

**TREATMENT OF PALM OIL MILL EFFLUENT USING  
HYBRID ANAEROBIC MEMBRANE BIOREACTOR AT DIFFERENT  
TEMPERATURES AND pH VALUES**

**LEONG HOONG SUM**

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

**Faculty of Engineering and Green Technology  
Universiti Tunku Abdul Rahman**

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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.

Signature : \_\_\_\_\_

Name : Leong Hoong Sum

ID No. : 14AGB05417

Date : \_\_\_\_\_

**APPROVAL FOR SUBMISSION**

I certify that this project report entitled “**TREATMENT OF PALM OIL MILL EFFLUENT USING ANAEROBIC MEMBRANE BIOREACTOR OF DIFFERENT TEMPERATURES AND pH VALUES**” was prepared by **LEONG HOONG SUM** 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.

Approved by,

Signature : \_\_\_\_\_

Supervisor : Dr. NG CHOON AUN

Date : \_\_\_\_\_

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**ABSTRACT**

Membrane fouling is considered as the major impediment to the widespread application of the membrane bioreactor (MBR) system as it affects the operating conditions, cost and performance of the whole system. In order to increase membrane fouling resistance within the system, performance of the anaerobic membrane bioreactor (AnMBR) system operated under different operational temperatures and pH values were assessed. The AnMBR which operated under thermophilic condition, 55 °C showed the highest COD removal efficiency which was 76.21 %  $\pm$  4.54 % compared to others AnMBRs operated under mesophilic condition. A suitable increment of operational temperature could accelerate hydrolysis of cellulose and hemicellulose into comparatively biodegradable components. The performance of the AnMBRs with controlled pH around 6.7 which is proved as the optimum pH for anaerobic digestion. However this study showed no significant improvement in terms of COD removal efficiency. This may be due to the increased pressure within the bioreactors after an unexpected production of foam clogging the biogas outlets. In this study, the integration of microbial fuel cell (MFC) into the AnMBRs did not contribute much improvement but showed declination in terms of COD removal efficiency and membrane fouling control. The declination of the performance of the combined system was due to the sensitivity of anaerobic microorganisms to the environmental conditions such as the change in feedstock from raw POME to the supernatant of MFC. The performance of MFC-AnMBRs may be affected during this period as the stability of the microbes community is yet achieved.

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**LIST OF SYMBOLS / ABBREVIATIONS**

W	Watt
J	Joules
AC	activated carbon
AD	anaerobic digestion
AnMBRs	anaerobic membrane bioreactors
BAC	biological activated carbon
BOD	biochemical oxygen demand
CAPEX	capital expenditure
COD	chemical oxygen demand
CAS	conventional activated sludge
EPS	extracellular polymeric substances
HRT	hydraulic retention time
iHF	immersed hollow fibre
LB-EPS	loosely bound extracellular polymeric substances
MBR	membrane bioreactor
MF	microfiltration
MFC	microbial fuel cell
MFC-AnMBRs	microbial fuel cell integrated anaerobic membrane bioreactors
MLSS	mixed liquor suspended solids
MLVSS	mixed liquor volatile suspended solids
OPEX	operational expenditure
OLR	organic loading rate
PAC	powdered activated carbon
PES	polyethersulfone
POME	palm oil mill effluent

QQ	quorum quenching
QS	quorum sensing
RO	reverse osmosis
NaHCO <sub>3</sub>	sodium hydrogen carbonate
SMP	soluble microbial product
SRT	sludge retention time
TMP	trans-membrane pressure
UF	ultrafiltration
VFA	volatile fatty acid

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## CHAPTER 1

### INTRODUCTION

#### 1.1 Background

Oil palm, scientific name (*Elaeis guineensis*) is one of the most beneficial crops in the tropical world uses to produce palm oil, one of the world's most produced and consumed oils (Najafpour et al., 2006). According to Malaysia Palm Oil Board (2014), palm oil production had made up 28.2 % of the overall world production of oils and fats from the year 2011 to 2012. Due to its low price, high production efficiency and stability characteristic, palm oil is used in various industries including food, cosmetic and hygiene products as well as containing the possibility to be used as a source for bio-fuel or biodiesel (Indonesia-Investments, 2016). In Malaysia, the oil palm industry shows an astonishing development which soon expanded into a multi-billion ringgit industry (Malaysia Palm Oil Board, 2014). By referring to Table 1.1, palm oil is significantly surpassed other major oil crops with its overwhelming productivity. Palm oil is the most efficient oil crops among the others which yield 3200 kg of oil per hectare per year. Besides, as a perennial, the crops are not susceptible to sudden changes in weather making the reliable supply of palm oil (Malaysia Palm Oil Board, 2014).

**Table 1.1: Average production of various major oil crops (Malaysia Palm Oil Board, 2014).**

<b>Crop</b>	<b>Oil per ha/yr (kg)</b>
Copra	356
Cottonseed	188
Groundnut	384
Palm oil	3200
Palm kernel oil	454
Rapeseed	556
Sesame seed	178
Soya bean	351
Sunflower seed	504

Because of the advantages as abovementioned, the hectarage of oil palm in Malaysia had increased tremendously from a mere 400 hectares in 1920 to 5 million hectares in 2013 which covers 13.2 % of the land in Malaysia. With such a large area of oil palm plantation, Malaysia can produce up to 94 million tonnes of fresh fruit bunches (FFB) to be processed to palm oil and export worldwide. As such, Malaysia had turned into the second largest palm oil producer in the world after Indonesia (Ding et al., 2016; Liew et al., 2015). Currently, palm oil holds the largest production in the tradings of oils and fats. Accompanied by the rise of palm oil plantation, the milling and refining sectors of oil palm were also increasing (Malaysia Palm Oil Board, 2014).

Palm oil mills in Malaysia tend to use wet palm oil milling process for the extraction crude palm oil from the oil palm's fruits. By utilizing adjacent freshwater resources, an enormous amount of water is obtained for the milling process from nearby freshwater resources. Throughout the process, less than 30 % by weight of the processed FFB is remained, leaving the rest as oil palm wastes along with large amount of wastewater (Liew et al., 2015; Yahaya & Lau, 2013).

The wastes from the production of palm oil include empty fruit bunches, mesocarp fibre and shell as well as palm oil mill effluent (POME). POME is the hardest and most expensive waste needed to be treated among the wastes created during the palm oil processing, and also the most harmful waste. POME is produced in large volumes in tonnes at a time. POME is a high strength wastewater, it has high BOD and COD concentrations which deplete the dissolved oxygen and suffocate aquatic life if disposed into the river without treatment or incomplete treatment. Raw or untreated POME having BOD as high as 25,000 mg/L in average (Yahaya & Lau, 2013).

During the initial stage of palm oil industry in 1960's, POME was often disposed into the rivers or managed by other methods casually as the people were unaware of the harmfulness of POME (Malaysia Palm Oil Board, 2014). The pollution caused by the small amount of POME, around 92,000 tonnes from 10 palm oil mills was still insignificant with the help of natural degradation. However, by the 1970's the bloom of palm oil industry bringing along with the discharge of a tremendous amount of waste had caused serious pollution. At that moment, the major problem faced by the industry was the shortage of proper POME treatment technology. In the process of solving problems, the government and the industry worked together to find the technology for treating POME, which had not yet appeared. Luckily, the treatment systems of organic industrial waste were suitable to POME treatment system. There are three forms of treatment system being widespread in palm oil industry including ponding system, aerated open tank digester system, and the closed anaerobic digester system (Malaysia Palm Oil Board, 2014).

By 1984, the law limits the POME discharge in Malaysia by 100 ppm. Since 2006, DOE Malaysia further limits the BOD requirement to 20 ppm for the environmentally sensitive areas in Sabah and Sarawak like Kinabatangan River while the new mills in Sabah require land irrigation additionally. The discharge standards of POME which were getting more stringent had pressurized the palm oil mills (Yahaya & Lau, 2013). Economically feasible treatment technologies consist of anaerobic, aerobic, and facultative processes have been carried forward for the treatment of POME. Studies show that over 85 % of the palm oil mills

applied the ponding system but only a few mills are implementing biogas recovery systems (Najafpour et al., 2006). Ponding system is not only a feasible method to treat high strength organic wastewater, but also low-cost, which requires less maintenance, and provides the process and operational simplicity. However, this system requires a large land area of about 1 to 5 hectares, long hydraulic retention times around 40 to 200 days and contributes to greenhouse gases emission mainly methane and carbon dioxide which could result to the greenhouse effect (Ding et al., 2016; Liew et al., 2015).

As the stringent discharge limit came into enforcement, ponding system is inadequate for POME treatment as the effluent can hardly meet 20 ppm BOD. Therefore, the adjunction of tertiary treatment technologies which also known as polishing systems to the existing ponding system is necessary to aid the entire POME treatment by enhancing organic matters, total suspended solids and colour removal. Various types of polishing system such as membrane bioreactor technology (MBR), biological-physiochemical treatment process, sequencing batch reactor (SBR)-constructed wetland system, and ozone integrated submerged fixed film biological process were capable to produce higher quality effluent and meet the discharge limit compliance. Although these polishing technologies show astonishing results in treating POME, the cost requirement is too high compared with the low-cost palm oil processes thus hinder their widespread applications in oil palm industry (Liew et al., 2015).

Among these polishing technologies, MBR system which consists of membrane filtration and microbial degradation is one of the most favourable methods in treating POME (Yuniarto et al., 2013). MBR is being used more frequently now as it can solve problems confronted by the conventional activated sludge process (ASP), more specifically is due to the difficulty in biomass separation with the treated water. MBR reduces reactor volume and footprint while providing good effluent quality (Petros et al., 2014). Currently, there are two major operational conditions for MBR system, namely aerobic and anaerobic condition. Under the anaerobic state, methane is produced from the digestion process in anaerobic MBR (AnMBR) which is then recovered and utilized as a renewable energy. Besides, anaerobic process does not required aeration results in

a lower energy cost compared to aerobic process. Thus, AnMBR provides a faster payback to investment making it an attractive alternative for POME treatment (Poh and Chong, 2009).

