Mill Effluent
PP - Polypropylene
PVDF - Polyvinylidene Difluoride
Q - Influent rate; Langmuir Constant
$q_e$ or $\frac{x}{m}$ - Adsorbent
$Q_{\text{per}}$ - Permeate flowrate
$Q_r$ - Return activated sludge rate
Qw - Sludge wastage rate
UF - Ultrafiltration
RAPD-PCR - Random Amplified Polymorphic DNA-PCR
RIS - Resistance in Series
Rm - Membrane resistance
RO - Reverse Osmosis
RPM - Revolutions per Minute
Rtot - Total Resistance
SBR - Sequential Batch Reactor
SCOD - Soluble COD
Si - Inert Soluble COD
SMBR - Side-stream Membrane Bioreactor
SMP - Soluble Microbial Product
SRT - Sludge Retention Time/Solid Retention Time
Ss - 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
µH - Heterotrophic Grow Rate
µ_{maxH} - Maximum specific Heterotrophic Grow Rate
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<td>UF</td>
<td>Ultrafiltration</td>
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<td>USEPA</td>
<td>United State Environmental Protection Agency</td>
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<tr>
<td>UV</td>
<td>Ultraviolet</td>
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<tr>
<td>V</td>
<td>Volume</td>
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<td>VSS</td>
<td>Volatile Suspended Solid</td>
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<td>X_e</td>
<td>MLSS in effluent</td>
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<td>X_i</td>
<td>Inert Particulate COD</td>
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<td>X_R</td>
<td>MLSS in return sludge of CAS</td>
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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 m³ of POME is generated (Vijayaraghavan et al., 2007). About 0.5 – 0.7 m³ 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 BOD₅ (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 °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 BOD5 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°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 biofouling 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 continuous 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 systems, 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 based 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


