TREATMENT OF PALM OIL MILL EFFLUENT USING COMBINATION OF MICROBIAL FUEL CELL AND ANAEROBIC MEMBRANE BIOREACTOR

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A project report submitted in partial fulfillment of the requirements for the award of the degree of Bachelor of Engineering (Hons.) Environmental Engineering

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DECLARATION

I hereby declare that this project report is based on my original work except for citation and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled "**TREATMENT OF PALM OIL MILL EFFLUENT USING COMBINATION OF MICROBIAL FUEL CELL AND ANAEROBIC MEMBRANE BIOREACTOR**" was prepared by **KONG HONG FENG** has met the required standard for submission in partial fulfillment of the requirements for the award of Bachelor of Engineering (Hons) Environmental Engineering at Universiti Tunku Abdul Rahman.

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ABSTRACT

Membrane fouling is a perennial problem that becomes a limiting step to the extensive application of membrane technology in industry. In order to reduce the fouling propensity, the effect of temperature on anaerobic membrane bioreactors (AnMBRs) which operated under mesophilic and thermophilic regimes was investigated, and they were found to have significant effect on AnMBRs performance. The difference in operational temperatures was associated to the biomass growth rate in the bioreactors. The highest COD removal efficiency was observed in mesophilic condition (45°C) with an average COD removal efficiency of as high as 95.60 ± 0.30%. Despite the excellent performance in removing the organic pollutant, the bioreactors operated at 45°C had the highest filtration resistance compared to others. In order to further improve the filtration performance, the AnMBRs were integrated with microbial fuel cell (MFC) instead of sole AnMBR in treating palm oil mill effluent (POME). The MFC acted as a pre-treatment unit prior to AnMBR and it was fed directly with POME. The supernatant from MFC was further treated by AnMBR. Noticeable improvement in filtration performance was observed in the combined system compared to sole AnMBR. Decrease in polysaccharide amount was observed in combined system which in turn suggested that the better filtration performance might be due to the capacity of MFC in reducing the filamentous bacteria where its presence is associated to high extracellular polymeric substances (EPS) secretion.

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LIST OF SYMBOLS/ ABBREVIATIONS

V	voltage
I	current
R	external resistance
P	power density
AC	activated carbon
AD	anaerobic digestion
AnMBRs	anaerobic membrane bioreactors
BAC	biological activated carbon
BOD	biological oxygen demand
COD	chemical oxygen demand
EPS	extracellular polymeric substances
HRT	hydraulic retention time
LB-EPS	loosely bound extracellular polymeric substances
MBR	membrane bioreactor
MF	microfiltration
MFC	microbial fuel cell
MLSS	mixed liquor suspended solids
MLVSS	mixed liquor volatile suspended solids
NOM	natural organic matter
PAC	powdered activated carbon
POME	palm oil mill effluent
PTFE	polytetrafluoroethylene
SMP	soluble microbial product

SRT	sludge retention time
TMP	transmembrane pressure
UF	ultrafiltration
VFA	volatile fatty acid

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CHAPTER 1

INTRODUCTION

1.1 Background

Oil palm is a perennial and valuable crop that grows in the tropical regions of the world like Indonesia and Malaysia, with hot and humid climate throughout the year and the production continues throughout the year (Garcia-Nunez et al., 2016). Its product, palm oil is cheap, production-efficient and highly stable oil that are widely used in a variety of foods, cosmetic, hygiene products and even potentially to be used as a source for biofuel, rendering palm oil to be one of the worlds's most produced and consumed oils (Indonesia-Investments, 2016). According to Malaysia Palm Oil Board (2014), the production of palm oil accounts for 28.2% in overall world production of oils and fats from year 2011 to 2012.

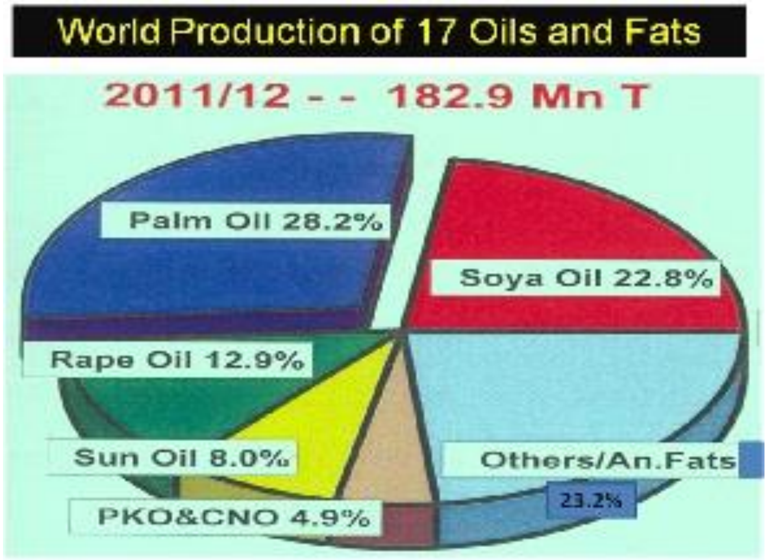

Figure 1.1: World Production of Oils and Fats (Malaysia Palm Oil Board, 2014)

The oil palm sector in Malaysia is indisputably a remarkable achievement and major contributor to the country's gross domestic product. The palm oil industry growing rapidly from a mere 400 ha of planted area in year 1920 to a nearly 5000000 ha of oil palm planted area in year 2011. With such a huge area of oil palm plantation, Malaysia is capable of producing more than 94 million tonnes of fresh fruit bunches to be processed by palm oil mills which are spread across the nation. This renders Malaysia to be the second largest palm oil producer in the world after Indonesia (Ding et al., 2016; Liu et al., 2015).

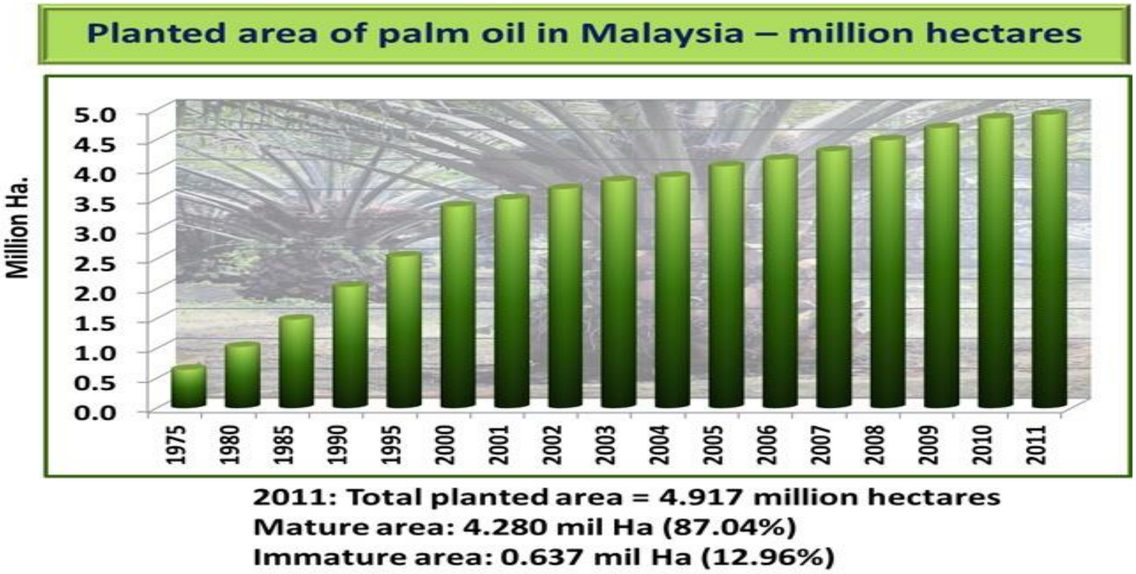

Figure 1.2: Planted Area of Palm Oil in Malaysia from Year 1975 to 2011(Malaysia Palm Oil Board, 2014)

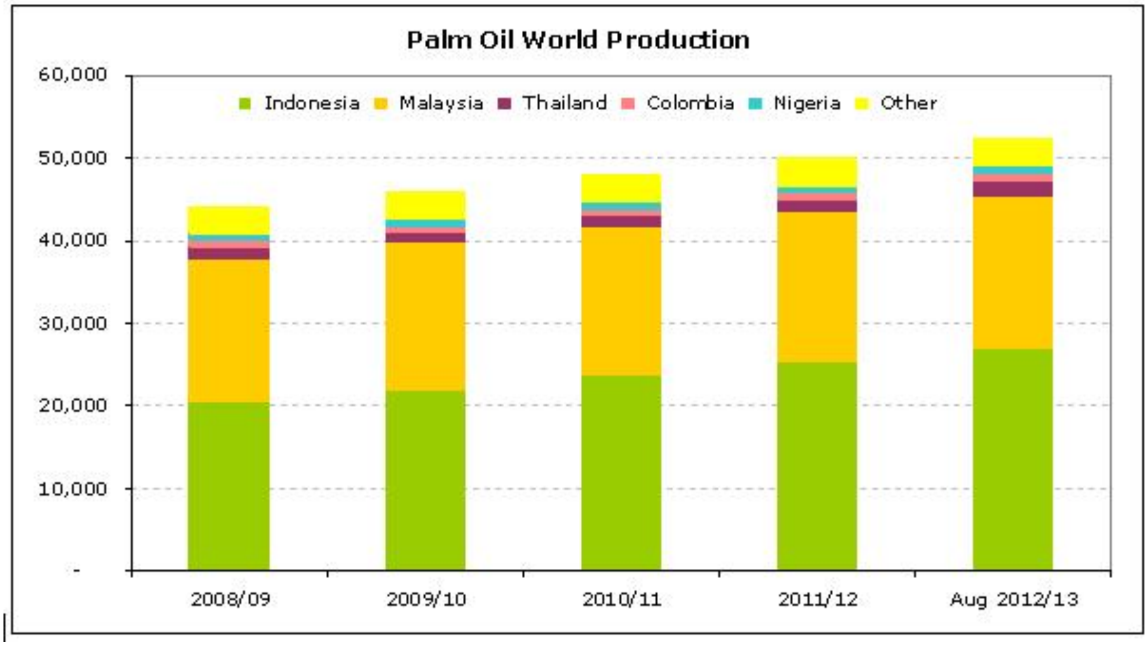

Figure 1.3: Palm Oil World Production (Agriculture Corner, 2012)

In Malaysia, extraction of crude palm oil from fresh fruit bunches is mainly through wet palm oil milling process. The milling process involves consumption of enormous quantities of water and is typically obtained from the adjacent freshwater resources which require very little treatment and pumping costs. The concomitant large production of wastewater from milling processes mainly comprises of palm oil mill effluent (POME) and used water. The used water is discharged into the drains or rivers without going neither into the effluent stream nor the wastewater treatment system. While POME, being one of the major pollution sources to water bodies require proper treatment prior to its disposal in order to meet the imposed discharge limit (Liew et al., 2015).

Three commonly adopted systems for POME treatment in Malaysia include (i) ponding system, (ii) open tank digester and the extended aeration system, and (iii) closed anaerobic digester and land application system (Malaysia Palm Oil Board, 2014). In overall, more than 85% of palm oil mills adopted ponding system as the POME treatment (Ding et al., 2016). A complete ponding system typically includes sand and oil traps, cooling ponds, acidification ponds, anaerobic ponds, facultative ponds and aerobic ponds. The sand and oil traps operate as the pre-treatment unit and the cooling ponds cool down the temperature (lower than 35°C) for the subsequent ponds. In short, ponding system is not only a feasible ways of treating high strength organic wastewater, but also economically feasible which requires little maintenance and offers process and operational simplicity. However, it requires a huge land area (1 ha-5 ha), long hydraulic retention times (HRT 40-200 days) and the concomitant release of methane by anaerobic digestion along with carbon dioxide are greenhouse gases that could contribute to greenhouse effect (Ding et al., 2016; Liew et al., 2015).

Due to the successful POME pollution abatement experiences, Malaysia is currently planning to revise the effluent quality standards towards a more stringent discharge limit where the BOD level of treated POME must not exceed 20 mg/L BOD_3. Hence, POME treatment solely by ponding system is inadequate in meeting the revised discharge limit; instead, POME polishing systems in combination with the existing ponding system is required to achieve further removal of organic matters, total suspended solids and color. A number of polishing systems such as membrane bioreactor technology (MBR), biological-physiochemical treatment processes, combination of ozone and submerged fixed film biological process and etc. is available and have the capability of producing high quality effluent and meeting the discharge limit compliance; however, the economic feasibility to implement these advanced technologies hinder their widespread application in oil palm sector (Liew et al., 2015).

Out of these POME polishing treatments, MBR system is one of the promising methods in treating POME. It is a process combining the membrane filtration with microbial degradation (Yuniarto et al., 2013). The MBR system can be divided into aerobic and anaerobic process. In anaerobic MBR system, methane produced from the digestion process can be recovered and used as a renewable energy, rendering it to be an interesting option for POME treatment (Poh and Chong, 2009).

1.2 Problem statement

Despite the fact that MBR system features various advantages such as higher organic removal efficiency, reduction in footprint and sludge production; still, membrane fouling remains as the perennial and primary challenge to deal with and limits the wide application of MBR technology (Hong et al., 2016).

Membrane fouling is resulted from interactions between foulants and membrane. The occurrence of membrane fouling is characterized by decreasing permeate flux or increasing transmembrane pressure and followed by decrease in membrane performance. In order to maintain the function of the membrane, frequent membrane cleaning is required which subsequently increase the energy consumption and deteriorate the membrane lifespan. Hence, this becomes a critical factor affecting the economic and technological viability of the processes (Cordova et al., 2016; Martin-Pascual et al., 2016). The major factors affecting fouling are biochemical kinetic parameters, temperature, membrane characteristics, mixed liquor characteristics, operational style and reactor hydraulic conditions. Therefore, membrane fouling mechanisms are very complicated due to the complex rheological and physiological characteristics of mixed liquors (Martin-Pascual et al., 2016). Instead of using MBR as sole treatment process, MBR can incorporate with technology like microbial fuel cell (MFC) to reduce the fouling propensity. Such integrated system achieves higher effluent quality and more efficient energy recovery. Several studies showed that the integrated system improved the membrane filterability by retarding membrane fouling by using synthetic wastewater as the feedstock (Tian et al., 2015; Su et al., 2013). However, the use of combined system in treating high strength wastewater like POME is yet to be studied.

In this study, MFC is incorporated into the AnMBR system (MFC-AnMBR) where the MFC acts as a pre-treatment unit prior to AnMBR and one of the operational conditions, temperature is manipulated and their impact on the degree of membrane fouling is observed.