## 1.2 Problem Statement

Even though MBR posses of several advantages including high treatment efficiency, small area requirement as well as low yet dense sludge production, membrane fouling problems continuous to impede the expansion of MBR among palm oil industries (Hong et al., 2016).

Membrane fouling is the main concern of the MBR design and system operation. Membrane fouling affects the operating conditions, cost and performance of the whole system while additional services such as pretreatment and membrane cleaning may be required. As the major impediment to the widespread application of the MBR system, membrane fouling attracts the attention of researchers to work on its characteristics and amelioration. Membrane fouling is the most serious drawback of this technology, as it may lead to permeate flux decline, which results to a more frequent cleaning of the membrane and possibility to replace the membrane which is very costly. The main foulants in MBR are the extracellular polymeric substances (EPSs) which are the excretions of the bacteria cells with high molecular weight that protect the bacteria by giving them adhesive and water retention ability (Petros et. Al., 2014).

By combining MBR with microbial fuel cells (MFC) which can generate electricity while treating wastewater, membrane fouling problems in MBR can be mitigated. MFC is a promising technology which was proven to improve the membrane fouling resistance of the combined system by modifying the sludge while treating wastewater (Karmakar, Kundu and Kundu, 2010; Tian et al., 2015). Besides, such combination leads to improvement of effluent quality in addition to energy recovery. However, this integrated system was only tested with synthetic

wastewater as the feedstock while the workability for wastewater with high COD such as POME is not well defined yet (Su et al., 2013; Tian et al., 2015).

In addition, the performance of MBR system is affected by the operating condition of MBR system such as pH value, transmembrane pressure, temperature, sludge retention time (SRT) and hydraulic retention time (HRT) (Sabia, Ferraris and Spagni, 2013). Changes of these operating parameters will alters the performance of MBR system with regard to treatment efficiency and membrane fouling tendency. Based on Tan (2017), the variation of operational temperature of the MBR system changes the characteristics of the mixed liquor which then alters the performances of the system. With the similar variation of operational temperatures, the pH value of the feed-in POME was modified as their influences on the performance of MBR system is determined. Furthermore, MFC is operated as a pretreatment unit prior to AnMBR to test the workability of the integrated system (MFC- AnMBR) with the aim to improve the membrane fouling resistance.

### **1.3 Objectives**

The objectives of this study are:

- i. To evaluate the performance and membrane fouling resistance of the AnMBR system in treating POME under different operational temperatures.
- ii. To study the effects of different pH value to the performance of AnMBR system in treating POME.
- iii. To assess the performance of the combined system consists of AnMBR and MFC.

## **1.4 Project Outline**

This research focuses on the improvement of anaerobic membrane bioreactor in terms of palm oil mill effluent treatment performance and membrane fouling control. As most of the membrane bioreactors in palm oil mills are operated under ambient temperature, the need of research to investigate the feasibility of manipulating the operation temperature is significant. Besides, the changes of performance and membrane fouling rate after adding microbial fuel cell before the anaerobic membrane reactor were also tested.

There are five chapters in this report. The first chapter reveals the background of study, problem statement and objectives of this research. Chapter two shows the literature review did on some relevant aspects of palm oil mill effluent treatment system, anaerobic membrane bioreactor and microbial fuel cell throughout the research period. Chapter three lists the methodology which includes sample preparation, sample analysis, experimental set-up, and studies. Chapter four states the results and discussion of the research where the key findings were emphasized. Lastly, chapter five includes the conclusion of this research and the recommendation of future studies with topics related to this research.

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 Anaerobic Membrane Bioreactor (AnMBR) Technology

Membrane bioreactor (MBR) is an advancement of wastewater treatment system which combines activated sludge process and membrane filtration (Hu et al., 2017; Neoh et al., 2017; Tan et al., 2017). This technology couples membrane separation technique to biological process, achieving solid-liquid separation of the mixed liquor (Xiong et al., 2016; Tan et al., 2017). As the popularity of anaerobic digestion for POME treatment is increasing, the combination of anaerobic digestion and MBR, namely anaerobic membrane bioreactor (AnMBR) further improves the performance of anaerobic digestion by retaining the slow-growing anaerobic sludge and nearly all suspended solids in the reactor (Hu et al., 2017; Neoh et al., 2017; Tan et al., 2017).

Generally, side-stream configuration and submerged configuration are the two possible configurations in integrating the membrane into the activated sludge process (Hoek and Tarabara, 2013). The major alteration of the side-stream and submerged configurations is the siting of membrane. For side-stream configuration, the membrane is located outside of the bioreactor whereas the membrane for submerged configuration is directly immersed in the mixed liquor, accompanied by an artificially intensified turbulence like biogas aeration. In the former case, the mixed liquor circulates through the membrane module at high cross flow velocity and relies on high transmembrane pressure (TMP) to maintain filtration and control fouling, 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 (Le-Clech, Chen and Fane, 2006; Gouveia et al., 2015; Hoek and Tarabara, 2013). While in the latter case, the way of siting of membrane eliminates 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). In fact, the overall lower operating cost obtained with the submerged configuration renders it to be more commonly applied (Gouveia et al., 2015).

Initially, anaerobic digestion has the advantages of lower energy consumption, high organic loading rate, low sludge production, and bioenergy recovery but a higher hydraulic retention time (HRT) (Hu et al., 2017; Ng et al., 2013; Tan et al., 2017). By coupling with membrane filtration system, AnMBRs decouples the sludge retention time (SRT) from the hydraulic retention time (HRT) of the reactor, which given sufficient time for digestion thus renders higher effluent quality and lesser sludge disposal (Xiong et al., 2016; Zhang et al., 2017). Furthermore, anaerobic membrane bioreactors (AnMBR) allows higher concentration of mixed liquor suspended solid (MLSS) of around 12000 mg/L. As mixed liquor suspended solids (MLSS) concentration resembles the amount of biomass, AnMBR which allows higher concentration of MLSS about 12,000 mg/L enables higher organic loading loads thus reduces its footprint (Tan et al., 2017). Unlike aerobic membrane bioreactors which is mainly applied to low to medium strength municipal wastewater treatment (Xiong et al., 2016), AnMBRs are applicable to treat high strength wastewater such as POME while producing methane as a valuable end-product (Zhang et al., 2017). Studies show that AnMBRs can achieve COD removal around 70 % to 90 % in the treatment of municipal wastewater, even under temperature as low as 20 °C (Düppenbecker et al., 2017; Xiong et al., 2016). In addition, AnMBR holds a remarkable disinfection capability in the discharged effluent as the membrane modules remove all colloidal solids, suspended and pathogens (Tan et al., 2017).

Despite of the numerous advantages brought by the coupling effect of activated sludge digestion and membrane filtration system, MBR had encountered membrane fouling problems especially in anaerobic bioreactors which restricted

the widespread of this technology (Hu et al., 2017; Chen et al., 2017; Zhang et al., 2017). According to Xiong et al. (2016), the accumulation of the dissolved part of activated sludge contributed the most to membrane fouling in MBRs. The microbial composition and extracellular polymeric substances (EPS) in the AnMBR form a layer of biofilm which the pores of the membrane modules to clog by attaching to the surface of the membrane. After that, the transmembrane pressure (TMP) in the reactors then strikes up and membrane fouling occurred (Neoh et al., 2017; Ng et al., 2013). The foulants in AnMBR cause less-reversible membrane fouling and lead to the need for more stringent maintenance such as backwashing and chemical cleaning, thus lowering the financial benefits of AnMBRs (Xiong et al., 2016). Recently, the fundamental mechanisms of membrane fouling are being studied, several solutions are suggested including pretreatment of the wastewater, modification of membrane materials and surfaces, as well as the addition of adsorbents, coagulants or flocculants (Zhang et al., 2017). In short, even though there are problems encountered, AnMBR is still a remarkable improvement which reduces energy consumption and environmental impacts compared traditional treatment system as well as recovering bioenergy (Hu et al., 2017).

As a matter of fact, the application of MBR system for municipal and industrial wastewater treatment is expanding constantly. The demand for higher quality discharge through the government legislation had driven the widespread of MBR technology. In addition to the merits of MBR system above-mentioned, there is still room for improvement in this technology as more and more research findings had rapidly advancing the performance of the MBR system (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 Palm Oil Mill Effluent (POME)

Palm oil industry in Malaysia processes the palm oil fruit to extract crude palm oil where an enormous amount of water is consumed. In processing every one tonne of fresh fruit bunches for oil extraction, approximately 1.5 m<sup>3</sup> of water is needed and almost half of the water is discharged as palm oil mill effluent (POME) (Ahmed et al., 2015). POME are produced and discharged from three principal sources namely clarification wastewater (60 %), sterilizer condensate (36 %) and hydrocyclone wastewater (4 %) (Tabassum, Zhang and Zhang, 2015). As the by-product of one of the largest industry in Malaysia, POME is a significant pollutant which tend to cause devastating impact on the water system of the natural environment. BioEnergy Consult (2015) suggested that the presence of organic and nutrient contents in POME gives it the capability of greatly depleting the oxygen content in the aquatic system.

Generally, raw POME with brownish appearance and high viscosity is discharged from the palm oil industry at a temperature range within 80 to 90 °C, which has brownish. Based on the information obtained from Malaysia Palm Oil Board (2014), Table 2.1 shows the detail characteristics of POME, showing that it is acidic with significantly high BOD and COD concentration, high salt content, high suspended solids as well as unpleasant odour (Ahmed et al., 2015; Tabassum, Zhang and Zhang, 2015).

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

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

Table 2.2 shows the discharge standards of POME from year 1978 to 2014 in term of several parameters including BOD, COD, oil and grease, pH, suspended solids, total solids, ammoniacal nitrogen (NH<sub>3</sub>-N), total nitrogen, and temperature. 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.

Current discharge standards of POME limit the effluent at lower BOD, suspended solids, oil and grease, NH<sub>3</sub>-N, and temperature which must be equal or less than 100 mg/L, 400 mg/L, 50 mg/L, 100 mg/L, and 45 °C respectively. The changes of discharge standard show the establishment of more and more stringent environmental laws on the discharge of POME as compared to year before 1984 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). In order to fulfill the discharge standards, ponding system, aerated open tank digester system, and the closed anaerobic digester systems are commonly implemented to treat POME (Malaysia Palm Oil Broad, 2014).

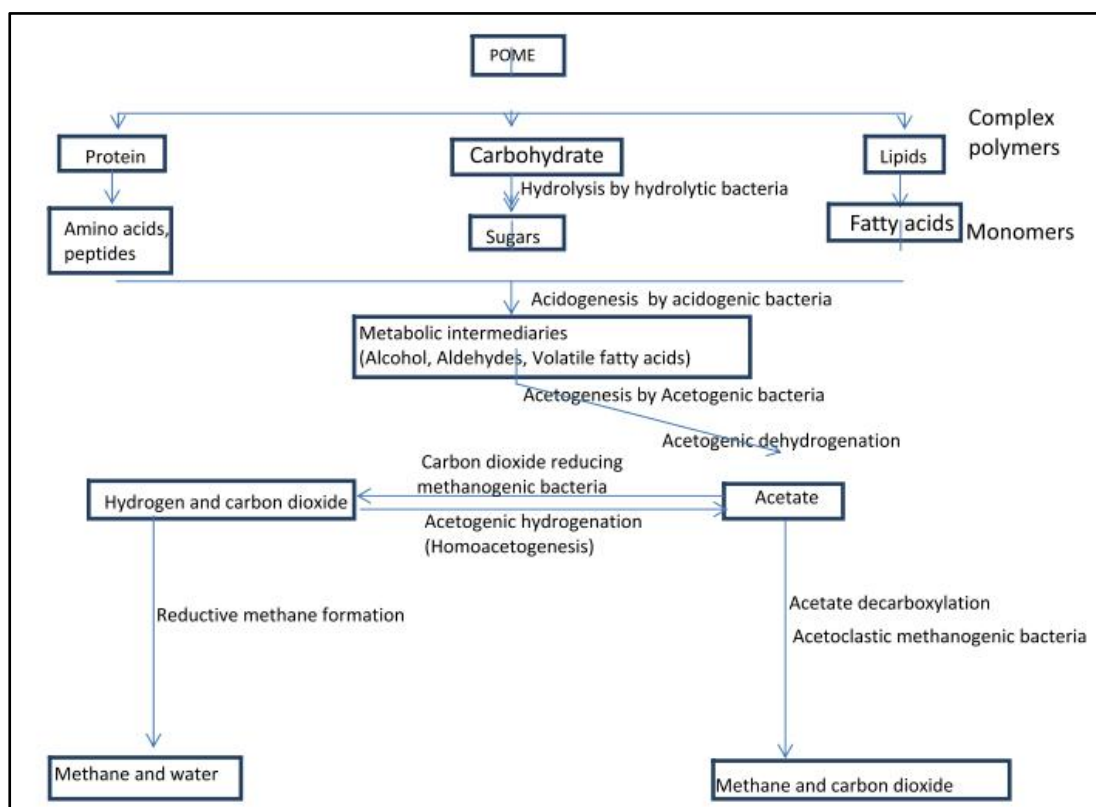
**Table 2.2: POME discharge standards (Malaysia Palm Oil Board, 2014).**

Parameter	Limits According to Periods of Discharge					
	1/7/78	1/7/79	1/7/80	1/7/81	1/7/82	1/1/84
	-	-	-	-	-	-
	30/6/79	30/6/80	30/6/81	30/6/82	31/12/83	thereafter
Biochemical oxygen demand	5000	2000	1000	500	250	100
Chemical oxygen demand	10000	4000	2000	1000	-	-
Oil and grease	150	100	75	50	50	50
pH	5-9	5-9	5-9	5-9	5-9	5-9
Suspended solids	1200	800	600	400	400	400
Total solids	4000	2500	2000	1500	-	-
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 except pH and temperature

### 2.3 Anaerobic Digestion (AD)

Most palm oil mills use anaerobic digestion (AD) as the primary treatment for POME (Poh & Chong, 2009). Anaerobic digestion is the degradation of complex organic matters to produce methane, carbon dioxide and water in the absence of oxygen. Anaerobic digestion is more attractive to the mills due to its low operational cost and valuable end-product which is biogas. Anaerobic digestion is often regarded as biomethanation process and its microbial synthesis pathway consists of four main stages including hydrolysis, acidogenesis, acetogenesis, and methanogenesis as shown in Figure 2.1 (Poh & Chong, 2009; Ohimain & Izah, 2017).



**Figure 2.1: Anaerobic digestion process of POME treatment (Ohimain & Izah, 2017).**

Each stage of the anaerobic digestion is carried out through a different subset of microorganisms operating in their own niche conditions (Naik et al., 2014). Hydrolysis involves the conversion of complex substances in POME i.e. lipids, protein and carbohydrates into monomers such as fatty acids, amino acids and sugars, respectively by hydrolytic microorganisms and/or their enzymes. These hydrolytic

bacteria include some species of *Clostridium*, *Bacillus* and *Staphylococcus*. During acidogenesis a.k.a. fermentation, acidogenic fermentative bacteria mainly *E. coli* and some species of *Staphylococcus*, *Pseudomonas*, *Bacillus*, *Desulfovibrio*, and *Clostridium* will break down the sugar, fatty acids and amino acids into metabolic intermediaries such as volatile fatty acids, alcohol, aldehydes. Volatile fatty acids are the most abundant product formed by these bacteria (Poh & Chong, 2009; Ohimain & Izah, 2017).

These metabolic intermediaries are further degraded by acetogenesis bacteria such as *Clostridium* and *Syntrophomonas* species during acetogenesis to produce acetate, carbon dioxide and hydrogen gas. Other products such as ethanol, lactate, propionate and butyrate are formed as well during acidogenesis. The last stage of the anaerobic digestion is methanogenesis and two groups of bacteria are involved in the process namely acetotrophic and hydrogenotrophic. Hydrogenotrophic methanogens use hydrogen as electron acceptor for methane production, while acetotrophic methanogens use formate as electron donor for methane and carbon dioxide reduction. Methanogenic bacteria directly used acetate from acetic acid as a substrate to produce biogas. The bacteria involved in methanogenesis are *Methanobacterium*, *Methanoplanus* and *Methanobacteria* (*Methanococcus*) (Poh & Chong, 2009; Ohimain & Izah, 2017).

According to Naik et al. (2014), the key factors that govern the productivity and stability of anaerobic bioreactors are feedstock variability, retention time, temperature and acidity of the system. The productivity of AD requires optimization between acid and methane forming processes. Excessive production and accumulation of VFAs caused by high organic loads in hydrolysis stage will lower the pH in the bioreactor. The activity of pH-sensitive methanogen will be inhibited and thus results in a lower production of biogas (Naik et al., 2014; Xu et al., 2014). The anaerobic digestion process is carried out by a large diversity of facultative anaerobes through many fermentative pathways (Ohimain & Izah, 2017). As such, the stability of the AD process is dependent on the inoculum mass and critical balance of different trophic groups, which reveals that the microbial community will change if the anaerobic digestion system is imbalanced (Xu et al., 2014).

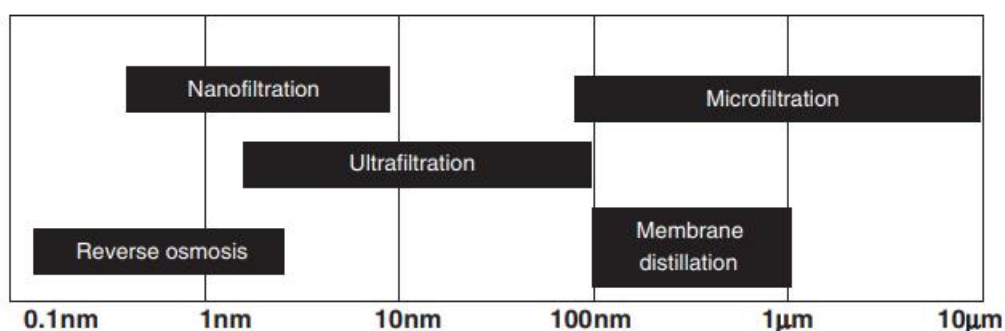
As compare to other alternative methods for POME treatment, anaerobic digestion has lower energy requirement as aeration is unnecessary. Besides, methane gas is produced as a valuable end product of anaerobic digestion which can be converted into electricity and gain excessive revenue. Nevertheless, the sludge created from the AD process can be used for land applications (Poh & Chong, 2009). The only drawbacks of AD are long retention time and difficulty of start-up as the microorganisms in AD processes have lower growth yield. Anyhow, the high-rate anaerobic bioreactor is introduced to overcome these drawbacks as well as capturing methane gas for utilization. By maintaining the anaerobic bioreactor under suitable pH and temperature, shorter retention time can be achieved while the addition of granulated seed sludge can easily shorten the start-up period for the growth of bacteria consortia (Poh & Chong, 2009; Shin et al., 2014). Last but not least, the combination of anaerobic and membrane reactors could improve the effluent quality (Li et al., 2017).

## **2.4 Membrane System in Wastewater Treatment**

Membrane systems establish superiority over conventional water treatment system by having higher treatment efficiency, smaller footprint and can simply take over several unit treatment processes. Due to these merits, membrane systems are commonly applied to wastewater treatment and served as tertiary treatment system to aid the removal of dissolved matter for instance, colloidal and suspended solids, non-biodegradable organic pollutants, and pathogenic microorganisms (Pulido, 2016). Various physical and chemical nature of membranes such as pore-size distribution, pore tortuosity and porosity, were manipulated to control the permeation of selective components (Singh & Heldman, 2014; Lalia et al., 2013).