1.3 Objectives

The objectives of this study are:

i) To compare the effects of different temperatures on the performance and membrane fouling control of the AnMBR system in treating POME.

ii) To evaluate the effect of MFC on the wastewater treatment performance and membrane fouling mitigation in MFC-AnMBR.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview of Membrane Bioreactor (MBR) Technology

Membrane bioreactor technology is the combination of biological treatment with the aids of activated sludge coupling with a direct solid-liquid separation by membrane filtration. In membrane filtration process, microfiltration or ultrafiltration membrane technology are used to completely retain the bacterial flocs and nearly all suspended solids within the bioreactor (Le-Clech, Chen and Fane, 2006). This renders the quality of water produced to be significantly higher than that generated by conventional treatment and excluding the necessity of having a further tertiary treatment (Judd, 2008).

By filtering the biomass through the membrane, the MBR technology not only effectively producing a high quality effluent but also shows substantial disinfection capability in the effluent produced as it removes all suspended, colloidal solids and bacteria including attached viruses or adsorbed compounds (Nguyen et al., 2016; Hoek and Tarabara, 2013; Santos, Ma and Judd, 2011). Besides that, the MBR process capable of operating at much higher mixed liquor suspended solids (MLSS) concentrations (about 12,000mg/L) such that higher volumetric loads are feasible, thereby giving rise to a small footprint (Trzcinski and Stucke,, 2016; Hoek and Tarabara, 2013).

Moreover, the MBR system requires less area compared to conventional activated sludge process (Nguyen et al., 2016). The conventional activated sludge process which comprises of activated sludge tank and settling tank are combined in the MBR system where the settling tank is replaced by membrane, rejecting the activated sludge from passing through the membrane and the sedimentation process is substituted by filtration process (Hoek and Tarabara, 2013). Such combination also results in higher concentration of activated sludge in the bioreactor and lower amount of wasted biosolids is produced (Le-Clech et al., 2005).

In general, there are two possible configurations in integrating the membrane into the activated sludge process which are side-stream configuration and submerged configuration (Hoek and Tarabara, 2013). In the former configuration, the membrane is located outside of the bioreactor. In order to maintain filtration and control fouling, the mixed liquor circulates through the membrane module at high cross flow velocity and relies on high transmembrane pressure (TMP), causing it to be energy-consuming and economically infeasible. By operating at such high cross flow velocity, the shear stress generated will as well jeopardize the microbial activity (Gouveia et al., 2015; Hoek and Tarabara, 2013; Le-Clech, Chen and Fane, 2006). While in the latter case, the membrane is directly immersed in the mixed liquor, accompanied by an artificially intensified turbulence like biogas aeration. This arrangement is to eliminate or mitigate fouling by preventing cake formation on the membrane surface with the aids of special equipment. However, additional energy consumption is required (Liu et al., 2016; Gouveia et al., 2015). The overall lower operating cost obtained with the submerged configuration renders it to be more commonly applied (Gouveia et al., 2015).

In the design of MBR system for wastewater treatment, both aerobic and anaerobic processes have been deployed. However, anaerobic MBR (AnMBR) is more commonly used in industrial applications due to its advantages compared to its aerobic counterpart. AnMBR requires lower cost as the absence of aeration and its capacity to treat high strength wastewater with less sludge production has rendered less energy requirement. Besides that, the capability of recovering the biogas as bioenergy from anaerobic digestion process in the bioreactor is one of the reasons in deploying AnMBR in industrial applications (Khan et al., 2016; Song et al., 2016).

In any application of membrane, membrane fouling has been a perennial problem even in the case of MBR system, despite its numerous attractive advantages over conventional activated sludge process. Membrane fouling occurs when the soluble and particulate materials deposit onto and into the membrane and this is due to the complex interactions between activated sludge mixed liquor and the membrane (Le-Clech, Chen and Fane, 2006; Le-Clech et al., 2005). The occurrence of membrane fouling is coupled with declination of flux and permeability, decreasing the efficiency of the MBR filtration and eventually causing higher operational costs due to the routine membrane cleaning (Hoek and Tarabara, 2013; Choi et al., 2006).

In fact, the MBR system is constantly growing in numbers and capacity across the municipal and industrial wastewater treatment sector and this is not only due to its advantages as aforementioned, but also with the increasingly stringent legislation governing effluent discharge and the rapidly advancing of the technology make the technology more viable, rendering them the key driver in the growth of the MBR technology (Judd, 2008). According to Global Industry Analysts Inc (2012), the global market for MBR technology is estimated to reach 888 million US dollar by the year 2017 and continue growing at a compound annual growth rate of 15.28% until year 2019.

2.2 Microbial Fuel Cell (MFC)

Microbial fuel cell (MFC), a promising technology with the capability of recovering energy and treating wastewater has shown an increase in interest among the academic researchers in the last decades (Tian et al., 2015; Karmakar, Kundu and Kundu, 2010). MFC utilizes the presence of electrochemically-active microorganisms as catalysts, oxidizing then converting the chemical energy stored in the organic matter in the wastewater into useful electrical energy while treating the wastewater (Ma et al., 2016; Su et al., 2013; Karmakar, Kundu and Kundu, 2010).

In general, the anaerobic respiring bacteria in the anodic compartment disintegrate the organic matter into carbon dioxide as the final product, along with the production of electrons and protons. These electrons are transported to the anode surface through several extracellular electron transfer mechanisms, including direct electron transfer via direct electron transfer via the membrane-bound c-type cytochrome and/or the bacterial nanowires, and indirect electron self-transfer mediated by shuttle molecules. The generated electrons are transferred using an external circuit and accepted by an electron acceptor in the cathode. For instance, in air cathode MFC with cathode being exposed to the air, oxygen is used as electron acceptor due mostly to its sustainability and amount (He et al., 2017; Ma et al., 2016). Meanwhile, the protons are oxidized to water in cathode. The oxidation of water could be done in either a separate chamber or separately in the same chamber (Karmakar, Kundu and Kundu, 2010).

The increasingly emerging and widespread application of MFC in wastewater treatment is largely due to its outstanding merits. The potential of MFC in addressing energy and environmental issues is irrefutable particularly in remote areas with biosensors equipped or integrated facilities that are capable of producing biohydrogen, carry out bioremediation with in-situ power source as well as treating wastewater. The capability of MFC in converting the substrate energy to electricity directly, rendering it to be more sustainable when come to implementation in wastewater treatment. Besides that, less excess activated sludge is generated compared to the processes of anaerobic digestion and conventional aerobic activated sludge treatment systems. Moreover, the insensitivity of MFC to operation environment renders it to be more viable. The necessity of having gas treatment and the need for aeration can be opted out, and hence reducing the energy input. This explains the widespread application of MFC particularly in locations with insufficient electrical infrastructures (He et al., 2017).

Despite the numerous advantages of MFC, some of the challenges remain unaddressed which subsequently hinder the commercialization of MFC technology. One of the barriers is the high operating cost of MFC where, on average, the cost of MFC is 30 times higher than that of conventional activated sludge treatment system in treating domestic wastewater. Such high capital cost is due mostly to its configuration and treatment capability, for instances, the use of expensive electrode materials such as current collector, catalysts and separator materials (He et al., 2017). Besides that, MFC acts as an independent wastewater treatment unit will not be practically applicable due to its poor effluent quality and low treatment efficiency (Tian et al., 2015). According to Kim et al. (2016), the power densities are corresponding to the COD concentrations of wastewater. Therefore, it is unlikely to achieve high power densities while meeting the stringent discharge limit of the wastewater to the environment. In order to overcome this issue, a post-treatment process is necessary to further reduce the COD of the treated effluent from MFC.

2.3 Integration of MBR with MFC

In order to meet the stringent effluent quality, wastewater treatment solely by MFC is insufficient (Tian et al., 2015). Thus, MFC is integrated with other systems such as MBR. The integration of MBR with MFC forms a bioelectrochemical membrane reactor, which takes advantage of both MBR and MFC, enhancing the effluent quality while achieving energy recovery (Su et al., 2013). In fact, membrane technology is widely implemented and has excellent filtering capability in removing all suspended, colloidal solids and bacteria including attached viruses or adsorbed compounds (Nguyen et al., 2016; Hoek and Tarabara, 2013; Santos, Ma and Judd, 2011). According to Su et al. (2013), the combined system of MBR and MFC was able to mitigate the membrane fouling through the modification of sludge. It was found that the combined system could operate twice as long as that in the conventional MBR. Furthermore, the report showed that the MFC could effectively reduce the loosely bound extracellular polymeric substances (LB-EPS) content by 22%. Such EPS are considered to be the major cause of membrane fouling in MBR. By integrating the MBR with MFC, it has the benefits to improve the effluent quality, recover energy produced and mitigate the membrane fouling.

2.4 Palm Oil Mill Effluent (POME)

In palm oil industry, the processing of palm oil fruit for extraction of crude palm oil requires enormous amount of water. In processing every one tonne of fresh fruit bunches for oil extraction, approximately 1.5m^3 of water is needed and almost half of the water is discharged as POME. This POME are produced and discharged from three principal sources which are clarification wastewater (60%), sterilizer condensate (36%) and hydrocyclone wastewater (4%) (Ahmed et al., 2015; Tabassum, Zhang and Zhang, 2015). POME, as the by-product of the palm oil extraction process is the most significant pollutant and capable of causing devastating impact on the water environmental system. The presence of organic and nutrient contents in POME gives it the capability of greatly depleting the oxygen content in the aquatic system (BioEnergy Consult, 2015).

In general, raw POME is a brownish and highly viscous liquid that discharged at a temperature between 80 to 90°C. It has a pH ranging from 4.0 to 5.0 and show significantly high biological oxygen demand (BOD) and chemical oxygen demand (COD), high salt content, high suspended solids and unpleasant odour (Ahmed et al., 2015; Tabassum, Zhang and Zhang, 2015). The detailed characteristics of POME are shown in Table 2.1.

Table 2.1: Characteristics of POME (Malaysia Palm Oil Board, 2014)

Parameter*	Mean	Range
pH	4.2	3.4-5.2
Biological oxygen demand (BOD)	25000	10250-43750
Chemical oxygen demand (COD)	51000	15000-100000
Total solids	40000	11500-79000
Suspended solids	18000	5000-54000
Volatile solids	34000	9000-72000
Oil and grease	6000	130-18000
Ammonical nitrogen	35	4-80
Total nitrogen	750	180-1400

*units in mg/L except pH

Before the establishment of stringent environmental laws on the discharge of POME, the untreated effluent is disposed into the adjacent water bodies. With the exponential growth in palm oil industry, water pollution arising from the POME discharged has alerted the government and the industry to the necessity of having treatment technologies that specifically treat POME prior to disposal as a measure of alleviating the POME pollution. Thereafter, ponding system, open tank digester and the extended aeration system, and the closed anaerobic digester and land application systems are commonly implemented to treat POME (Malaysia Palm Oil Broad, 2014).

In order to abate and control the POME pollution, Environmental Quality Regulations associated with detailed POME discharge standards was enacted in year 1978 with the BOD being the primary parameter in the standards. The discharge standards have changed over time with an increasingly stringent requirement on the BOD present in treated POME (Malaysia Palm Oil Board, 2014). This is to minimize the impacts of POME on the ecosystem. The POME discharge standards are demonstrated in Table 2.2.

Table 2.2: POME Discharge Standards (Malaysia Palm Oil Board, 2014)

Parameter*	**Limits According to Periods of Discharge**					
	1/7/78 - 30/6/79	**1/7/79 - 30/6/80**	**1/7/80 - 30/6/81**	**1/7/81 - 30/6/82**	**1/7/82 - 31/12/83**	**1/1/84 - thereafter**
pH	5-9	5-9	5-9	5-9	5-9	5-9
Biological oxygen demand	5000	2000	1000	500	250	100
Chemical oxygen demand	10000	4000	2000	1000	-	-
Total solids	4000	2500	2000	1500	-	-
Suspended solids	1200	800	600	400	400	400
Oil and grease	150	100	75	50	50	50
Ammoniacal nitrogen	25	15	15	10	150	100
Total nitrogen	200	100	75	50	-	-
Temperature (°C)	45	45	45	45	45	45
*units in mg/L expect pH and temperature						

2.5 Anaerobic Digestion (AD)

The AnMBR system comprises of two components which are membrane module and anaerobic bioreactor. The operating principle behind this is driven by filtration and anaerobic digestion respectively (Khan et al., 2016). Anaerobic digestion is a reduction process with a number of biochemical reactions taking place in the bioreactor where the biodegradable materials are broken down by microorganisms under anoxic conditions, with the formation of methane as the end product (Adekunle and Okolie, 2015).

Anaerobic digestion involves four major steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis. The initial step involves the enzyme-mediated transformation of insoluble organic materials and higher molecular mass compounds like carbohydrate and proteins into derivatives such as sugar and amino acids. Such transformation is performed by strict anaerobes such as bacterides and clostridia (Adekunle and Okolie, 2015).

In acidogenesis, the monomers produced are converted further into volatile fatty acids (VFAs), alcohols, hydrogen and carbon dioxide by acidogenic bacteria. The products of acidogenesis, especially VFAs and alcohols cannot be utilized by methanogens directly. Therefore, the third phase involves the conversion of long chain VFAs and alcohols into methanogenic substrates like acetate, hydrogen and carbon dioxide. These intermediate products from the previous phase are utilized by methanogen in the methanogenesis process and produce methane as the final product (Adekunle and Okolie, 2015).

In anaerobic digestion, optimization between acid and methane forming processes is essential. This is because excessive production and accumulation of VFAs in hydrolysis stage will decrease the pH in the bioreactor and the pH-sensitive methanogen will be inhibited. This could lead to system failure of the digester (Naik et al., 2014; Xu et al., 2014).

2.6 Membrane

A membrane is act as a selective barrier between two adjacent phases, regulating the transport of substances between two compartments. Membrane involves liquid-solid separation which does not require additives, and they can be performed isothermally at low temperatures, rendering lower energy consumption compare to other thermal separation process (Ulbricht, 2006). In MBR system, microfiltration (MF) and ultrafiltration (UF) membranes are commonly implemented to retain microbial cells and proteins respectively. This is achieved through sieve mechanism where the sizes of compounds become the determinant in allowing the compounds to pass through the membrane pores (Waszak and Gryta, 2015).

2.6.1 Membrane Process Classification

2.6.1.1 Microfiltration (MF)

Microfiltration is a pressure-driven membrane process that removes suspended colloids and macromolecular materials larger than 100nm at a low pressure, where the operating transmembrane pressure ranging from 95 to 276kPa. The excellent performance of MF in the removal of turbidity, bacteria and protozoa popularize the application in municipal drinking water and wastewater treatment. However, MF still possess some limitations due to their large pore sizes, for instance, they are ineffective for removing natural organic matter (NOM), viruses and other dissolved contaminants. In order to overcome these limitations, coagulation pretreatment or addition of PAC can be considered (Hoek and Tarabara, 2013).

2.6.1.2 Ultrafiltration (UF)

Similar to MF, UF is a pressure-driven membrane process except that it has smaller pore sizes and operate at a pressure higher than MF process, which is about 7bar (700kPa). The pores size of UF membrane generally ranging from a few nanometers to about

100nm. Species having molecular weights ranging from about 300 to 1000 Da will be retained by UF and this includes proteins, viruses, starches, gums and dispersed colloidal compounds such as pigments (Hoek and Tarabara, 2013).

2.6.2 Membrane Modularization

The purpose of membrane modularization is to pack a large area of active membrane into a relatively small volume and thereby increasing packing density while maintaining system hydraulics to minimize concentration polarization, fouling and scaling. Modularization reduces the capital cost of a membrane-based system by reducing the required footprint of the system. In brief, there are four basic module configurations developed: (1) tubular; (2) plate-and-frame; (3) spiral wound; (4) hollow fiber (Hoek and Tarabara, 2013). General characteristics of four basic module configurations are shown in Table 2.3, while the respective advantages and limitations of each membrane module is summarized and tabulated in Table 2.4.

Table 2.3: Comparisons of Four Basic Membrane Module Configurations (Hoek and Tarabara, 2013)

Parameter	Tubular	Hollow fiber	Plate-and-frame	Spiral wound
Cost/area	High	Low	High	Low
Replacement cost	High	Moderate	Low	Moderate/low
Packing density	Poor	Excellent	Good/fair	Good
Hold up volume	High	Low	Medium	Medium
Fouling resistance	Excellent	Poor	Good/fair	Good/fair
Cleaning efficiency	Excellent	Good	Fair/poor	Fair/poor

Table 2.4: Advantages and Disadvantages of Four Basic Membrane Module Configurations (Hoek and Tarabara, 2013)

	Advantages	Disadvantages
Tubular	-able to tolerate high feed water concentrations of suspended solids -membrane can be cleaned both mechanically and chemically	-relatively high cost and low packing density
Plate-and-frame	- membrane is easy to clean	-High labor and offline time during mechanical cleaning or replacement of membrane -loading and reloading of membrane plates can damage the membrane
Spiral wound	-larger packing density by rolling up the flat sheet -significantly smaller system footprint requirements	-cannot be mechanically cleaned -presence of stagnant areas which require higher operating pressures to minimize fouling and scaling -shorter membrane lifespan owning to frequent chemical cleaning
Hollow fiber	-ultrahigh packing density -able to undergo periodic backwashing without membrane delamination	-sensitive to fouling and plugging by particulate matter due to relatively low free space between fibers

2.7 Membrane Fouling

In MBRs, there are five mechanisms which are responsible for the occurrence of membrane fouling: (1) adsorption of solutes or colloids within or on membranes; (2) deposition of sludge flocs onto the membrane surface; (3) formation of a cake layer on the membrane surface; (4) detachment of foulants attributed mainly to shear forces; (5) the spatial and temporal changes of the foulant composition during the long-term operation such as the change of bacteria community and biopolymer components in the cake layer. In short, membrane fouling is defined as the undesirable deposition and accumulation of microorganisms, colloids, solutes and the cell debris within or on the membranes with the consequence of reducing the permeability of the membrane (Meng et al., 2009).

In general, the behavior of membrane fouling is characterized by a three stage fouling history where the first stage shows an initial short-term rapid rise in transmembrane pressure (TMP), while second stage shows a long-term weak rise in TMP and the last stage is indicated by TMP jump. The occurrence of TMP jump is the indication of severe membrane fouling (Meng et al., 2009). According to Hwang et al (2008), the occurrences of TMP jump is due to the sudden increase in the concentration of extracellular polymeric substances (EPS) at the bottom of cake layer. The increase in the EPS concentration is related to the death of bacteria in the inner cake layer due to oxygen transfer limitation.

The occurrence of membrane fouling is attributed to various factors such as sludge characteristics, operational parameters, membrane materials and feed water characteristics, either directly or indirectly. Sludge characteristics are the main determinant that has direct influence on the formation of membrane fouling, while fouling factors like operating parameters (e.g. ratio of food-to-microorganism) indirectly result in fouling through the modification of the activated sludge (Liu et al., 2013; Meng et al., 2009).

Membrane fouling can be classified into three types based on the cleaning practices, namely removable fouling, irremovable fouling and irreversible fouling. Removable fouling is caused by loosely attached foulants and associated with the formation of cake layer. It can be cleaned with ease via physical cleaning. For irremovable fouling, the pore is blocked and foulants are strongly attached on the membrane. In this case, fouling can only be removed by chemical cleaning. For irreversible fouling, it is a permanent fouling and cannot be removed by any means (Meng et al., 2009).

2.7.1 Fouling Components

The occurrence of membrane fouling is mainly due to biological fouling and organic fouling, while partly is due to inorganic fouling, although they happen concurrently during the filtration process. In biological fouling, the bacteria cells or microbial flocs deposit, growth and undergo metabolism on the membrane surface and eventually form a biocake. These deposited cells have higher surface hydrophobicity than the suspended sludge, rendering them to adhere to the surface tightly (Meng et al., 2009). The SMP and EPS are biologically secreted by the deposited cell and further exacerbate biofouling. In organic fouling, it is characterized by the deposition of biopolymers (e.g. protein and polysaccharide) on the membrane surface. These biopolymers facilitate the formation of cake layer as evident by substantial amount of protein and polysaccharide on it (Lin et al., 2013).

The inorganic fouling can either be formed by chemical or biological precipitation. Chemical polarization is responsible for chemical precipitation, causing higher concentration of retained salts on the membrane. Example of predominant salts in inorganic fouling is carbonates. Both aeration process and generation of CO_2 by microorganisms lead to super-saturation of carbonates which subsequently enhance the formation of precipitate and membrane scaling (Meng et al., 2009). Whereas in biological precipitation, metal clusters and metal ions are caught by the biocake layer through charge neutralization and bridging effect and subsequently fasten the membrane fouling (Lin et al., 2013).

2.7.2 Fouling Control

The occurrence of fouling is a continuous recurring and undesirable phenomena in any membrane application. Membrane fouling not only decreasing the permeate flux of the membrane but also increasing the operating cost for the industries like expenses used in maintenance of membranes. Therefore, proper fouling control is one of the key operating considerations for MBR systems.

According to Le-Clech, Chen and Fane (2006), fouling control is divided into two main groups which are membrane cleaning for the fouling removal and precautionary measures taken before the occurrence of fouling. The removal of fouling can be achieved physically or chemically, depending on the fouling condition on the membrane surface. The common physical cleaning in reducing membrane fouling rate is backwashing. Backwashing can effectively remove most of the reversible fouling due to pore blocking and partially dislodge loosely attached sludge cake from the membrane surface through flow reversion, either by air or water as a backwashing medium. In the design of backwashing, two determinants are to be considered: frequency and duration, in order to achieve optimized backwashing with respect to energy and permeate consumptions (Ming et al., 2017; Le-Clech, Chen and Fane, 2016).

In long time operation with accumulation of irreversible fouling on the membrane surface, physical cleaning becomes ineffective in mitigating the fouling. In this case, chemical cleaning which involves maintenance cleaning with higher chemical concentration or intensive chemical cleaning, each with different time-period basis, is recommended. Instead of having frequent intense cleaning, maintenance cleaning is indispensable in maintaining design permeability as frequent intense cleaning can damage the membrane integrity. In chemical cleaning, sodium hypochlorite and citric acid are commonly used as cleaning agents for organic and inorganic foulants or metal-associated structures respectively (Le-Clech, Chen and Fane, 2006).

Proper fouling control before the occurrence of fouling is also an effective way in alleviating rapid and severe membrane fouling. Measures such as pretreatment of feed, optimization of membrane and operating conditions and modification of biomass characteristics can be implemented. Pretreatment like pH adjustment of feed is required to protect the permeability and lifespan of the membrane. Besides, removal of excessive amount of inorganic matter like magnesium and calcium prior to the treatment is needed as they could affect the formation and compactness of the cake layer (Lin et al., 2013). While in membrane optimization, membrane can be modified by implanting polar organic functional group onto the membrane surface through plasma treatment. This increases the hydrophilicity of the membrane which in turn improves the anti-fouling properties and leading to better filtration performance (Lin et al., 2013; Le-Clech, Chen and Fane, 2006).

The anti-fouling properties can also be improved through modifying the biomass characteristics. The modification of biomass characteristics can be achieved through the addition of coagulant, flocculent and adsorbent agent. Coagulant like alum dissolves in water and forms hydroxide precipitates that are capable of adsorbing suspended particles, colloids and soluble organics, forming large microbial flocs and reducing the fouling propensity (Lin et al., 2013). Adsorbent agent like powdered activated carbon (PAC) can significantly increase the uptake of soluble organics like the EPS present in activated sludge through the formation of biologically activated carbon after a long-term operation. Lastly, optimizing operational conditions like hydrodynamic conditions and flux can help to control fouling. For instance, better hydrodynamic conditions can be achieved through increasing the air scouring intensity and time. Moreover, by operating the system at sustainable flux where the TMP increases gradually at an acceptable rate, such that chemical cleaning in unnecessary, can helps to control membrane fouling (Lin et al., 2013; Le-Clech, Chen and Fane, 2006).

2.8 Operating Condition of MBR System

In MBR system, the operating condition plays significant role in determining its performance. In general, operating condition can be classified into two categories which are membrane and biological operating conditions. In the former case, it includes flux, transmembrane pressure and backwashing; while biological operating condition involves temperature, sludge retention time (SRT) and hydraulic retention time (HRT) (Sabia, Ferraris and Spagni, 2013).

2.8.1 Sludge Retention Time (SRT)

SRT is a vital factor potentially affecting the performance of MBR system; it can influence filterability and biomass characteristics like bioactivity, biodegradation kinetics and particle size distribution (Sabia, Ferraris and Spagni, 2013). A long SRT is generally beneficial to the system as it could minimize the yield of sludge which in turn saves the cost for the handling and disposal of sludge. The lower yield of sludge is attributed to the majority of the cells are in an endogenous respiration state instead of physiological state for growth (Ouyang and Liu, 2009). At higher SRT, it is often associated with the development of microbial biomass. Such biomass are capable of degrading macromolecules such as polysaccharide, carbohydrates and protein and ultimately producing less biopolymer which can attribute to membrane fouling (Sabia, Ferraris and Spagni, 2013).

Moreover, increase in SRT is related to the decrease in sludge granule sizes. The system tends to have lower F/M ratio and inert substances accumulate at higher SRT. As a consequence, the decrease of bonding force associated with the presence of strong shear force can decrease the sludge floc size (Ouyang and Liu, 2009). However, a study by Han et al. (2005) indicates that when the system is subjected to too long SRT, excessive membrane fouling is likely to occur due to large amount of foulants and increase in sludge viscosity in the system. In overall, the effect of SRT shows significant impact and attains good performance in the removal of COD (Ouyang and Liu, 2009; Pollice et al., 2008).

2.8.2 Hydraulic Retention Time (HRT)

Similar to SRT, the influence of HRT on the membrane performance and membrane fouling is not negligible. According to Deng et al. (2016), a MBR system with lower HRT is more prone to membrane fouling, the results obtained show that lower HRT could shorten filtration period and deteriorate filterability. Similar trend is observed where decrease in HRT will accelerate membrane fouling (Aida Isma et al., 2014; Gao, Tao and An, 2012).

At lower HRT, increase in organic loading rate and flux are observed and both of them are relevant to membrane fouling (Gao, Tao and An, 2012). Besides that, lower HRT tends to concentrate the biomass within and subsequently increase sludge viscosity. As a result, the increased suction force at higher TMP and the increased drag force toward the membrane at higher fluxes induce more readily deposition of large amounts of bound EPS and biopolymer cluster on membrane surface to form a cake layer and eventually lead to pore blocking (Deng et al., 2016). Although lower HRT can causes fouling propensity, COD removal is not affected by HRT changes (Gao, Tao and An, 2012).

2.8.3 Flux

Membrane flux plays a significant role in MBR filtration characteristics and membrane fouling. The operating flux need to be controlled well below the critical flux for sustainable operation of MBR system (Wang et al., 2006). Reaching the critical flux during the operation is associated with the increase of TMP and filtration resistance as more sludge particles are attached to the membrane than being removed by the cross flow. Various factors such as activated sludge properties (e.g. temperature and viscosity), module specific parameters (e.g. cross flow intensity) and module geometry have significant impacts on critical flux (Hoek and Tarabara, 2013). The study conducted by Kimura et al. (2008) further verified that increase in membrane flux will significantly increase the filtration resistance. During the initial stage of operation, design flux is imposed gradually to allow small and ordered fouling layer to slowly develop. Rapid increase in membrane flux should be avoided as it will result in disordered structure and greater hydraulic resistance (Le-Clech et al., 2013).

2.8.4 Temperature

In MBR which involves the anaerobic digestion, temperature exerts a significant role on the performance and stability of the process. The operational temperature can be classified into three regimes which are psychrophilic (lower than 20°C), mesophilic (30-45°C) and thermophilic (55-65°C) temperature (Lin et al., 2009). The good operational performance in mesophilic temperature renders it to be widely adopted for anaerobic digestion, whereas the use of thermophilic regime is less extensive because it is highly susceptible to environmental changes and thus poorer process stability. Despite the application of thermophilic anaerobic digestion is limited, it is known to present several advantages such as an increased destruction rate of organic solids and elimination of pathogen (Meabe et al., 2013; Lin et al., 2009).

The biomass growth rate of microbial community is heavily dependent on the operational temperature, for instance, relatively lower operational temperatures tend to reduce the biomass growth rate (Martinez-Sosa et al., 2011). Besides, increase in temperature could significantly enhance the filtration performance (Meabe et al., 2013). However, fouling propensity is higher in thermophilic temperature due to the higher production of soluble microbial products (SMP) and extracellular polymeric substances (EPS) and the significant decrease in sludge floc size in thermophilic temperature under long-term operation is responsible for increased filtration resistance (Lin et al., 2009).

2.9 Activated Carbon (AC)

The widespread application of activated carbon as adsorbent in industrial fields such as water treatment is due to its highly developed internal surface area, porous structure and high degree of surface reactivity, rendering it to have high adsorption capacity (Tzvetkov et al., 2016). Activated carbon is manufactured from a wide range of carbonaceous precursors such as coal, wood and biomass sources through physical and chemical activation process (Byamba-Ochir et al., 2016).

In general, activated carbon come with various sizes and can be classified according to their sizes such as powdered and granular form. A number of studies have shown that the addition of powdered activated carbon (PAC) can be beneficial to the MBR system (Nguyen et al., 2014; Gai and Kim, 2008; Munz et al., 2007). According to Gai and Kim (2008), addition of PAC can extend the continuous filtration time and consequently alleviate the membrane fouling. Besides that, PAC can enhance effluent quality by facilitating the removal of turbidity and organic matter, work as buffer against shock loads of inhibitory compounds and improve sludge dewaterability (Satyawali and Balakrishnan, 2009; Gai and Kim, 2008).