Pore size distributions of the membrane were used to classify different membrane processes such as microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. The ranges of pore size of the membrane used in different membrane processes were showed in Figure 2.2 (Lalia et al., 2013). For different

membrane processes, there are different hydraulic resistances on the membrane surface which needed to be overcome by particular pressure levels. Besides, hydrostatic pressure built in the system acts as the driving force which allows the permeation of the selected components from the feed in solutions (Singh & Heldman, 2014). For wastewater treatment system, microfiltration (MF) and ultrafiltration (UF) are commonly being used while reverse osmosis (RO) is well-developed for water purification and desalination (Lalia et al., 2013).



**Figure 2.2: Range of membrane pore size for different types of membrane systems (Lalia et al., 2013).**

Microfiltration system is widespread in drinking water and wastewater treatment sectors due to its ability to remove suspended solids, turbidity, bacteria and protozoa (Hoek and Tarabara, 2013). Microfiltration membrane has an average pore size ranging from 0.1- 10  $\mu\text{m}$  and is generally operated under a hydraulic pressure ranging from 100 to 200 kPa (Lalia et al., 2013; Singh & Heldman, 2014).

Ultrafiltration membrane has an average pore size ranging from 0.001 to 0.1  $\mu\text{m}$  (Lalia et al., 2013). The smaller pore size of ultrafiltration had given it the ability to remove high molecular weight solutes such as colloidal and suspended matters, as well as condensation of solid, fat, and lipid components. In addition, ultrafiltration also retains bacteria and viruses which renders its wide application for water disinfection industry to produce drinkable water (Pulido, 2016; Ahmad et al., 2006). The trans-membrane pressure for the operation of ultrafiltration membrane ranges from 100 to 700 kPa (Singh & Heldman, 2014).

### 2.4.1 Membrane Module Configurations

There are four major types of membrane module configurations used in reverse osmosis and ultrafiltration system: plate-and-frame, tubular, spiral-wound, and hollow-fiber (Singh & Heldman, 2014). The designs of these configurations are generally based on planar and cylindrical geometry and their brief description was listed in Table 2.3 (Radjenović et al., 2008). In addition, the performances of these membrane module configurations in terms of the process-related properties were tabulated in Table 2.4 (Singh & Heldman, 2014).

**Table 2.3: Brief description of four major types of membrane modules (Radjenović et al., 2008).**

<b>Configurations</b>	<b>Brief description</b>
Plate-and-frame	Flat-sheet membranes are sealed onto plates and arranged uniformly with separators to form modules. When wastewater passes the membrane, permeate flows into the outlet through the piping system under each module in vacuum state
Tubular	The application of this module is relatively less demanded compared to others. Tubular membranes are regularly loaded into pressure vessels and operated in the side-stream configuration where mixed liquor is pumped through the vessels.
Spiral-wound	This configuration is widespread in nanofiltration and reverse osmosis process. Flat shape membranes are wound around the outlet for permeate. The dimensions of the modules are standardize by majority to ease the installation and reduce the production cost. Installation of multiple modules in parallel or series can be done to increase the capacity of filtration process.
Hollow-fiber	A bundle of closely packed hollow fibers being plastered in epoxy bar connected to the outside of the casing. The direction of flow is reversible and the membranes can operated under pressure or vacuum.

**Table 2.4: Properties of four major types of membrane modules (Singh & Heldman, 2014).**

<b>Properties</b>	<b>Membrane Module Configurations</b>			
	Plate-and-frame	Tubular	Spiral-wound	Hollow-fiber
<b>Flux density</b>	Low	Low	Moderate	High
<b>Hold up volume</b>	Moderate	High	Low	Low
<b>Cleaning efficiency</b>	Low	High	Low	Moderate
<b>Mode of replacement</b>	By sheets	By tubes	By module	By entire bundle
<b>Replacement labor</b>	High	Moderate	High	Moderate
<b>Suspended solids accumulation</b>	Low/moderate	Moderate/high	Low	High

#### 2.4.2 Membrane Fouling

Membrane fouling obstructs the process of membrane filtration (Said et al., 2015). Membrane fouling indicates the deterioration of membrane performances in terms of life-span, permeability, and selectivity caused by the blockage of the surface and inside the pores of the membrane. Regular cleaning and maintenance as well as over design of the membrane system were required to ensure the workability of the system, maintain flux and quality of the permeate (Pulido, 2016; Said et al., 2015). In general, membrane fouling occurs in MBR because of five mechanisms: (1) adsorption of colloids and solutes on or within membranes; (2) deposition of biomass flocs onto the surface of membranes; (3) cake layer formation on the surface of membranes; (4) displacement of foulants due to shear forces; (5) the temporal and spatial changes of the foulant composition as the bacteria community and biopolymer components in the cake layer changes with the long-term operation. In brief, membrane fouling is the results of undesirable deposition and accumulation of colloids, solutes, microorganisms, and cell debris within or on membranes (Meng et al., 2009).

According to Iorhemen, Hamza, and Tay (2016), membrane fouling can be categorized into three main stages. The first stage shows the initial conditioning

fouling which is caused by initial solute adsorption and pore blocking, while the second stage shows gradually increase in trans-membrane pressure (TMP) due to the formation of biofilm which further blocks the membrane pores. Lastly, the continuous clogging of pores causes the local flux to increase due to the fouling. When the local flux exceeds a critical value, particle deposition accelerates and cake layer structure changes abruptly causing the sudden increase in TMP. Furthermore, more EPS is released as the microbes in the inner layer of biofilms tend to die due to suffocation (Gkotsis et al., 2014).

Membrane fouling can be further classified into three types of fouling in terms of the degree of cleaning which are removable fouling, irremovable fouling and irreversible fouling. The removable fouling is caused by loosely attached foulants which can be simply removed by physical cleaning routine such as backwashing. The irremovable fouling is caused by strongly attached foulants blocking the pore during filtration and requires chemical cleaning to restore the performances of the membrane. However, the irreversible fouling is a permanent fouling which cannot be removed by any means (Meng et al., 2009).

### **2.4.3 Membrane Foulants**

Membrane fouling is the result of various of physicochemical and biological mechanisms and is aggravated by concentration polarization which severely increases the concentration of foulants within or on the membrane (Gkotsis et al., 2014). Based on the biological and chemical characteristic, membrane foulants comprises of biofoulants, organic and inorganic foulants. Biofoulants refers to the bacteria and their metabolic products which contributes to membrane fouling. Biofouling starts with the attachment of bacteria on the surface of the membrane, which then reproduces on the membrane surface causing the formation of biocake and thus blocks the membrane (Iorhemen, Hamza and Tay, 2016). The biocake formation on the membrane is the results of a long-term application of MBR and is inevitable (Neoh et al., 2017).

Organic foulants in membrane bioreactors refer to biopolymers, like polysaccharides and proteins which are found in metabolic products of bacteria which are also known as extracellular polymeric substances (EPS). In MBR, loosely bound EPS and soluble microbial products (SMPs) form an abundance of large-sized free organic solutes, namely biopolymer clusters (BPC). The formation and accumulation of BPCs on the membrane surface are relatively hard to remove and also causes severe fouling (Iorhemen, Hamza and Tay, 2016).

Inorganic foulants are inorganic substances including cations and anions such as  $Mg^{2+}$ ,  $Al^{3+}$ ,  $OH^-$ , etc. which precipitate onto the membrane surface and cause biological precipitation of inorganic-organic complexes. There are two main mechanisms which contribute to the inorganic fouling in MBR, crystallization and particulate fouling. Precipitation of ions occurs on the membrane surface during crystallization and then follows by the convective transportation of colloidal particles in the water to the surface of the membrane causing particulate fouling of the membrane (Iorhemen, Hamza and Tay, 2016).

#### **2.4.4 Fouling Control and Mitigation Strategies**

As fouling is constantly interfering with the process of MBR system, proper fouling control and prevention strategies is considered and implemented. Membrane fouling mitigation strategies can be divided into five groups which are: (1) feed pretreatment; (2) Physical and chemical cleaning protocols; (3) operational conditions modification; (4) chemically or biochemically modification of mixed liquor; (5) membrane surface modification. Pretreatment of feed includes screening or sedimentation of the feed-in wastewater before entering the MBR system. Although MBR can effectively replace several pretreatment units in wastewater treatment system, feed pretreatment is still necessary to reduce the fouling propensity of the membrane (Gkotsis et al., 2014).

Under physical and chemical cleaning protocols, physical cleaning is carried out frequently to remove the removable foulants while chemical cleaning is conducted once or twice a year to remove the irremovable foulants. The general parameters of

physical cleaning include duration, frequency and flux. Physical cleaning can be done by backwashing or relaxation. Studies showed that relaxation is preferable than backwashing as backwashing with permeate will cause blockage in the pores of the membrane. Relaxation, on the other hand, allows foulants to move away from the membrane surface into the biomass by the concentration gradient. Chemical cleaning which also known as intensive cleaning is normally being conducted when the filtration process is retarded as the permeability of the membrane diminished (Gkotsis et al., 2014).

Modification of the characteristics of mixed liquor can be done by either chemically or biochemically through various of methods. Based on Iorhemen, Hamza and Tay (2016), the current studies showed that membrane fouling reduction in MBR system can be done by addition of coagulants, adsorbents, granular materials with air scouring as well as an innovative approach of using quorum quenching technology. The addition of coagulants such as alum [ $Al_2(SO_4)_3$ ] and ferric chloride ( $FeCl_3$ ) promotes the formation of larger size flocs which improve membrane filtration. Besides, adsorbents such as powdered activated carbon (PAC) serve as media for the attachment and growth of microbes subsequently increase the density of the mixed liquor and thus reduce the membrane fouling propensity. Nevertheless, granular materials with air scouring were applied to MBR system to enhance the detachment of foulants from the membrane. This method provides continuous physical cleaning which successfully reduced the formation of cake layer on the membrane and prolongs the frequency of chemical cleaning (Gkotsis et al., 2014).