The addition of PAC within the MBR system can provide a habitat similar to natural ecosystem for the microorganisms in the activated sludge, leading to the formation of biologically activated carbon (BAC) sludge. The formation of BAC allows the simultaneous occurrence of the adsorption and biodegradation rather than a single biological process. The combination of the processes leads to the formation of a biofilm ecosystem which consists of immobilized, acclimatized and succession bacteria. The biofilm formation enhances partial bioregeneration of saturated BAC that is previously absorbed by the PAC (Ng et al., 2013). According to Nguyen et al. (2014), it is necessary to periodically withdraw and replenish PAC for stable performance of PAC. Hence, frequent and smaller-dose PAC addition is recommended.

CHAPTER 3

METHODOLOGY

3.1 Experimental Setup

One single chamber and air cathode MFC with a volume of 1L was constructed. In single chamber MFC, one side of the cathode layer was exposed to the ambient air while the other side was in contact with the wastewater. The MFC came with three valves which were biogas probe, supernantant and sludge collector. Both anode and cathode layer were connected with a copper wire as electron conductor. Resistor and multimeter were used to complete the circuit. The SRT and HRT of the MFC were kept at 30 and 12.5 days respectively with 5g/L of PAC being added. The MFC was operated at room temperature.

Besides that, four 1L of AnMBRs were installed. The AnMBRs were divided into four batches (each with a 1L of AnMBR) and was kept in water baths with different temperatures of ambient temperature, 35°C, 45°C and 55°C. The operation was divided into two stages. The first stage involved feeding AnMBRs with raw POME as influent while the second stage involved the combination of MFC and AnMBRs in treating the POME. The POME was pre-treated by MFC and the effluent from MFC acted as the feedstock to AnMBRs. All AnMBRs were equipped with biogas probe, supernantant and sludge collector. Meanwhile, each bioreactor was connected to an inverted measuring cylinder via silicone pipe for determining volume of biogas produced through water displacement method. All the bioreactors were added with 5g/L of PAC. The SRT and HRT of the AnMBRs were controlled at 30 and 12.5 days respectively. Such operating conditions used were based on the finding of previous studies in optimizing the performance of AnMBR as conducted by previous FYP students.

3.1.1 Air Cathode Preparation

Carbon cloth was selected as the materials of anode and cathode. The carbon cloth used for submerged anode is 0% wet proofed while for the cathode layer is 30% wet proofed. In order to produce 30% wet proofed of carbon cloth, a mixture containing 0.7g fine carbon powder (USP grade), 9.1mL of deionized water, 21.5mL of Triton X-100 surfactant were mixed together for 1 hour, followed by the addition of one gram of Polytetrafluoroethylene (PTFE) into the mixed solution and continued the mixing for another 30 minutes. Later, the solution was placed and sonicated in the ultra-sonicator bath for 15 minutes, followed by 5 minutes of mixing. The 15 minutes sonication process and 5 minutes mixing process were repeated one more time. Next, 2.75g of fine carbon powdered was added into the mixture and mixed for another 1 hour. The mixed solution would become slurry. The slurry (20% wt solid) was then prepared to be applied on the water facing side of cathode carbon cloth using silkscreen technique. The cathode water facing side coated with this slurry would develop into carbon based layer (CBL). The coated cathode carbon cloth was then heated between two hot plates for 30 minutes at 280°C using furnace. The cathode carbon cloth was heated continuously at 343°C for another 2.5 hours before completing the steps.

On the other hand, air facing side of cathode was coated with PTFE solution. The cathode was allowed to dry for 10 minutes before it was being heated in furnace at 350°C for 15 minutes. The method of preparing air facing side cathode were repeated another three times before it was ready to be used in MFC.

3.2 Materials Used

3.2.1 Powdered Activated Carbon (PAC)

The PAC used in this study is extra pure Charcoal Powdered Activated Carbon supplied by Gene Chem. The general specification of the PAC is illustrated in Table 3.1.

Table 3.1: Specifications for PAC Used in Bioreactors

Composition	Value
pH	4.7-7.5
Soluble matter in ethanol	0.20 %
Soluble matter in hydrochloric acid	0.20 %
Chloride (Cl)	0.10 %
Sulfur compound (SO_4)	0.15 %
Iron (Fe)	0.10 %
Zinc (Zn)	0.10 %
Heavy metal (Pb)	0.01 %

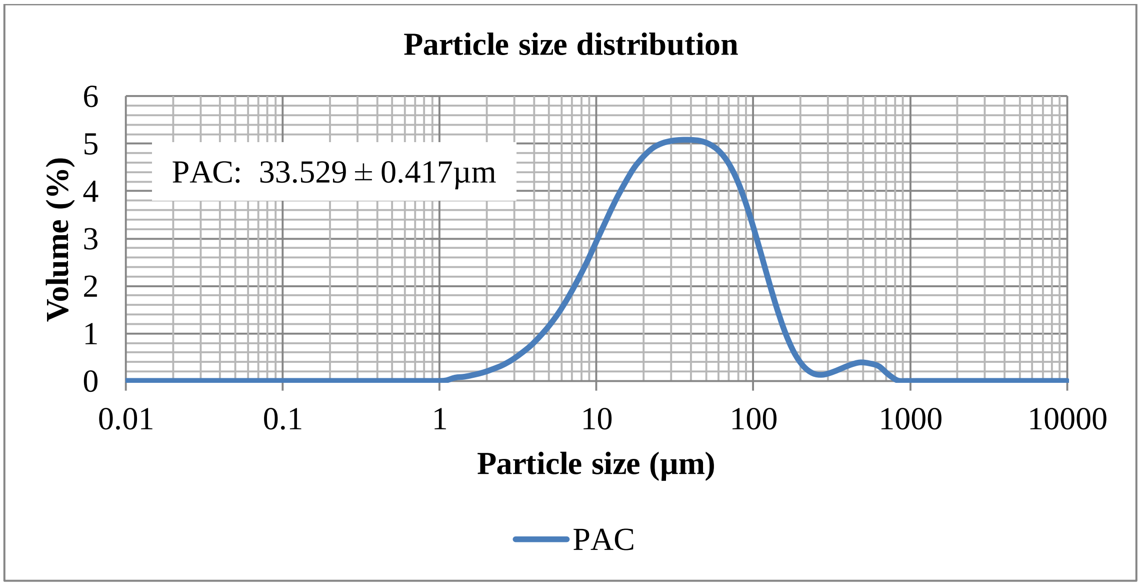

Figure 3.1: Particle Size Distribution of PAC in Terms of Volume

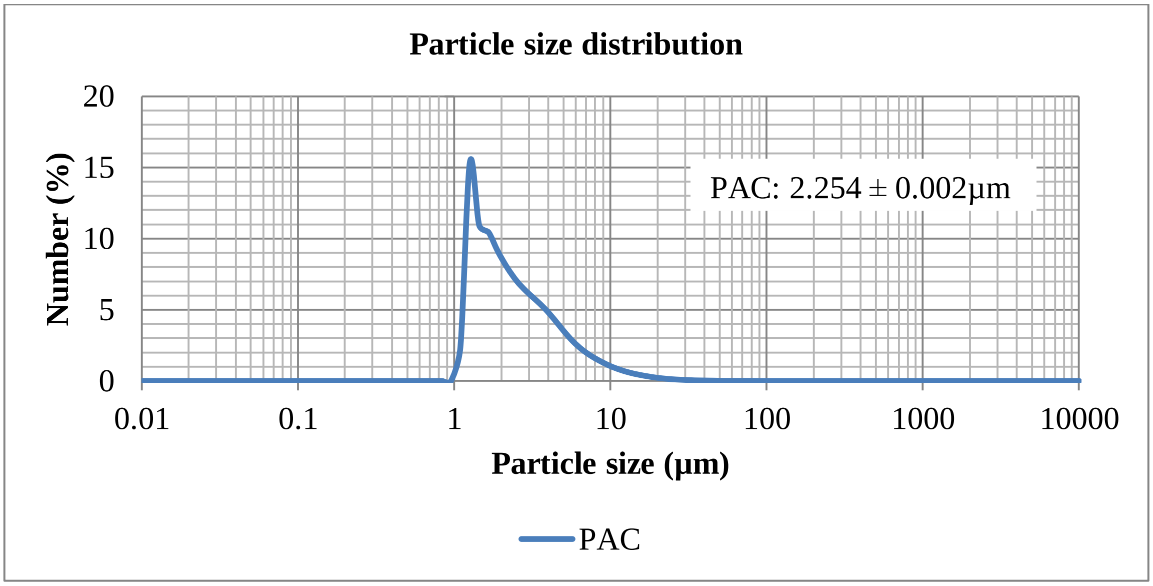

Figure 3.2: Particle Size Distribution of PAC in Terms of Number

3.2.2 Palm Oil Mill Effluent (POME)

The POME, a high strength industrial wastewater was treated by using it as the feed to the AnMBR system. It was supplied by Tian Siang Holdings Sdn Bhd which is located in Air Kuning, Perak. A filtered sieve with mesh size of 0.053mm (No. 270) was used to filter the POME feedstock prior to feeding into the system.

3.3 Analytical Methods

3.3.1 Mixed Liquor Suspended Solid (MLSS) and Mixed Liquor Volatile Suspended Solid (MLVSS)

Mixed liquor suspended solid (MLSS) and mixed liquor volatile suspended solid (MLVSS) were determined by using the procedures from Standard Method, 21st Edition. The crucibles, each with a glass microfiber filter AH-934 placed in it were heated at 550 °C for 15 minutes by using muffle furnace. Then, the heated crucibles with filter paper in it were stored and cooled down in the desiccator for 20 minutes before weighing. The mass of crucibles were measured by using M-power Analytical Balance AZ214. Thereafter, 1mL of sample was applied to the filter paper and filtered by using vacuum suction pump. Next, the filtered sample was left inside the oven for 2 hours at a temperature of 105°C. After the filtered sample was left in desiccator for 15 minutes, the weight of the samples was measured to determine the MLSS. The sample was subsequently heated in furnace for 15 minutes at 550°C. Once the sample was left cool down, sample weight was measured to determine the MLVSS.

3.3.2 Chemical Oxygen Demand (COD)

The COD of raw POME, supernatant and permeate water were analyzed by following the 5220 D Closed Reflux Colorimetric Standard Method as stated in Standard Method, 21st Edition. The samples retrieved were diluted to a ratio of 1:25 prior to adding into the COD test kit. High range (HR) and high range plus (HR+) HACH COD test kit were used depending on the concentration of the samples. Then, the test kits with added samples were heated in the COD reactor (HACH-DRB 200) for 2 hours at 150°C. The samples were allowed to cool down after heating for 2 hours. The COD value of each sample was determined by using HACH UV/VIS spectrophotometer (HACH DR 6000).

3.3.3 Polysaccharide

The concentration of polysaccharide in supernatant and permeate water were determined by using phenol-sulfuric acid method. The samples collected were diluted with a ratio of 1:25. Then, mixture solution containing 14mL of phenol and 36mL of distilled water was prepared. 1mL of mixture solution was retrieved and added into the vial containing 1mL of sample, followed by 5mL of 1 mol/L H_2SO_4. The vial was wrapped with aluminium foil wrapper due to light sensitive characteristic of phenol. Next, the samples were placed in Vortex Shaker for 15 seconds at 1500 rpm. The samples were then allowed to settle for 15 minutes in the absence of light. The polysaccharide concentration was measured by using HACH UV/VIS spectrophotometer (HACH DR 6000).

3.3.4 Particle Size Analysis

Particle size distribution of powdered activated carbon used and microbial floc size were determined by using Malvern Mastersizer 2000 particle size analyser. The particle size of the sample was analysed in terms of volume and number.

3.3.5 pH measurement

The pH of the sample was measured by using a pH meter (Hanna HI-2550). The pH meter was calibrated by using buffer solution with a pH of 4, 7 and 10 prior to the usage to avoid unnecessary error. The pH electrode was rinsed with cleaning agent and distilled water each time before testing.

3.3.6 Cross Flow Filtration

The supernatant from each bioreactor was used as the input to cross flow filtration system and the output, permeate water was collected. Conventional membrane was used to filter the supernatant. The pressure used to force the fluid to pass through the membrane is known as trans-membrane pressure and was measured and recorded by a TMP transducers and digital pressure data logger respectively. The COD and polysaccharide concentration in the permeate water were analyzed.

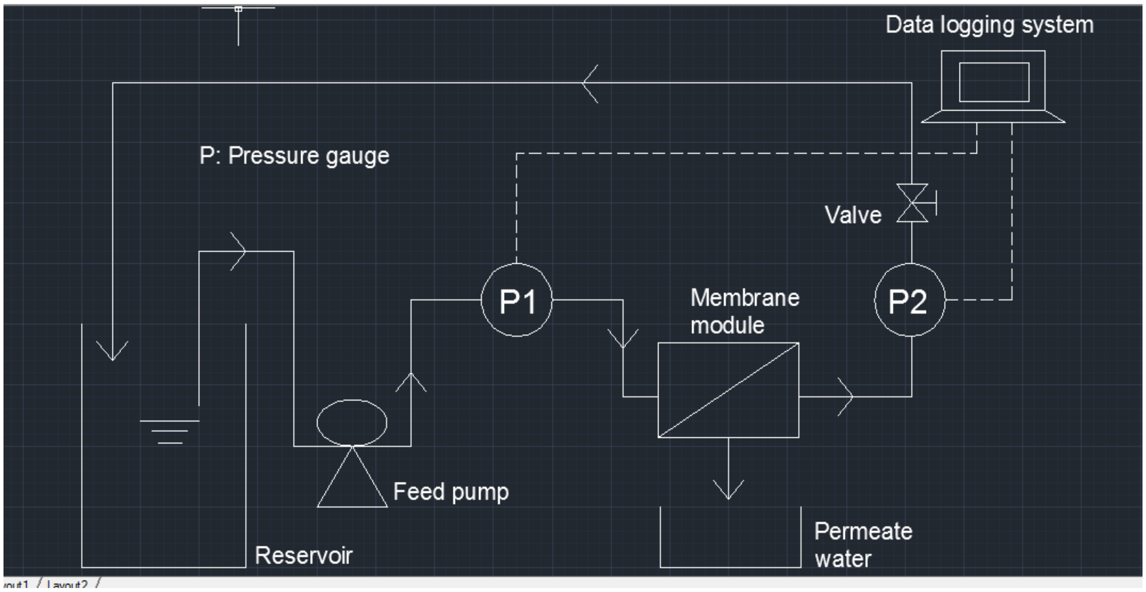

Figure 3.3: Schematic Diagram of Cross Flow Filtration Process

3.3.7 Electrical Power Production

The anode and cathode was connected by a 100Ω external resistor and the electricity generated by MFC was measured by using a multimeter. The voltage of the MFC was measured in volt (V). By applying the Ohw's law, current (I) could be calculated.

$$v = IR \tag{3.1}$$

Where

v = voltage, V

I = current, A

R = external resistance, Ω

The power production of MFC was calculated in terms of volumetric power density. The equation of volumetric used as follow:

$$P = \frac{v^2}{RV} \tag{3.2}$$

Where

P = volumetric power density, W/m^2

v = voltage, V

R = external resistance, Ω

V = volume of anode chamber, m^3

CHAPTER 4

RESULTS AND DISCUSSIONS

This chapter discusses the performances of (i) hybrid anaerobic bioreactors, (ii) anaerobic membrane bioreactor (AnMBRs), (iii) microbial fuel cell (MFC), (iv) hybrid anaerobic bioreactors incorporated with MFC and (v) anaerobic membrane bioreactor incorporated with MFC (MFC-AnMBRs). All of the bioreactors were operated under different temperatures while the microbial fuel cell was in ambient temperature. The performance of the bioreactors were assessed in terms of efficiencies of COD and polysaccharides removal, the amount of MLSS and MLVSS, particle size distribution, membrane fouling and flux rate. While MFC was assessed in terms of efficiency of COD removal, amount of MLSS and MLVSS, and power generation.

4.1 Assessment of Performance of Hybrid Anaerobic Bioreactors Operated under Different Temperatures

In this study, four hybrid anaerobic bioreactors, namely R-1, R-2, R-3 and R-4 were set up with the different temperatures consist of ambient temperature, 35°C, 45°C and 55°C respectively. The R-1, R-2 and R-3 were cultivated in the mesophilic temperature regimes while R-4 fell under the thermophlic temperature regimes. Their performances in treating the POME were investigated and the overall treatment performances were tabulated in Table 4.1.

4.1.1 Effect of Temperature in COD Removal

Throughout the study, it has been found that the bioreactor with the controlled temperature of 45°C (R-3) achieved the highest treatment efficiency compared to the other bioreactors, while the bioreactor operated under the ambient temperature (R-1) manifested the lowest treatment efficiency. The efficiencies of COD removal for R-3 and R-1 were 93.39 ± 0.19 and 65.59 ± 0.66% respectively.

The operational temperature strongly influences the anaerobic processes and their performance. According to Kim, Ahn and Speece (2002), mesophilic temperatures have long been employed in most commercial-scale anaerobic digester and yielding good operational performance, whereas, the use of thermophilic regimes are less extensively implemented due to poorer process stability and it's highly sensitive to the environmental change. Despite the fact that the thermophilic temperature appears to be less promising, thermophilic anaerobic digestion is known to present several advantages such as an increased destruction rate of organic solids and the elimination of pathogens (Meabe et al., 2013). Throughout the study, the process instability of R-4 was observed as indicated by the relatively large standard deviation in the COD removal efficiency (79.23 ± 9.36%) compared to the other bioreactors. A number of factors can contribute to poor process stability such as higher vulnerability as a result of less diverse microbial community, accumulation of propionate which could potentially result in inhibition and increased toxicity of intermediates at the thermophilic temperature range (Ghasimi et al., 2015; Labatut, Angenent and Scott, 2014).

In terms of COD removal efficiency, R-3 showed the best and relatively stable treating performance compared to the rest of the bioreactors, while R-1 showed the lowest COD removal efficiency in spite of they both are categorized as mesophilic processes. This is because the biomass growth rate is closely associated with operational temperature. At low operational temperature, low biomass growth rate will be observed, rendering difficulty in maintaining biomass concentration as considerable amounts of biomass can be washed-out from the reactor. Anaerobic treatment at low temperatures can limit the processes of hydrolysis, breakdown and solubilization of complex organic matter to soluble substrates (Martinez-Sosa et al., 2011).

Optimal pH is essential for anaerobic digestion where both acidogenic bacteria and methanogenic bacteria co-exist; the optimal pH range for the system is 6.8-7.4. The functionality of the micro-organisms will be affected under imbalance pH. For instance, when pH becomes too low, the capability of methanogens in converting the acids into methane will be inhibited. (Naik et al., 2014). According to Kunacheva, Soh and Stuckey (in press) low pH can leads to acidification of the cytoplasm, which is sufficient to inhibit microbial growth as the cell is unable to synthesize normal cellular components. Out of the four hybrid anaerobic bioreactors, only R-3 managed to maintain in the optimal pH range. The drop in pH can be attributed to various factors such as the accumulation of long-chain fatty acids (LCFA) resulting from the hydrolysis of neutral lipids (Labatut, Angenent and Scott, 2014). Besides, POME as the feedstock to the bioreactors is an acidic and high strength wastewater can result in a sudden drop in pH and thus influencing the microbial metabolism (Gao et al., 2010). The feedstock needs to be monitored to ensure that it is either having enough alkalinity, or not too easily hydrolyzed so as to cause a fall in the pH (Naik et al., 2014).

Table 4.1: Performance of Hybrid Anaerobic Bioreactors Operated under Different Temperatures

Parameter	**R-1**	**R-2**	**R-3**	**R-4**
Temperature, °C	ambient	35	45	55
SRT, days	30	30	30	30
HRT, days	12.5	12.5	12.5	12.5
Raw POME pH	4.21 ± 0.01	4.21 ± 0.01	4.21 ± 0.01	4.21 ± 0.01
Supernatant pH	4.83 ± 0.01	4.98 ± 0.01	7.4 ± 0.01	5.65 ± 0.01
PAC dosage, g/L	5	5	5	5
Raw PAC size, D_{50} (volume), µm	33.528 ± 0.417	33.528 ± 0.417	33.528 ± 0.417	33.528 ± 0.417
Raw PAC size, D_{50} (nunber), µm	2.256 ± 0.002	2.256 ± 0.002	2.256 ± 0.002	2.256 ± 0.002
Feed POME COD, mg/L	85858 ± 9623	85858 ± 9623	85858 ± 9623	85858 ± 9623
COD of supernatant, mg/L	29546 ± 571	25835 ± 795	5679 ± 161	17834 ± 8037
Polysaccharide of supernatant, mg/L	41.40 ± 4.06	25.94 ± 0.27	44.62 ± 5.30	36.14 ± 1.54
Removal efficiency of COD, %	65.59 ± 0.66	69.91 ± 0.93	93.39 ± 0.19	79.23 ± 9.36

4.1.2 Assessment of MLSS and MLVSS in Hybrid Anaerobic Bioreactors Operated under Different Temperatures

The content of activated sludge comprises of organic and inorganic matter, and the organic matter content indirectly reflects the quantity of active microorganisms in sludge. In activated sludge, MLSS comprises of microorganism and non-viable organic materials or insoluble solids while the MLVSS represents the biomass concentration in the sludge (Jo et al., 2016). On the other hand, the ratio of the MLVSS to MLSS (MLVSS/MLSS) is used as an indication to sludge activity (Fan et al., 2015). In this study, the MLSS, MLVSS and the ratio of the four bioreactors were measured and tabulated in Table 4.2.

Table 4.2: Comparison of MLSS and MLVSS in Hybrid Anaerobic Bioreactors Operated under Different Temperatures

Parameter	**R-1**	**R-2**	**R-3**	**R-4**
MLSS, mg/L	36400 ± 529	43000 ± 2615	19133 ± 1963	27533 ± 462
MLVSS, mg/L	33133 ± 808	38133 ± 1804	16467 ± 3239	23933 ± 2157
MLVSS/MLSS ratio	0.91 ± 0.02	0.89 ± 0.03	0.86 ± 0.08	0.87 ± 0.07

According to Fan et al. (2015), the conventional MLVSS/MLSS ratio in wastewater treatment plants is about 0.75, while Bitton (1998) stated that the typical range for the ratio of MLVSS/MLSS lies between 0.65 and 0.90. The ratio is used to indicate whether there are sufficient microorganisms present to digest the sludge. Except for R-1 which is slightly deviated from the range, all of the bioreactors were within the range of 0.65-0.90.

Based on Table 4.2, R-2 has the highest MLVSS content, followed by R-1 and R-4 while R-3 has the lowest MLVSS content, the respective MLVSS were 38133 ± 1804, 33133 ± 808, 23933 ± 2157 and 16467 ± 3239 mg/L. The MLVSS of R-1, R-2 and

R-4 were higher than R-3 despite R-3 showed the best treating efficiency in terms of COD removal. The unexceptionally high content of MLVSS in R-1, R-2 and R-4 might be due to the buildup of soluble microbial products (SMP) as a response to environmental stresses such as low pH and low temperature. The presence of SMP in biological treatment systems can negatively impact the system such as affecting the performance in terms of COD removal and causes membrane fouling (Kunacheva, Soh and Stuckey, in press). The production of SMP can contribute to the organic content in the sludge and hence rendering a relatively higher MLVSS content in R-1, R-2 and R-4 compared to R-3.

4.1.3 Effect of Temperature on Microbial Floc Size in Hybrid Anaerobic Bioreactors

The composition of sludge suspension varies from mainly sludge flocs, colloids, biopolymer matters like SMP and EPS, metals and inert particles where the sludge flocs are the predominated components in sludge suspension. The sludge floc accounts for more than 90% of total biomass in MBR systems (Zhao et al., 2015). The size distribution of sludge floc is one of the primary parameters which exert important roles in membrane fouling (Shen et al., 2015). The particle size distribution of sludge flocs in terms of volume and number in all bioreactors were analyzed and shown in Figure 4.1 and Figure 4.2.

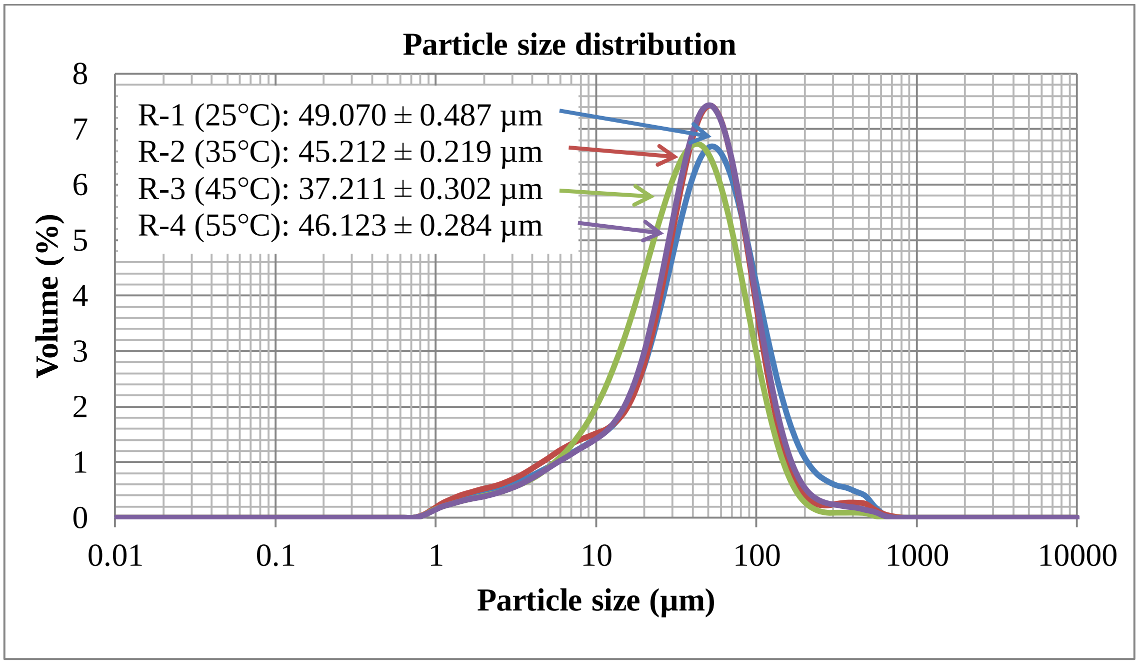

Figure 4.1: Sludge Floc Sizes Distribution of Hybrid Anaerobic Bioreactors in Terms of Volume

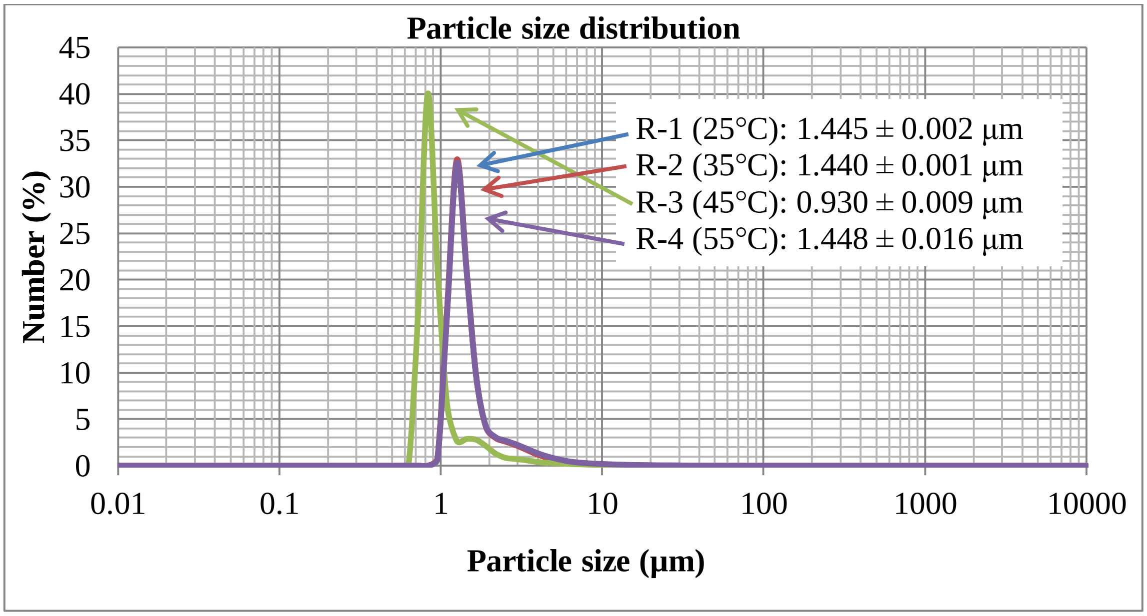

Figure 4.2: Sludge Floc Sizes Distribution of Hybrid Anaerobic Bioreactors in Terms of Number

From Figure 4.1, R-3 with the best treatment efficiency has the smallest floc size while the R-1 with the lowest treating efficiency has the biggest floc size in terms of volume. According to Naik et al. (2014), smaller particles increase the productivity of the system, largely due to the increased surface area for increased biological activity. Hence, the smaller in size of the sludge flocs in R-3 have larger surface area available for biological activity. Meabe et al. (2013) reported that the temperature can significantly influence the sludge's rheological properties. It was found that at higher temperature, the particle sizes will be smaller. From the study of Jeison and van Lier (2008), it was found that long-term continuous operation under thermophilic condition can significantly reduce the sludge floc size. However, floc size in R-4 operated under thermophilic range was larger compared to R-3 operated under mesophilic regime. This could possibly due to the change of pH in R-4 which drastically shifts the relative numbers of different species in a heterogeneous population. Besides that, cell morphology and structure can be affected by pH variation which in turn influences the flocculation and adhesion phenomena (Yu and Fang, 2003).