The idea of quorum quenching (QQ) was introduced to MBR technology for membrane fouling mitigation through quorum sensing (QS) manipulation. Quorum sensing is the communication system between bacteria by chemical signal molecules to coordinate their behaviour within the population, which also trigger their own biosynthesis such as EPS which is the main foulant of the membrane. As bio-fouling correlated with quorum sensing, QS signal degradation has been approached. Quorum quenching which counters quorum sensing by inactivate the signal molecules by modification or catalyzed degradation, inhibit signal detection and signal biosynthesis. Currently, quorum quenching is commonly applied in water treatment systems such as micro or ultrafiltration and tested with synthetic

wastewater for wastewater treatment system. This new technique may be possible to prevent membrane fouling in MBR system in treating POME as well (Gkotsis et al., 2014).

## **2.5 Integration of MBR with Microbial Fuel Cell (MFC)**

Microbial fuel cell is a prospective treatment system with the ability to reclaim energy, suggesting that academic researchers have increased interest in recent decades (Karmakar, Kundu and Kundu, 2010; Tian et al., 2015). The on-going redox reaction occurs by several types of bacteria in MFC including electrochemically-active microorganisms which disintegrate organic matter in wastewater and directly produce electricity (Ma et al., 2016; Su et al., 2013; Karmakar, Kundu and Kundu, 2010). However, the treatment efficiency of MFC is relatively low renders it unsuitable to act as a self-standing wastewater treatment system (Tian et al., 2015). Hence, it is advisable to provide post-treatment methods subsequent to MFC for further improvement of treatment performance for the entire system (Kim et al., 2016).

According to Tian et al. (2015), wastewater treatment merely by MFC is inadequate to meet the stringent discharge standards (Tian et al., 2015). The combination of MFC with other treatment systems such as MBR appears to be promising as the combined system was able to treat wastewater efficiently while generating electricity as renewable energy (Su et al., 2013). In fact, membrane system provides high removal efficiency as the membrane modules remove all suspended, colloidal solids and pathogens (Tan et al., 2017). Besides, MFC was able to modify the sludge in the combined system which prolong membrane fouling up to twice the time as for conventional MBR. Based on Su et al. (2013), MFC was able to successfully decrease the amount of loosely bound extracellular polymeric substances (LB-EPS) which is the main foulant of membrane to approximately 22%. Thus, MBR and MFC makes an ideal combined system as it has several merits including better treatment efficiency, production of renewable energy and higher membrane fouling resistance.

## 2.6 Operating Condition of MBR System

Operating condition of MBR system can be categorized into membrane and biological operating conditions. Both of them play substantial role in determining the performance of MBR system. Sabia, Ferraris and Spagni (2013) suggested that the membrane operating condition includes flux, transmembrane pressure and backwashing whereas the biological operating condition involves temperature, sludge retention time (SRT) and hydraulic retention time (HRT).

### 2.6.1 Sludge Retention Time (SRT)

SRT is a vital factor potentially affecting the performance of MBR system as 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 & 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 & 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 & Liu, 2009; Pollice et al., 2008).

### **2.6.2 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).

### **2.6.3 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 & 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., 2003).

#### **2.6.4 Temperature**

The performance of the anaerobic process is highly affected by the operational temperature of the bioreactor. Currently, mesophilic (35 - 40 °C) condition and thermophilic (55 - 70 °C) condition are the two common temperature regimes being used in conventional anaerobic digestion (Choong, Chou and Norli, 2017). As the operational temperature drops, the growth rate of anaerobic microorganisms will also decline; in contrast, anaerobic microbes in higher temperature are able to withstand higher organic load which leads to better treatment performance (Ferrer et al., 2015; Mao et al., 2015). However, the stability of thermophilic anaerobic digestion is relatively lower which limits the widespread application of anaerobic digestion in this regime (Choong, Chou and Norli, 2017).

#### **2.6.5 Activated Carbon (AC)**

The addition of powdered activated carbon (PAC) in the membrane bioreactor (MBR) is proven to enhance the biodegradation process of the activated sludge as well as improving the filtration performance (Ng et al., 2013; Nguyen et al., 2014; Xiao et al., 2017). PAC acts as a bio-carrier to facilitate the adsorption of organics and the growth of microorganisms to develop a complex matrix, namely biologically activated carbon (BAC). BAC assures the biological processes in MBR involving a larger amount of microorganisms (Hu et al., 2017). By attaching the microbes to the surface of the PAC, BAC enables biodegradation of the pollutants previously adsorbed by the PAC thus enhance partial bioregeneration of

saturated BAC (Aghamohammadi et al., 2007; Ng et al., 2013). Besides, the application of PAC remarkably increases the retention of soluble contaminants in BAC which enhance the biodegradation of compounds which takes more time to biodegrade (Nguyen et al., 2014). The adsorption effect created by the addition of PAC reduces extracellular polymeric substances (EPSs) in the bioreactor and other fine foulants such as TOC, fine colloids, soluble metabolic products (SMPs) and trace organics in the supernatant (Ng et al., 2013).

Through adsorption process, PAC modified the characteristics of sludge flocs including morphological, component and microbial properties to facilitate biological PAC formation. PAC increases the sludge flocs' strength, which was determined to be a major mechanism of fouling mitigation and thus improves fouling control (Hu et al., 2017; Ng et al., 2013; Xiao et al., 2017). Other beneficial effects of using BAC include substrate removal enhancement, activated sludge filterability improvement, and better loading shock resistance performance (Ng et al., 2013). However, withdrawal and replenishment of PAC are required to maintain the beneficial effects of adding PAC into the MBR system (Nguyen et al. 2014). Generally, hybrid MBR which contains PAC showed better pollutant removal of COD, NH<sub>3</sub>-N and colour as well as improving filtration performance in terms of higher flux and lower filtration resistance during stable operation (Hu et al., 2017).

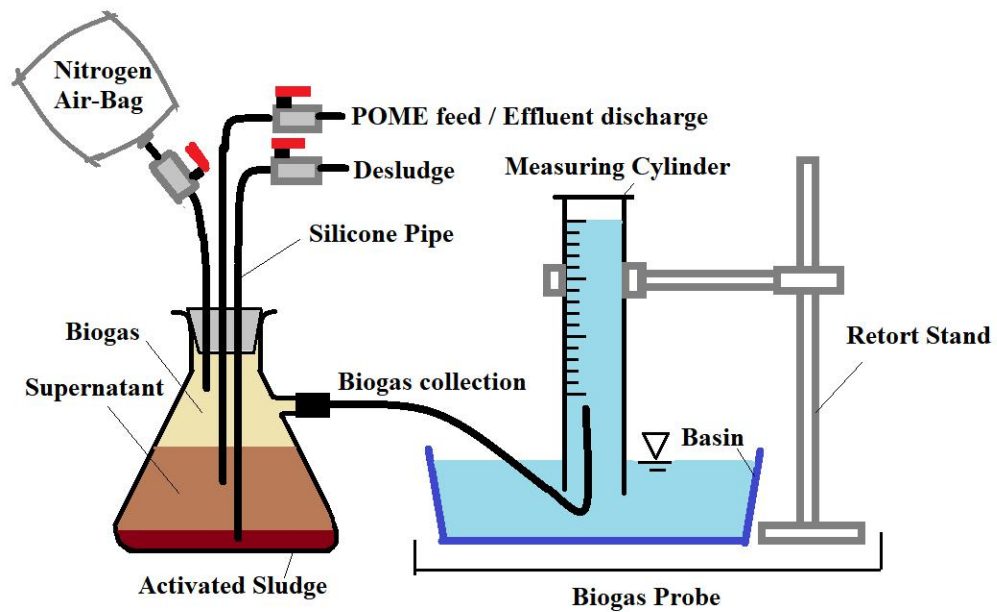
## CHAPTER 3

### METHODOLOGY

#### 3.1 Experimental Setup

##### 3.1.1 Anaerobic Membrane Bioreactor (AnMBR)

The anaerobic membrane bioreactor consisted of two stages, anaerobic bioreactor and flow filtration system. Raw POME fed into the anaerobic bioreactor was treated with bio-degradation processes and then the effluent was transferred into a cross-flow membrane test rig for further filtration treatment. As shown in Figure 3.1, each anaerobic bioreactor consisted of a 1 L Buchner flask sealed with a plastic cover at the head which is attached to three openings: feeding and discharging pipe, desludging pipe and nitrogen air-bag while the flask's sidearm was connected to biogas probe. The air-bag pipe was connected to a nitrogen air-bag which was used to aid the effluent discharging and desludging processes. While pressing the air-bag, the inflow of nitrogen gas had created sufficient air pressure to pump out the effluent and sludge. Besides, the volume of biogas produced by the bioreactors was determined by water displacement method via biogas probe as shown in Figure 3.1. Each pipe was attached to a closed metal valve to prevent the entering of oxygen gas thus maintaining an anaerobic circumference in the reactor. The valves were closed all the time except when the pipes were going to serve their respective purposes such as feeding, desludging, nitrogen gas pumping and etc.



**Figure 3.1: Schematic diagram of anaerobic bioreactor.**

### 3.1.2 Operational Procedure

By changing the temperature of the immersion heater, four sets of batch type anaerobic bioreactors were submerged in water heated to various temperatures, namely ambient, 35 °C, 45 °C and 55 °C. Ambient temperature means no heating was carried out and the temperature varied from 25 °C to 30 °C. Within each set of the temperature range, the anaerobic bioreactors were further distinguished by feeding with POME with original pH or modified pH. The pH modified POME is prepared by adding sodium bicarbonate or alternatively named as sodium hydrogen carbonate ( $\text{NaHCO}_3$ ) to the raw POME until the pH changes to around 6.7. In general, with the change of water bath temperature, namely ambient temperature, 35 °C, 45 °C and 55 °C, four anaerobic bioreactors which were feed by raw POME were denoted as A-4, B-4, C-4 and D-4 respectively while another four anaerobic bioreactors which were feed by pH modified POME were denoted as A-7, B-7, C-7 and D-7 respectively. After evaluating the performance of MBR system by modifying the operational temperature and pH value, the workability of adding MFC prior to MBR system in terms of the performance is tested. In this part of the study, POME was first feed into MFC to be treated and

then the supernatant is extracted and feed into AnMBRs as feedstock. There are two MFCs, both operated at ambient temperature but feed with POME of different pH as for the AnMBRs. The HRT and SRT for the anaerobic bioreactors and MFC were kept at 4 and 30 days respectively. The PAC content in the anaerobic bioreactors and MFC was kept at 5 g/L of the bioreactors volume. Replenishment of PAC was conducted correspond to the desludging volume assuming all the PAC was contented in the sludge. The operation conditions of this experiment such as SRT, HRT and PAC dosage were based on the finding of previous studies in optimizing the performance of the POME treatment as conducted by previous FYP students (Kong, 2017).