4.1.4 Membrane Fouling Control in Anaerobic Membrane Bioreactors Operated under Different Temperatures

Cross-flow filtration was performed to determine the overall efficiencies of bioreactors by using polymer membrane. The supernatant from each hybrid anaerobic bioreactors was retrieved and underwent cross-flow filtration process. The effluent that underwent filtration process is known as permeate and was collected and analyzed for its quality in terms of COD and polysaccharide removal efficiencies. The bioreactors, R that underwent filtration process henceforth shall be referred correspondingly to as AnMBR. The tested results were tabulated in Table 4.3.

In terms of COD and polysaccharide removal efficiencies, AnMBR-3 achieved the highest removal efficiencies for both parameters which were 95.60 ± 0.30 and 73.01 ± 0.08% respectively. This is in accordance with the result obtained for R-3 operated at 45°C, thus indicating the highest biomass growth rate among the others. While AnMBR-

1 showed the lowest COD and polysaccharide removal efficiencies which were only 75.50 ± 0.42 and 60.21 ± 1.03% respectively. The lowest removal efficiencies showed by AnMBR-1 is mostly due to the low temperature which become the limiting factor for the growth of biomass and thus affecting its performance.

Table 4.3: Performance of Anaerobic Membrane Bioreactors towards Membrane Fouling Control

Parameter	AnMBR-1	AnMBR-2	AnMBR-3	AnMBR-4
COD of permeate, mg/L	21037 ± 358	20233 ± 791	3782 ± 260	15331 ± 433
Polysaccharide of permeate, mg/L	16.47 ± 0.43	8.34 ± 0.11	12.04 ± 0.04	13.30 ± 0.08
Removal efficiency of COD, %	75.50 ± 0.42	76.44 ± 0.92	95.60 ± 0.30	82.14 ± 0.50
Removal efficiency of polysaccharide, %	60.21 ± 1.03	67.84 ± 0.24	73.01 ± 0.08	63.20 ± 0.23

EPS such as protein and polysaccharide is biologically secreted as the metabolic product of the microbial community and it exerts significant role in membrane fouling. As showed in Table 4.1, R-3 has the highest production of polysaccharide which is 44.62 ± 5.30 mg/L compared to the others. Polysaccharide can contribute to higher propensity for fouling due to their large-size nature and gelling properties. The polysaccharides, comprise of numerous blocks can contribute to gelling properties through the cross-linked chains in the polysaccharides. The formation of thin impermeable gels on membrane surface can significantly increase the filtration resistance (Meng et al., 2017). Besides, R-3 has the smallest sludge floc size compared to others. As reported by Shen et al. (2015), small flocs have higher tendency to adhere to the membrane surface. This is because the reduction in floc size substantially increases the attractive specific interaction energy in contact, rendering the higher adhesion ability of small flocs. Moreover, denser cake layer formation was observed in small flocs compared to that formed by large ones, which correlated with higher specific cake resistance. Meng et al. (2017) also stated that high EPS concentration and large specific surface area renders the small flocs to be the main initial colonizers on the membrane surface.

In this study, the fouling propensity was determined by the time required to reach 1 kPa under the constant flux. As shown in Figure 4.3, AnMBR-3 reached the threshold, 1 kPa in the shortest time which was about 45 minutes. This could be due to the highest polysaccharide concentration and the smallest floc size it possessed. While AnMBR-2 took the longest time, about 86 minutes to reach the threshold. This could be due to the relatively low concentration of polysaccharide produced compared to the others.

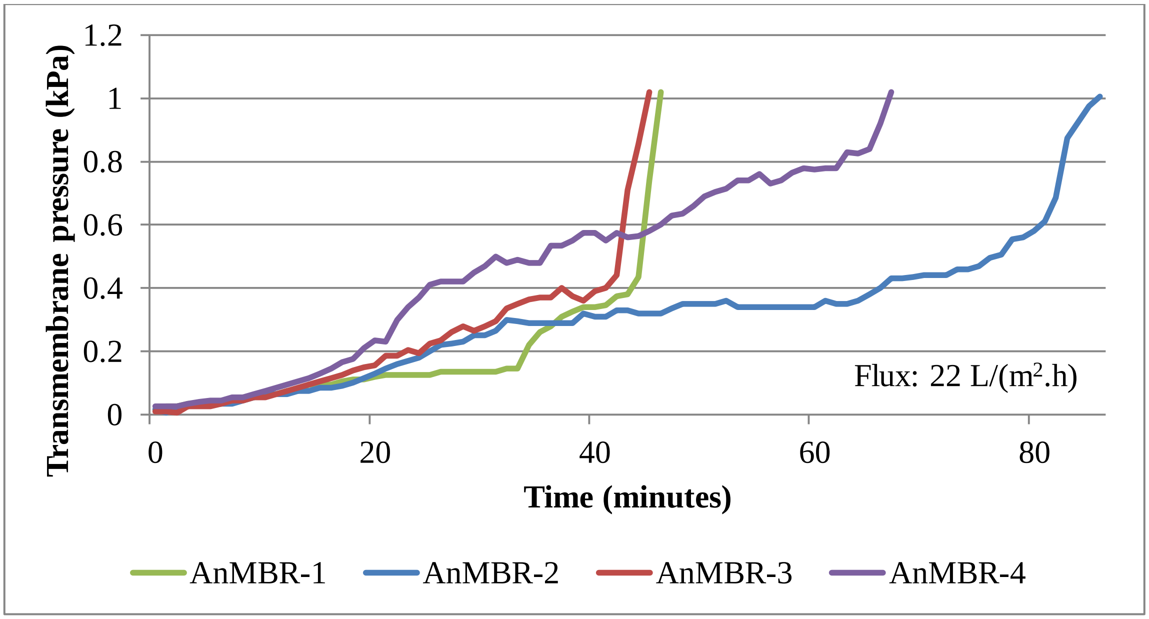

Figure 4.3: Comparison of TMP Profile for Anaerobic Membrane Bioreactors Operated at Different Temperatures

4.2 Assessment of Performance of MFC

One MFC was constructed to determine and compare the COD removal efficiency with AnMBRs and MFC-MBR. The overall treating performance of MFC was tabulated in Table 4.4. The SRT, HRT, PAC size and dosage used were similar to the operating conditions of hybrid anaerobic bioreactors. The MFC was operated under the ambient temperature. The pH recorded was 5.23 ± 0.01, which was slightly off from the optimal pH range, 6.8-7.4 for anaerobic processes (Naik et al., 2014). The ratio of MLVSS/MLSS was kept in the range of 0.65- 0.90 (Bitton, 1998). The COD removal efficiency for MFC was 72.67 ± 2.70% which was slightly better compared to R-1 and R-2. Besides, the power produced from MFC was measured. The average power density for MFC with a total volume of 1615.56 cm^3 was 0.062 W/m^3.

Table 4.4: Operating Conditions and Treatment Performance of MFC under Ambient Temperature

Parameter	MFC
Temperature, °C	Ambient
SRT, days	30
HRT, days	12.5
Raw POME pH	4.21 ± 0.01
Supernatant pH	5.23 ± 0.01
PAC dosage, g/L	5
Raw PAC size, D_{50} (volume), µm	33.528 ± 0.417
Raw PAC size, D_{50} (nunber), µm	2.256 ± 0.002
Raw POME COD, mg/L	85858 ± 9623
COD of supernatant, mg/L	23468 ± 2321
Removal efficiency of COD, %	72.67 ± 2.70
MLSS, mg/L	34000 ± 1562
MLVSS, mg/L	30333 ± 1206
MLVSS/MLSS	0.89 ± 0.02
Average voltage, V	0.10
Average power density, W/m^3	0.062

4.3 Assessment of Performance of Hybrid Anaerobic Bioreactors Integrated with MFC

The hybrid anaerobic bioreactors were combined with MFC where the effluent from MFC was used as the feedstock to hybrid anaerobic bioreactors in order to determine the performance of combined system. The overall treatment performance was tabulated in Table 4.6.

4.3.1 Wastewater Treatment Performance in Hybrid Anaerobic Bioreactors Integrated with MFC

The treatment performance of the combined system was evaluated in terms of COD removal efficiency. By integrating MFC into hybrid anaerobic bioreactors, the results showed increase in COD removal efficiencies for all the bioreactors. The results also showed similar trend compared to hybrid anaerobic bioreactors as discussed in the previous section, where R-3 achieved the highest COD removal efficiency while R-1 attained the lowest COD removal efficiency. The COD removal efficiencies for R-3 and R-1 were 97.07 ± 0.70 and 77.13 ± 1.07 % respectively. The improved COD removal efficiencies can be due to the activities of electroactive bacteria and common bacteria stimulated by electricity, which subsequently metabolized the COD (Su et al., 2013). Besides that, Liu, Cheng and Logan (2005) reported that MFCs could effectively consume the volatile fatty acids such as acetate and butyrate where their presence could potentially inhibit the process. The removal of these inhibitory by-products might enhance the treating performance of the system in terms of COD removal.

Table 4.5: Treatment Performance of Hybrid Anaerobic Bioreactors Combined with MFC under Different Temperatures

Parameter	R-1	R-2	R-3	R-4
COD of supernatant, mg/L	19635 ± 923	17883 ± 368	2512 ± 605	17217 ± 400
Polysaccharide of supernatant, mg/L	29.17 ± 0.59	24.11 ± 0.58	33.6 ± 0.30	26.61 ± 0.22
Removal efficiency of COD, %	77.13 ± 1.07	79.17 ± 0.43	97.07 ± 0.70	79.95 ± 0.47

After integrating the hybrid anaerobic bioreactors with MFC, the amount of polysaccharides present in the supernatant for all the bioreactors were lower than that in hybrid anaerobic bioreactors (e.g. from 44.62 ± 5.30 to 33.6 ± 0.30 mg/L in R-3). The decrease in the amount of polysaccharide might be due to the higher activity of the microbes in MFC-MBR for biodegradation of the polysaccharide (Tian et al., 2015).

4.3.2 Assessment of MLSS and MLVSS in Hybrid Anaerobic Bioreactors Integrated with MFC

From Table 4.6, the MLSS and MLVSS in the combined system showed a similar trend as in hybrid anaerobic bioreactors, where R-3 has the lowest MLVSS and R-2 has the highest MLVSS, the respective values were 15000 ± 586 and 32140 ± 1376 mg/L. The ratios of MLVSS to MLSS for all the bioreactors were kept in the range of 0.65-0.90 as well. However, after the integration of hybrid anaerobic bioreactors with MFC, decreases in both MLSS and MLVSS were observed. The reduction in MLSS and MLVSS in combined system could be due to the fact that using MFC as a pre-treatment unit for POME treatment prior to AnMBR could help to reduce the content of organic matter such as COD and polysaccharide present in AnMBR. Besides, the decreases are probably due to the increase activity of microbes in the systems which contributed to higher degradation rate of SMP (Tian et al., 2015).

Table 4.6: Comparisons of MLSS and MLVSS in Hybrid Anaerobic Bioreactors Integrated with MFC

Parameter	**R-1**	**R-2**	**R-3**	**R-4**
MLSS, mg/L	29600 ± 625	36400 ± 732	18200 ± 1058	20600 ± 1142
MLVSS, mg/L	27200 ± 946	32140 ± 1376	15000 ± 586	18000 ± 581
MLVSS/MLSS	0.90	0.88	0.82	0.87

4.3.3 Assessment of Microbial Floc Size in Hybrid Anaerobic Bioreactors Integrated with MFC

The particle size distribution for sludge floc was determined after the integration of hybrid anaerobic bioreactors with MFC. Decrease in the floc size in terms of volume was observed for all four bioreactors. The decrease in floc size can be attributed to the reduction of the loosely bound extracellular polymeric substances (LB-EPS) such as carbohydrate in sludge. Tian et al. (2015) also stated that less filamentous bacteria was observed in the compact structure due to microbial aggregation in MFC-MBR. The formation of loose aggregates and increase in floc size can occur due to the excess growth of filamentous bacteria. In addition, increase in the secretion of EPS, higher hydrophobicity of sludge and more irregularly shaped flocs are associated with the increase of filamentous bacteria.

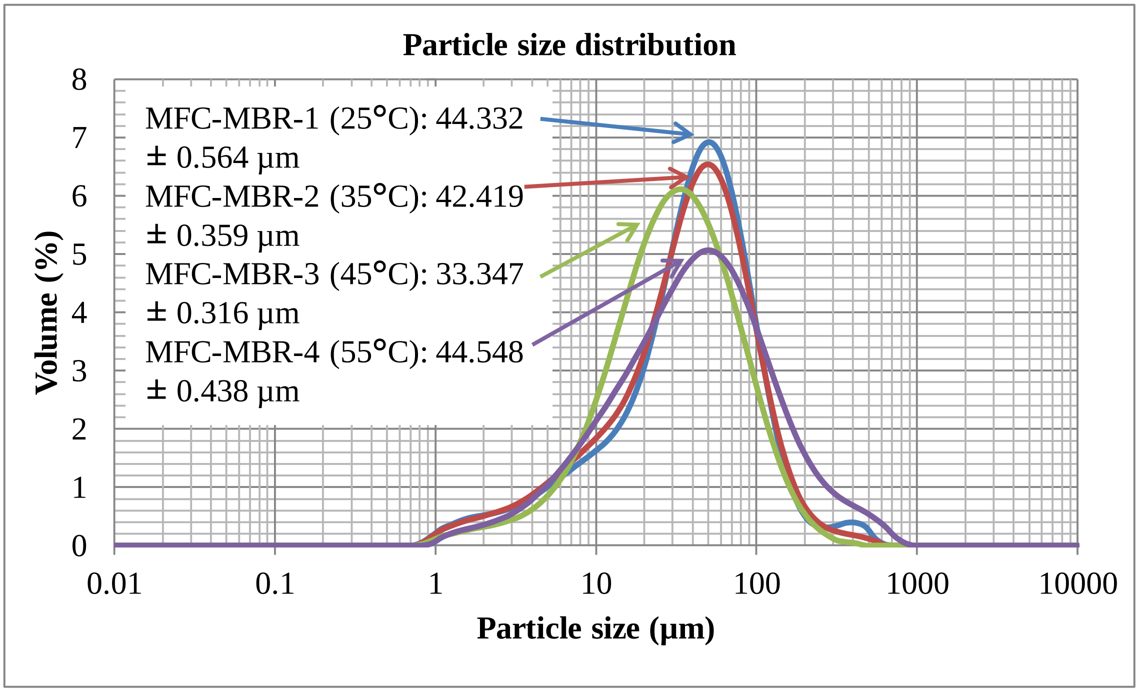

Figure 4.4: Sludge Floc Sizes Distribution of Hybrid Anaerobic Bioreactors Integrated with MFC in Terms of Volume

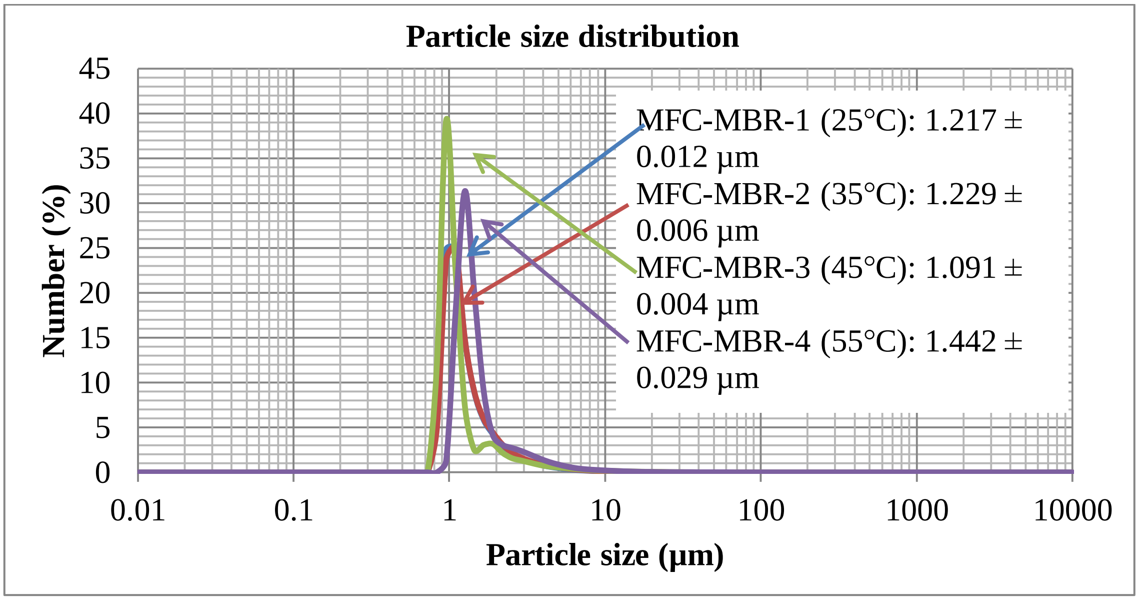

Figure 4.5: Sludge Floc Sizes Distribution of Hybrid Anaerobic Bioreactors Integrated with MFC in Terms of Number

4.3.4 Membrane Fouling Mitigation by Integrating Hybrid Anaerobic Bioreactors with MFC

Cross-flow filtration was conducted on the hybrid anaerobic bioreactors integrated with MFC in order to determine the effect of integration of MFC with hybrid anaerobic bioreactors in mitigating membrane fouling. The bioreactors combined with MFC that went through filtration process henceforth shall be referred correspondingly to as MFC-AnMBR. It can be observed that higher COD removal efficiencies for all four MFC-AnMBRs were achieved compared to AnMBR, where MFC-AnMBR-3 has the highest COD removal efficiency, 97.66 ± 0.41% in comparison with others operated at different temperatures. The incorporation with MFC technology helps to enhance COD removal. The presence of electroactive bacteria and capacity of MFC in utilizing inhibitory substances largely contributed to increase in the rate of COD metabolism (Su et al., 2013; Liu, Cheng and Logan, 2005). The overall COD removal efficiencies by MFC, AnMBRs and MFC-AnMBRs were compared and showed in Figure 4.6.

The amount of polysaccharides present in the effluent of MFC-AnMBRs were lower compared to those present in AnMBRs as indicated in Figure 4.7. The lower amount of polysaccharides in MFC-AnMBRs was may be attributed to the higher microbial activity for polysaccharide degradation and the decrease in the number of filamentous bacteria which are associated to the increased EMP secretion (Tian et al., 2015; Su et al., 2013).

Table 4.7: Performance of MFC-AnMBRs towards Membrane Fouling Control

Parameter	**MFC-AnMBR-1**	**MFC-AnMBR-2**	**MFC-AnMBR-3**	**MFC-AnMBR-4**
COD of permeate, mg/L	16006 ± 139	13513 ± 283	2010 ± 133	12675 ± 675
Polysaccharide of permeate, mg/L	11.07 ± 0.24	8.02 ± 0.37	10.91 ± 0.12	9.46 ± 0.17
Removal efficiency of COD, %	81.36 ± 0.76	84.26 ± 0.83	97.66 ± 0.41	85.24 ± 0.59
Removal efficiency of polysaccharide, %	62.05 ± 0.98	66.74 ± 0.42	67.53 ± 0.25	64.45 ± 0.53

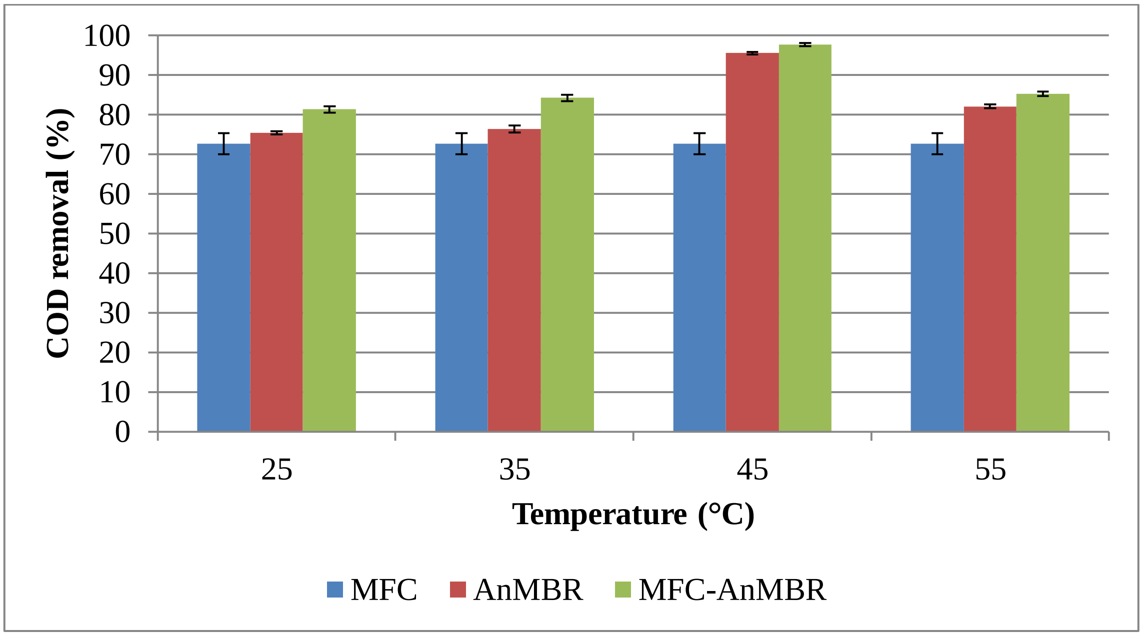

Figure 4.6: Comparisons of Overall COD Removal Efficiencies in MFC, AnMBRs and MFC-AnMBRs

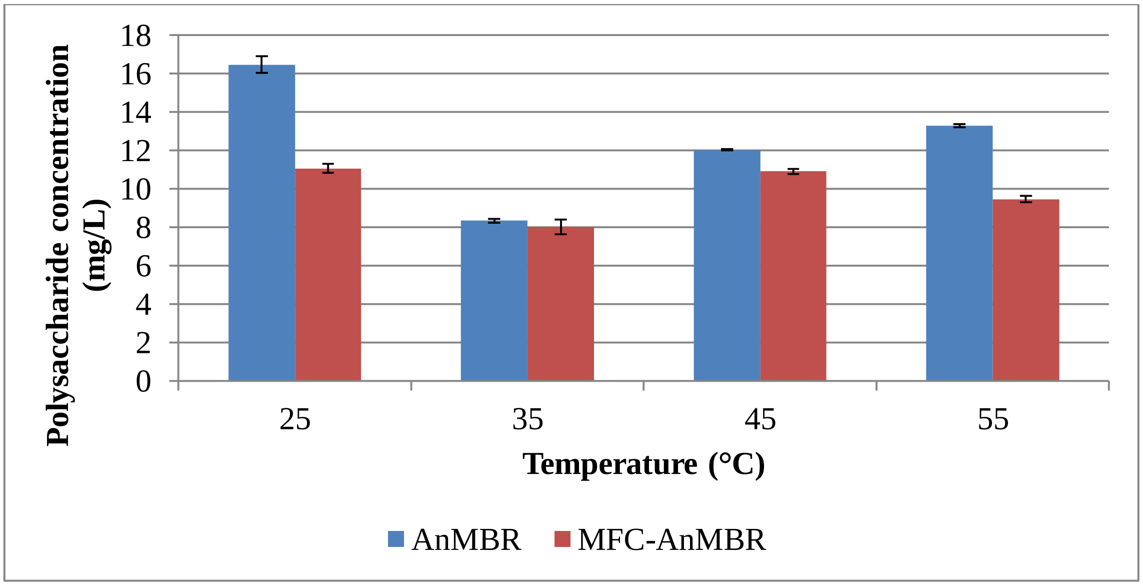

Figure 4.7: Comparison of Amount of Polysaccharide Present in AnMBRs and MFC-AnMBRs

TMP changes in AnMBRs and MFC-AnMBRs operated under different temperatures, ranging from 25, 35, 45 and 55°C were showed in Figure 4.8, 4.9, 4.10 and 4.11 respectively. From these figures, it can be observed that the time required for MFC-AnMBRs to reach the threshold, 1kPa was relatively longer compared to AnMBRs, indicating better filtration performance in MFC-AnMBRs compared to AnMBRs. By integrating MFC into AnMBR system, the MFC helps to reduce the filamentous bacteria where its presence can lead to higher secretion in EPS. The excessive EPS might exert significant impact on sludge properties. It begins with the weakening of cell attachment, followed by the deterioration of floc structure, yielding highly porous sludge flocs with a low density, poor bioflocculation, great cell erosion and retarded sludge-water separation. The altered sludge structure would result in high filtration resistance and lead to severe membrane fouling (Su et al., 2013). Hence, the decrease in EPS concentration was expected to help in the mitigation of membrane fouling.