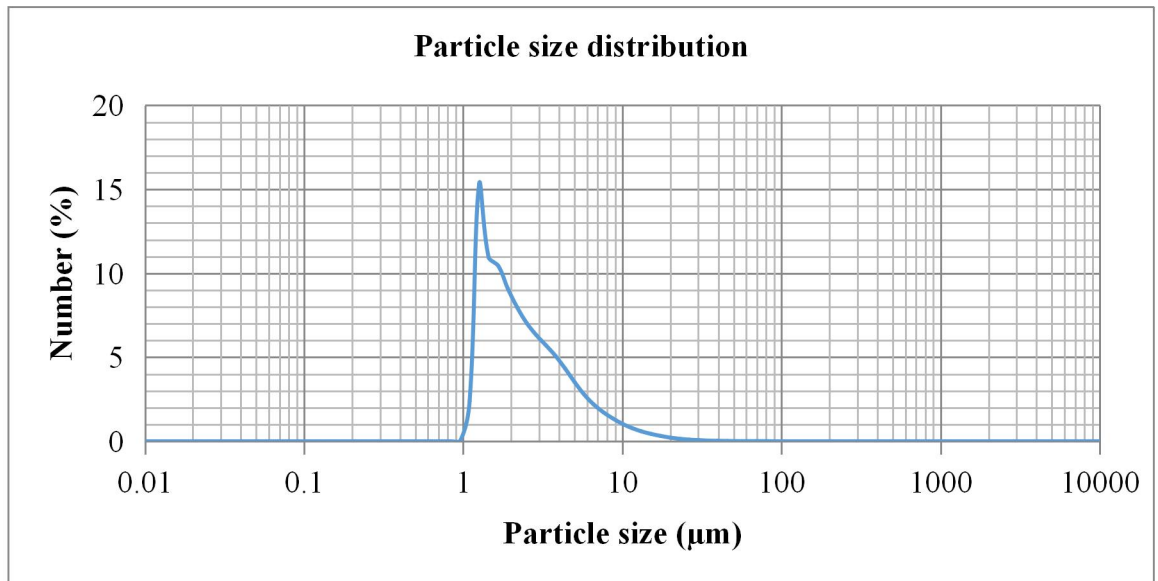
## 3.2 Sample Collection and Material Preparation

### 3.2.1 Powdered Activated Carbon (PAC)

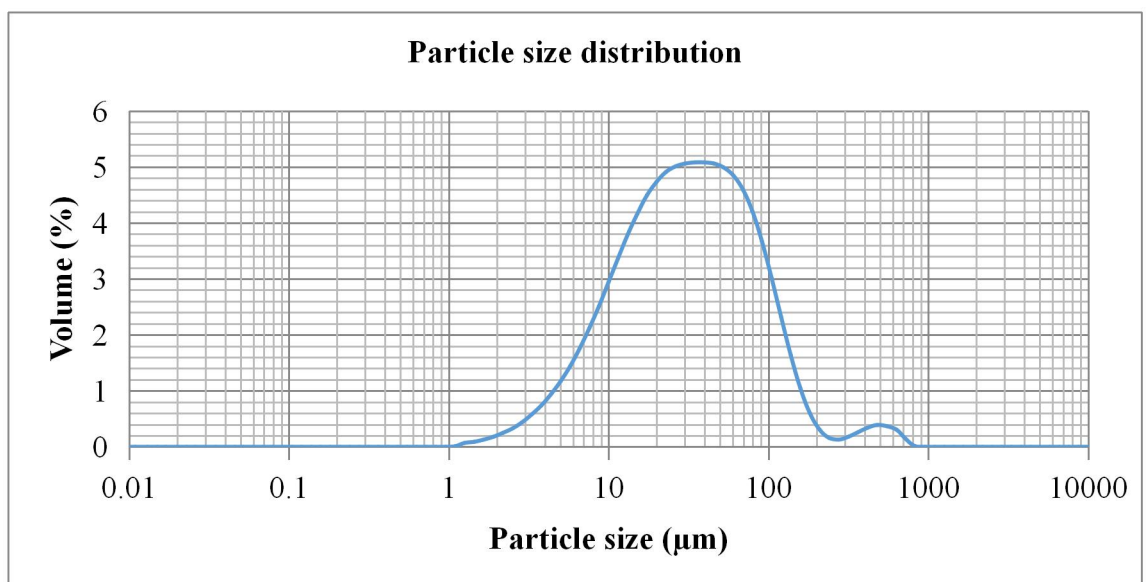
Extra pure Charcoal Activated Powder from Gene Chem Enterprise Inc. was used in this research to serve as PAC supplement for the AnMBRs. The specification of the PAC is listed in Table 3.1 while the particle size distribution of PAC based on number and volume distributions was displayed in Figures 3.2 and 3.3, respectively.

**Table 3.1: Specifications for PAC used throughout the experiment.**

Composition	Value
pH	4.7-7.5
Chloride (Cl)	0.10 %
Zinc (Zn)	0.10 %
Heavy metal (Pb)	0.01 %
Iron (Fe)	0.10 %
Soluble matter in ethanol	0.20 %
Soluble matter in hydrochloric acid	0.20 %
Sulfur compound (SO <sub>4</sub> )	0.15 %



**Figure 3.2: Particle size distribution of PAC based on number distribution.**



**Figure 3.3: Particle size distribution of PAC based on volume distribution.**

### 3.2.2 Palm Oil Mill Effluent and Sludge

The palm oil mill effluent and sludge subjected to this experiment were supplied by a palm oil mill located in Air Kuning, Perak known as Tian Siang Holdings Sdn. Bhd. The distance between the laboratory and this palm oil mill was 24.2 km away (31 minutes by car), while each trip took about two hours including the time

used for sample collection. The POME sample was collected from the sampling pipe right after the cooling pond. The POME sample was considered as raw POME as the POME was not undergone any treatment yet after discharged from the palm oil mill. The raw POME sample was filtered through a sieve with 0.053 mm mesh size to remove unwanted matters such as sand or bugs. Sludge from the desludging pipe of the sequencing batch reactor was collected. The sludge which looks like black slurry was the source of anaerobic bacteria required for the biodegradation process in this experiment.

### **3.3 Analytical methods**

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

MLSS and MLVSS concentrations were tested according to the procedures in 21st Edition of Standard Method. A glass microfiber filter AH-934 was placed into a crucible before heated at 550 °C in a muffle furnace for 15 minutes. Then, the heated crucible with filter paper was kept for cooling down in a desiccator for 20 minutes before weighing. The mass of crucible was measured by using M-power Analytical Balance AZ214. After that, 1mL of the sludge sample retrieved during desludging was dropped onto the filter paper and filtered by using vacuum suction pump. Next, the crucible with the filtered sample was heated at 105 °C for 2 hours and then placed into a desiccator again for 15 minutes. The crucible with the heated sample was weighted. The concentration of the MLSS was equal to the measured value minus the weight of crucible with plain filter paper. The sample was subsequently heated in the muffle furnace at 550 °C for 15 minutes. After cooling down for 15 minutes in the desiccator, the sample was weighed again and the weight loss of the sample after heated in the muffle furnace was the concentration of the MLVSS (Kong, 2017).

### 3.3.2 Chemical Oxygen Demand (COD)

The COD of feed-in POME and permeate from AnMBRs were analyzed in accordance with 5220 D Closed Reflux Colorimetric Standard Method, 21st Edition. Samples from raw POME, supernatant from MFC and anaerobic bioreactor were diluted with a dilution factor of 1 : 25 and then 2 ml of the diluted samples were added into their respective COD test kits including blank kit added with 2 mL of distilled water for calibration purpose. 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) at 150 °C for 2 hours. The samples were allowed to cool down after heating for 2 hours. The COD value of each sample was determined by utilizing HACH DR 6000 UV/VIS spectrophotometer. The blank kit was placed into the spectrophotometer for zeroing before testing the COD of other samples (Kong, 2017).

### 3.3.3 Polysaccharide

The polysaccharide concentration in feed-in POME, supernatant and permeate solution were measured via phenol-sulfuric acid method. A mixture solution containing 14 mL of phenol and 36 mL of distilled water was prepared. 1 mL of mixture solution was retrieved and added to the vial containing 1 mL of the undiluted sample, followed by 5 mL of 1 mol/L H<sub>2</sub>SO<sub>4</sub>. Due to the light-sensitive characteristic of phenol, the vial was wrapped with aluminium foil wrapper before the mixing of the solutions. After that, the samples were placed in Vortex Shaker at 1500 rpm for 15 seconds. The samples were then allowed to settle for 15 minutes. The concentration of polysaccharide was determined by utilizing HACH DR 6000 UV/VIS spectrophotometer (Kong, 2017).

### **3.3.4 Protein**

The concentration of protein in the feed-in POME, supernatant and permeate solution were determined via Bradford protein assay. The samples were diluted with the ratio of 1 : 2. 5 mL Bradford Reagent with bovine serum albumin (BSA) as standard was added to the test tube by using pipette followed by 0.5 mL of each diluted sample. After that, the samples were placed in Vortex Shaker at 1500 rpm for 15 seconds. The samples were then allowed to settle for 15 minutes. The protein concentration was determined by utilizing HACH DR 6000 UV/VIS spectrophotometer (Kong, 2017).

### **3.3.5 Particle Size Analysis**

Particle size distribution of the PAC used in this study and the biomass floc retrieved from the bioreactors were measured by using Malvern Mastersizer 2000 particle size analyser. The sample particle sizes were determined based on number and volume distributions (Kong, 2017).