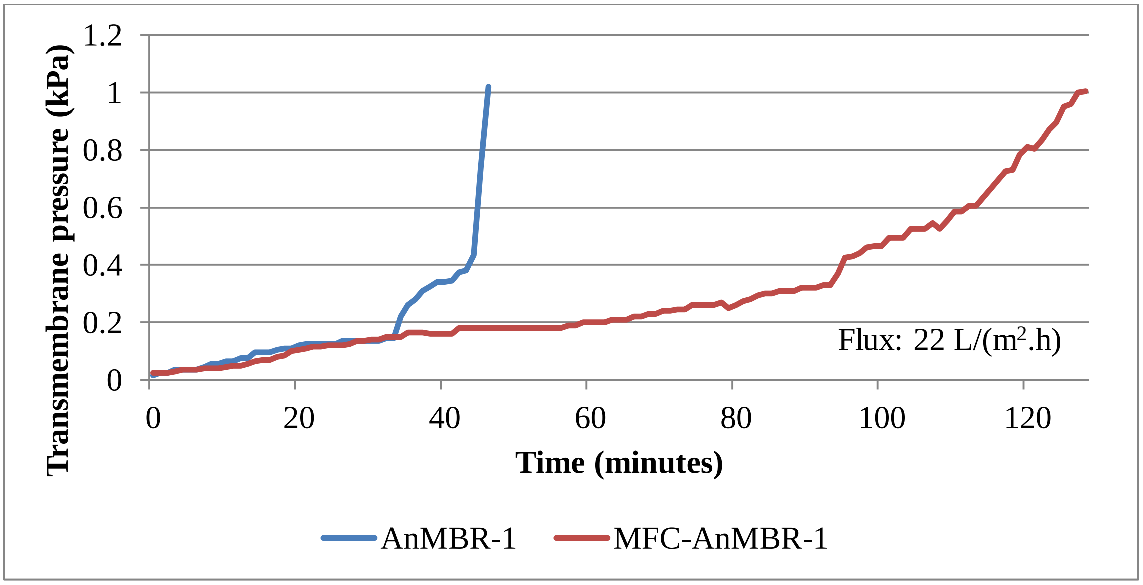

Figure 4.8: Comparison of TMP Profile for AnMBR and MFC-AnMBR Operated at 25°C

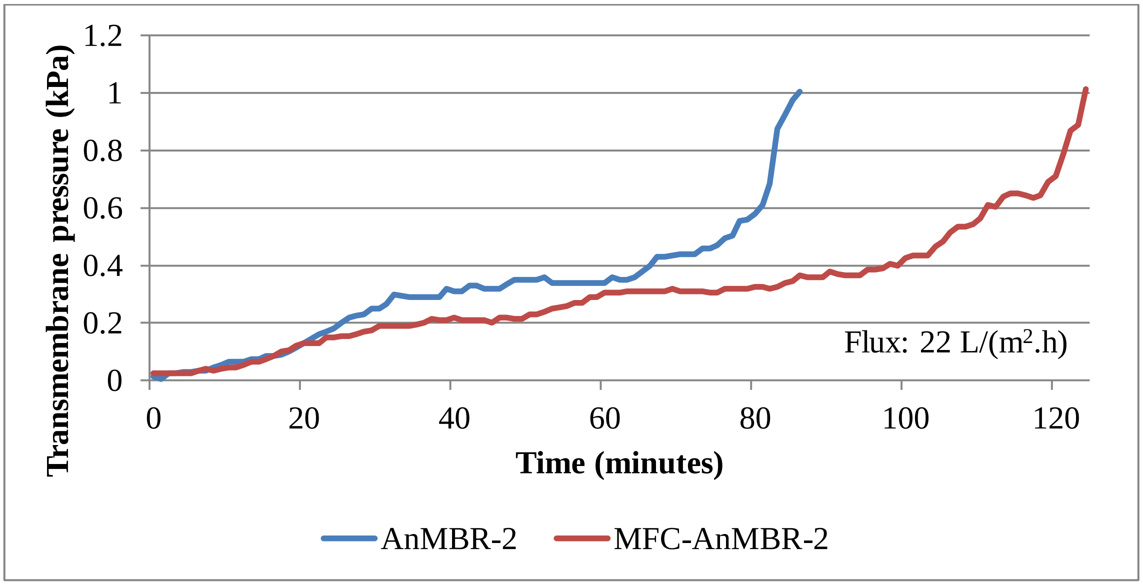

Figure 4.9: Comparison of TMP Profile for AnMBR and MFC-AnMBR Operated at 35°C

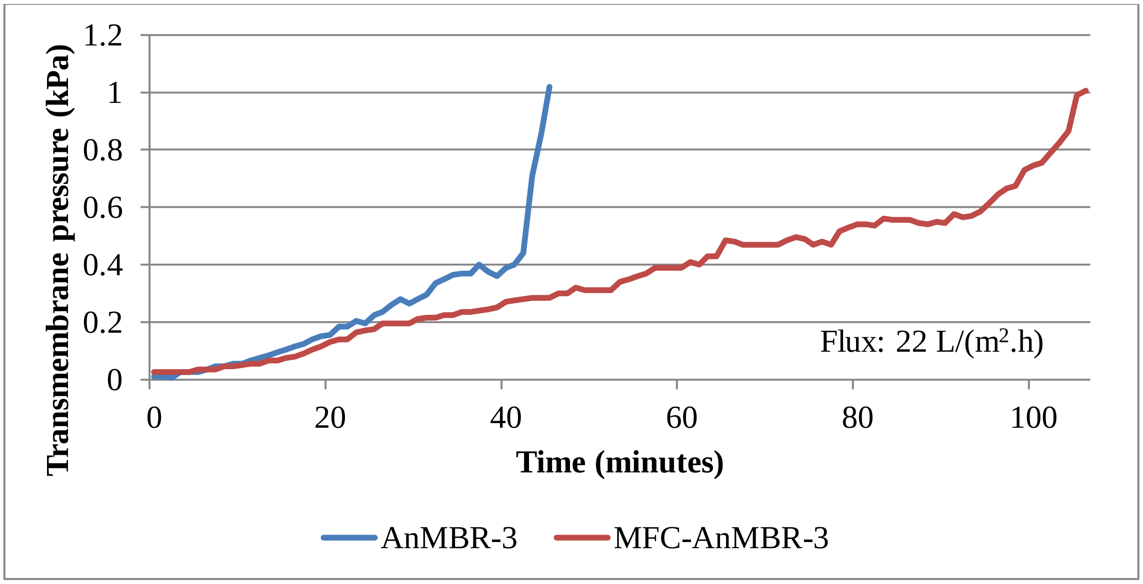

Figure 4.10: Comparison of TMP Profile for AnMBR and MFC-AnMBR Operated at 45°C

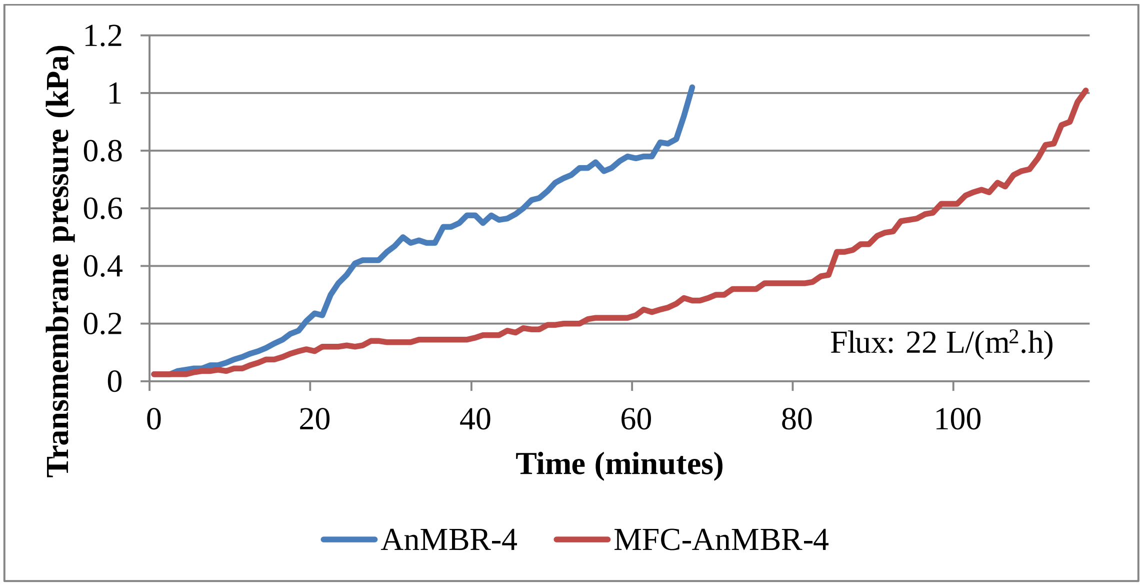

Figure 4.11: Comparison of TMP Profile for AnMBR and MFC-AnMBR Operated at 55°C

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The treatment performance of AnMBR operated at mesophilic temperature, 45°C, R-3 was the best among others AnMBRs in terms of COD removal efficiency. The increase in operational temperature enhances the biomass growth rate which subsequently improves the processes of hydrolysis, breakdown and solubilization of complex organic matter to soluble substrates. Higher amount of polysaccharide was observed in AnMBR operated at 45°C. Polysaccharide as a biologically secreted metabolic product is associated with the biomass growth rate. R-3 has the highest biomass growth rate as indicated by the highest polysaccharide concentration among others despite the fact that it has the lowest MLVSS content. The unusually high content of MLVSS in R-1, R-2 and R-4 might be due to the accumulation of SMP as a response to environmental stresses such as low pH and low temperature. Besides, long term operation under mesophilic range is relatively stable compared to thermophilic temperature in terms of COD removal efficiency. Operation at thermophilic temperature is more prone to the accumulation of inhibitory substances which could potentially lead to system failure. Under mesophilic regimes, the size of sludge floc tends to decrease with the increasing temperature. The higher in the amount of polysaccharide and smaller floc size renders AnMBR operated at 45°C to be more prone to membrane fouling compared to others.

By combining the MFC with AnMBRs, it was noticed that the overall COD removal efficiencies were higher compared to sole AnMBRs. Besides, the combined system demonstrated better filtration performance compared to AnMBR. By using MFC as a pre-treatment prior to AnMBR, it helps to reduce fine foulants and filamentous bacteria where its presence is associated with high EPS secretion. Decreases in fine foulants and EPS secretion reduce fouling propensity and thus better filtration performance.

5.2 Recommendations

Despite the control of temperatures and the integration of MFC with AnMBR could enhance the overall performance, mainly COD removal and filtration performance, the results obtained are yet to be the best possible outcome. Improvement can be made to ameliorate the performances of AnMBR and MFC-AnMBR. Some of the viable recommendations are suggested and shown as follows:

i) Constant and gentle stirring should be provided to achieve homogeneous mix in the bioreactor for stable results. The speed of the stirrer should be controlled to avoid the disturbance of biofloc formation.
ii) Pre-treatment such as pH adjustment on feed should be conducted to avoid pH shock on the system. The occurrence of pH shock affects the performance of the bioreactor and secret more SMP which subsequently leads to higher fouling propensity.
iii) Optimum SRT should be investigated particularly in system involving anaerobic digestion where the biomass growth rate is relatively slower. Hence, a longer SRT is usually more beneficial than a short SRT.

iv) The effects of polysaccharide and sludge floc size on membrane fouling should be further investigated to determine the dominant factor in contributing to membrane fouling.

v) The electricity recovered from MFC should be utilized effectively in the combined system. The electricity produced provides an external electrical field which interacts with the bound water in the sludge flocs. Such interaction could help to mitigate membrane fouling.

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APPENDICES

Appendix A: Experimental Set-up

Figure A1: Hybrid Anaerobic Bioreactors operated at ambient temperature

Figure A2: Hybrid Anaerobic Bioreactors operated at 45°C

Figure A3: Hybrid Anaerobic Bioreactors operated at 55°C (left) and 35°C (right)

Figure A4: Microbial Fuel Cell operated at ambient temperature

Appendix B: Laboratory Analytical Instruments

Figure B1: COD Reactor

Figure B2: UV-Vis Spectrophotometer (DR 6000)

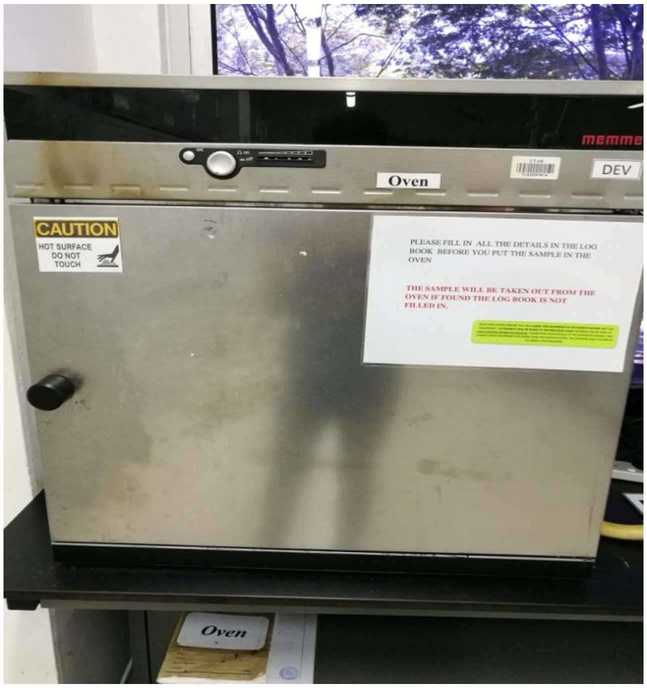

Figure B3: Oven

Figure B4: Muffle Furnace

Figure B5: Particle Size Analyzer

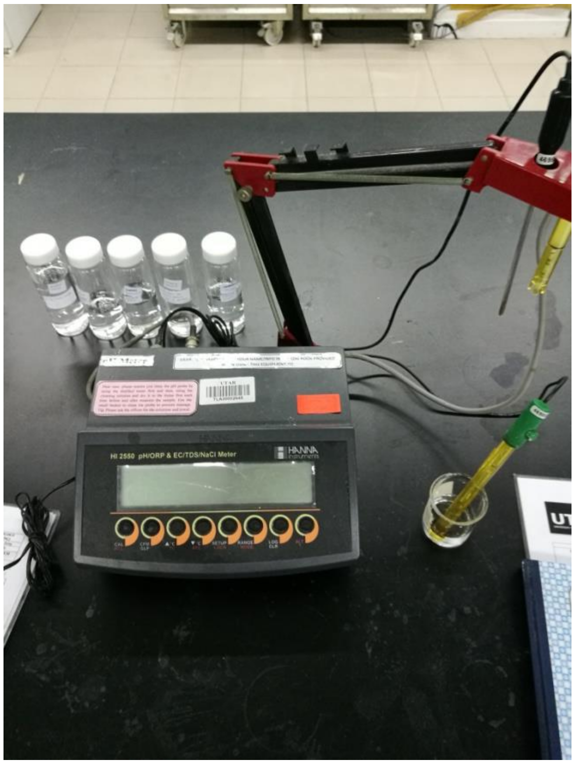

Figure B6: pH Meter

Figure B7: Analytical Balance

Figure B8: Cross Flow Membrane Test Rig

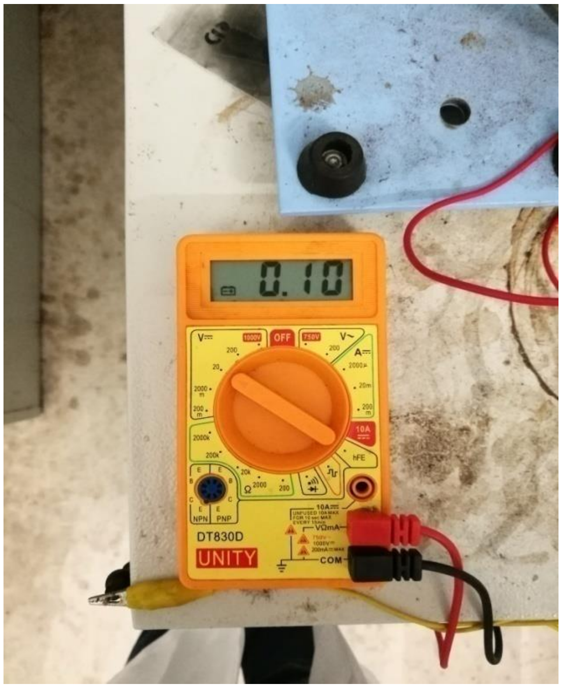

Figure B9: Multimeter

Appendix C: Materials

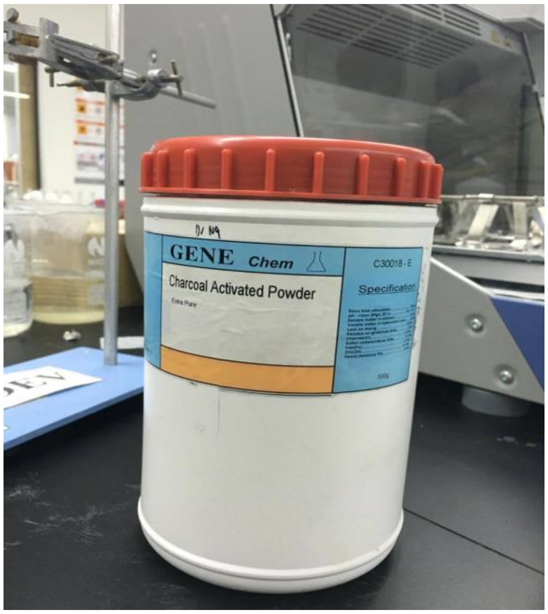

Figure C1: Powdered Activated Carbon (PAC)

Figure C2: Palm Oil Mill Effluent (POME)

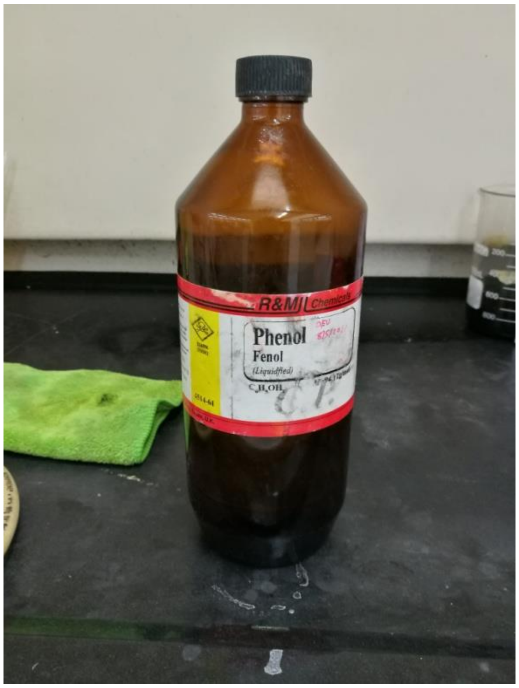

Figure C3: Phenol

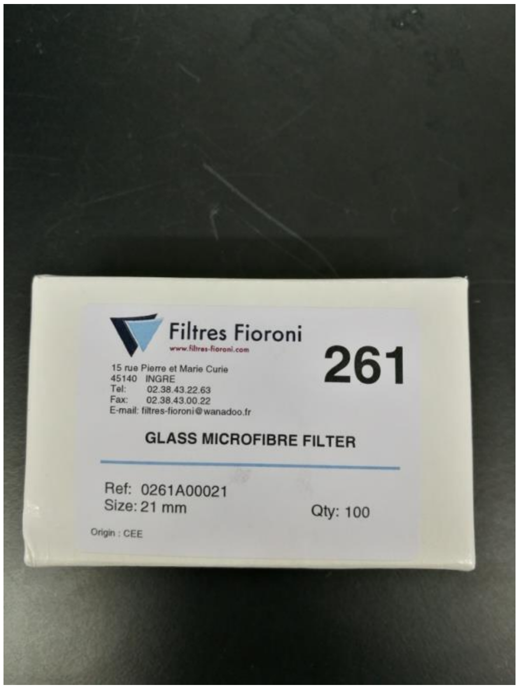

Figure C4: Glass Microfibre Filter