### **3.3.6 pH Measurement**

The pH meter used to measure the pH value of the raw POME, supernatant from anaerobic bioreactors was Hanna HI-2550. Calibration of the pH meter was conducted by using the buffer solution of pH 4, 7 and 10 before testing to avoid unnecessary error. The pH electrode was rinsed with the cleaning agent and distilled water each time before testing (Kong, 2017).

### 3.3.7 Biogas Production

The biogas production from anaerobic bioreactors was measured by water displacement method. In total, there were eight biogas probes each consisted of an inverted 250 mL measuring cylinder connected to the reactors with silicone pipes. The inverted measuring cylinder was filled with water and then placed into water bath covers half of the cylinder body. The initial reading of the water level in the inverted cylinder was recorded. Biogas generated from the bioreactors would be transferred to the cylinder and the water level will slowly decrease. The final reading of the water level was recorded and the cylinders were refilled with water twice per day to prevent overflow of the biogas which will lead to inaccurate results (Chai, 2016).

### 3.3.8 Cross Flow Filtration

Figure 3.4 shows schematic diagram of cross flow filtration process. The supernatant retrieved from each bioreactor was added and allowed to flow in the cross-flow filtration system. Hybrid PES membrane cast formerly was used to filter the supernatant. This process was carried to complete the treatment mechanism of AnMBR in order to collect permeate samples and to test the trans-membrane pressure, TMP of the system. TMP is the pressure force required to push the fluid supernatant through the membrane module. When the filtration test started, two pressure transmitter, P1 and P2 were measured the TMP and the results were recorded in digital pressure data logger. The experiment stopped when the TMP reached 1 kPa and the test was repeated with other samples of the supernatant. As for the permeate collected, its COD, polysaccharide and protein concentration were analyzed to determine the overall performance of AnMBR (Kong, 2017).

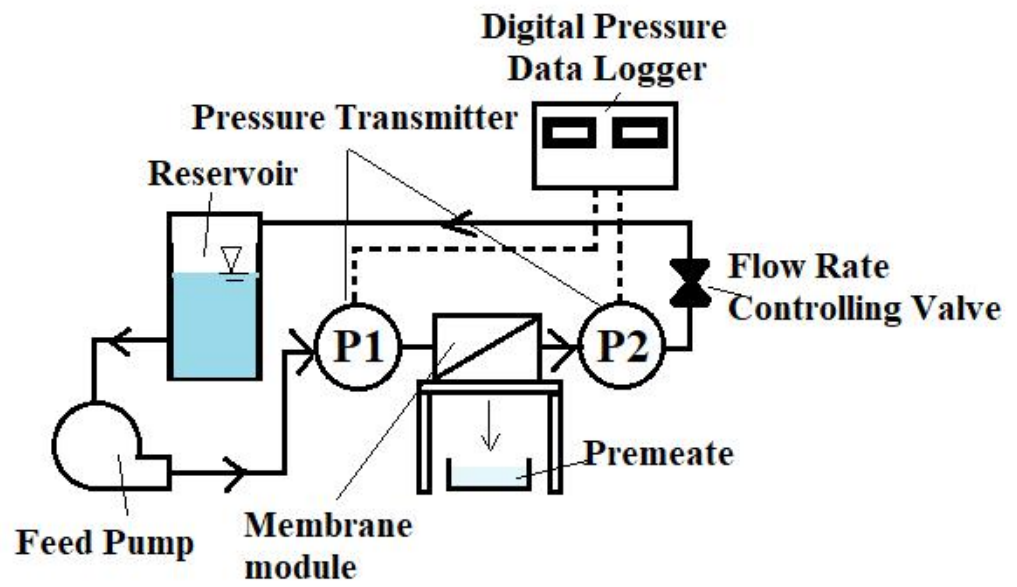


Figure 3.4: Schematic diagram of cross flow filtration process.

## CHAPTER 4

### RESULTS AND DISCUSSION

This chapter discussed the performance of hybrid anaerobic membrane bioreactor (AnMBRs) along with its interaction with the microbial fuel cell (MFC-AnMBRs). The bioreactors in this study were operated at various temperatures while being fed by POME of different pH (around 4.3 and 6.7). The performance of AnMBRs was assessed with regards to COD, polysaccharide, and protein removal efficiency, MLSS and MLVSS concentration, particle size distribution, membrane fouling rate and biogas production. While the change in performance of anaerobic membrane bioreactor after being incorporated with MFC was also assessed regarding COD, polysaccharide, and protein removal efficiency, as well as membrane fouling rate.

#### **4.1 Assessment of Performance of Anaerobic Membrane Bioreactors of Different Operational Temperatures and pH Values**

In this study, four batches of hybrid anaerobic bioreactors were set up under different operating temperatures, namely ambient, 35 °C, 45 °C and 55 °C which were denoted as A-4, B-4, C-4 and D-4 respectively. A-4, B-4 and C-4 were cultivated in the mesophilic condition while the cultivation of D-4 fell under the thermophilic condition. In order to evaluate the effect of operational pH on the performance of the bioreactors, sodium hydrogen carbonate ( $\text{NaHCO}_3$ ) also known as baking soda was added to the raw POME to modify the pH of the

feed-in POME to around 6.7. Reactors A7, B7, C7 and D7 were feed with pH modified raw POME while reactor A4, B4, C4 and D4 were fed with raw POME with its original pH of around 4.3. The supernatant discharged from each bioreactor was retrieved to undergo cross-flow filtration process. After that, permeate solutions from each bioreactor were collected tested in terms of COD, polysaccharide and protein removal efficiency. Figure 4.1 shows the COD removal efficiency of anaerobic membrane bioreactors operated under different temperatures and pH. The combination between the bioreactors and the membrane filtration system was regarded as AnMBRs and their performances in treating palm oil mill effluent were studied and tabulated in Table 4.1.

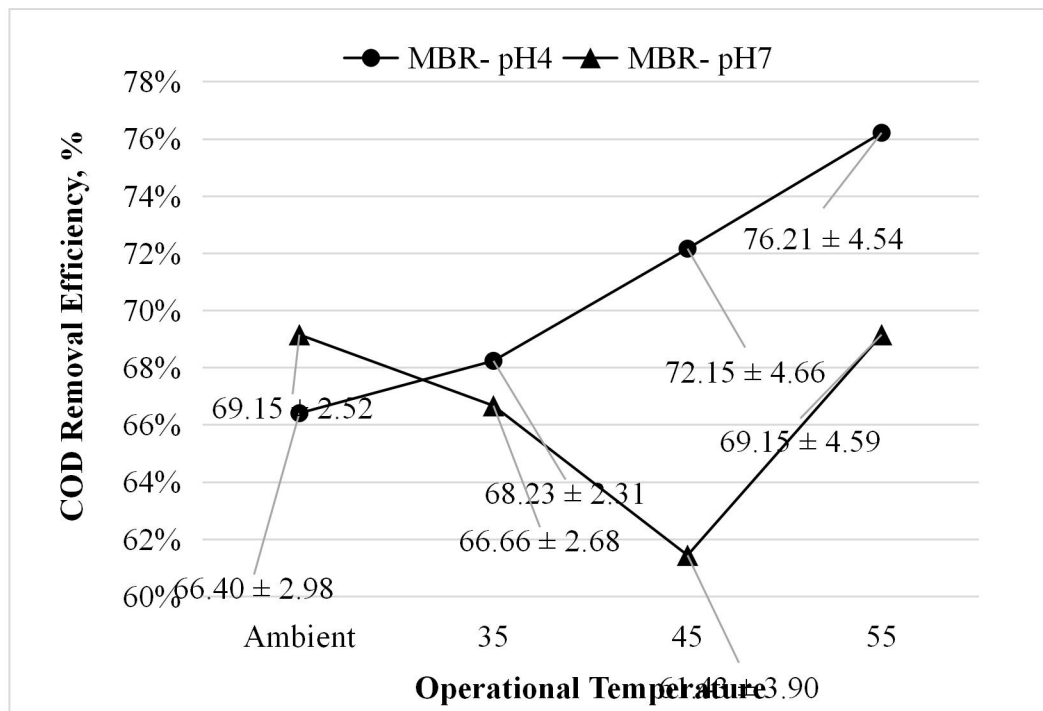
#### **4.1.1 Effect of Operational Temperature and pH in COD Removal**

Based on Figure 4.1, the COD removal efficiency for AnMBRs which were fed by raw POME without pH modification increased with the increment of operation temperature from ambient (25 °C to 30 °C) to 55 °C. Among the AnMBRs which were fed by raw POME without pH modification ( $\approx$ pH 4.3), the AnMBR under the operational temperature of 55 °C (D-4) showed the highest removal efficiency while the AnMBR operated at ambient temperature (A-4) showed the lowest treatment efficiency. The COD removal efficiencies for D-4 and A-4 were 76.21 %  $\pm$  4.54 % and 66.40 %  $\pm$  2.98 % respectively.

The performance of the anaerobic process is highly affected by the operational temperature of the bioreactor. Currently, mesophilic (35 - 40 °C) condition and thermophilic (55 - 70 °C) condition are the two common temperature regimes being used in conventional anaerobic digestion (Choong, Chou and Norli, 2017). According to Mahmud, Jahim and Abdul (2017), raw POME freshly discharged from the palm oil mill at a high temperature of about 80 - 90 °C is more suitable to be treated at the thermophilic condition. Besides that, anaerobic digestion of POME under thermophilic condition has been frequently reported to have higher substrate degradation and COD removal, a capability to be operated at high organic loading rate (OLR) and larger biogas production.

**Table 4.1: Performance of anaerobic membrane bioreactors of Different Operational Temperatures and pH Values.**

<b>Parameter</b>				
Temperature, °C	ambient	35	45	55
Bioreactor volume, mL	1000	1000	1000	1000
HRT, days	4	4	4	4
SRT, days	30	30	30	30
PAC dosage, g/L	5	5	5	5
PAC size, D <sub>50</sub> (volume), μm	33.53 ± 0.42	33.53 ± 0.42	33.53 ± 0.42	33.53 ± 0.42
Feed-in POME COD, mg/L	54500 ± 8069	54500 ± 8069	54500 ± 8069	54500 ± 8069
	<b>A-4</b>	<b>B-4</b>	<b>C-4</b>	<b>D-4</b>
Feed-in POME pH	4.34 ± 0.5	4.34 ± 0.5	4.34 ± 0.5	4.34 ± 0.5
Supernatant pH	4.82 ± 0.08	4.86 ± 0.08	4.82 ± 0.07	4.84 ± 0.12
COD of permeate, mg/L	18279 ± 3788	17304 ± 3886	15146 ± 5210	12938 ± 4060
Removal efficiency of COD, %	66.40 ± 2.98	68.23 ± 2.31	72.15 ± 4.66	76.21 ± 4.54
	<b>A-7</b>	<b>B-7</b>	<b>C-7</b>	<b>D-7</b>
Feed-in POME pH	6.70 ± 0.1	6.70 ± 0.1	6.70 ± 0.1	6.70 ± 0.1
Supernatant pH	6.80 ± 0.15	6.87 ± 0.14	6.93 ± 0.15	7.09 ± 0.14
COD of permeate, mg/L	16781 ± 3872	18089 ± 3527	20988 ± 4068	16797 ± 4325
Removal efficiency of COD, %	69.15 ± 2.52	66.66 ± 2.68	61.43 ± 3.90	69.15 ± 4.59



**Figure 4.1: COD removal efficiency of anaerobic membrane bioreactors of Different Operational Temperatures and pH Values.**

Although the stability of thermophilic anaerobic digestion is often being questioned due to the prone of volatile fatty acid accumulation, this defective condition was not obviously shown in this study as the performance of D-4 was relatively good compared to other AnMBRs (Choong, Chou and Norli, 2017). Although the thermophilic condition may not seem promising, anaerobic digestion under thermophilic temperature is known to have several advantages, such as improved filtration, lesser microbial washout and higher disinfection capability compared to mesophilic reaction (Meabe et al., 2013; Choong, Chou and Norli, 2017). In addition, the process of hydrolysis which involves the disruption and solubilization of complex organic substances in POME to soluble substrates is inhibited by anaerobic digestion at low temperature (Martinez-Sosa et al., 2011).

Operation of anaerobic digestion under optimal pH is necessary as the methanogens in anaerobic digestion are vulnerable to the surrounding pH value and only function well at pH 6.8 to 7.4. When the surrounding pH deviates too much from the optimum pH, the microbial growth of methanogens will be inhibited and the conversion of acids into methane will be ceased (Tan et al., 2017; Naik et al., 2014). Contradictorily, methanogenesis can only be carried out after acidogenesis which

generates the substrate volatile fatty acids (VFAs) which contribute to the reduction in digester pH. Hence, sodium hydrogen carbonate ( $\text{NaHCO}_3$ ) also known as baking soda was added into the feed-in POME to provide adequate alkalinity in AnMBRs with controlled pH, namely A-7, B-7, C-7 and D-7 to resist the pH change caused by the presence of VFAs (Choong, Chou and Norli, 2017). Regrettably, the performance of the AnMBRs with controlled pH around 6.7 does not show a significant improvement in terms of COD removal efficiency as shown in Figure 4.1. A-7 which is operated at ambient temperature is the only AnMBR which shows an improvement upon the modification of pH, with the COD removal efficiency of  $69.15 \% \pm 2.52 \%$ .

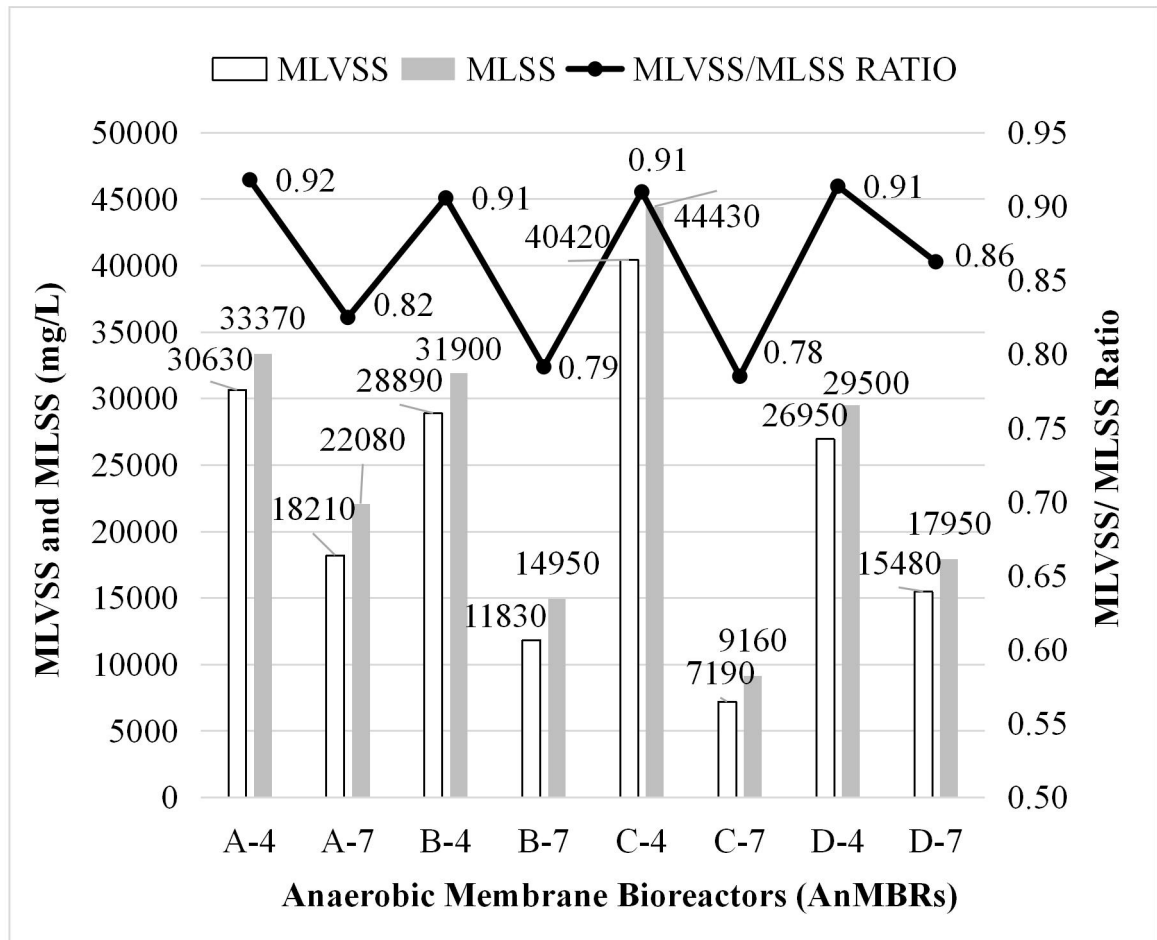
The deterioration of COD removal efficiency even though optimum pH is maintained within these AnMBR may be due to the generation of carbon dioxide gas from the reaction between  $\text{NaHCO}_3$  and acetic acid in the bioreactors (Helmenstine, 2017). Through acetogenesis which is one of the stages of anaerobic digestion, acetic acid was generated and accumulated in the bioreactors (Poh & Chong, 2009; Ohimain & Izah, 2017). Along with the feed-in POME,  $\text{NaHCO}_3$  was added into the bioreactors then reacts with acetic acid and formed a huge amount of brownish foam occupied the entire space above the supernatant of the bioreactors. The brownish foam may block the biogas outlet and further increase the pressure in the bioreactors. According to Ohimain & Izah (2017), high pressure in the anaerobic digester applied stress to the methanogens causing the reduction of growth rate and population hence resulting to the lower treatment efficiencies among the AnMBRs with controlled pH.

#### **4.1.2 Assessment of MLSS and MLVSS Concentration in Anaerobic Membrane Bioreactors of Different Operational Temperatures and pH Values**

Activated sludge consists of organic and inorganic matter, while the quantity of organic matter consequently reveals the amount of living microbes in the sludge (Fan et al., 2015). Microorganisms and non-viable organic materials are the general content of MLSS in activated sludge and the MLSS concentration is commonly used to correlate with the abundances of particular microorganisms (Jo et al., 2016). MLVSS is the particulate solid concentration which represents the concentration of biomass in the sludge including non-microbial organic matter and cellular debris (Bitton, 1998). MLVSS/MLSS ratio is a common indicator used to evaluate the sludge activity (Fan et al., 2015). The MLSS, MLVSS and MLVSS/MLSS ratio were determined and tabulated in Figure 4.2.

According to Bitton (1998), typical MLVSS/MLSS ratio in activated sludge falls in the range between 0.65 and 0.90. Based on Figure 4.2, the MLVSS/MLSS ratios of AnMBRs without pH modification were significantly higher than the AnMBRs fed with pH controlled POME while these ratios were also slightly exceeded the upper limit of the range of 0.65- 0.90.

As above mentioned, the MLVSS content represents the biomass concentration in the anaerobic digester which affects the performance of the degradation process of the activated sludge. As shown in Figure 4.2, the MLVSS content of AnMBRs operated with controlled pH, A-7, B-7, C-7 and D-7 were 18 210 mg/L, 11 830 mg/L, 7190 mg/L and 15 480 mg/L respectively. These MLVSS contents correspond to their respective COD removal efficiency of  $69.15 \pm 2.52$  %,  $66.66 \pm 2.68$  %,  $61.43 \pm 3.90$  % and  $69.15 \pm 4.59$  % thus coherent to the fact that removal of COD was increased with increase in MLVSS (Kumar et al., 2014). However, the MLVSS contents of AnMBRs without pH modification do not show any correlation to their respective COD removal efficiency. This may be due to the different floc size of the activated sludge which will also affect the performance of anaerobic digestion.



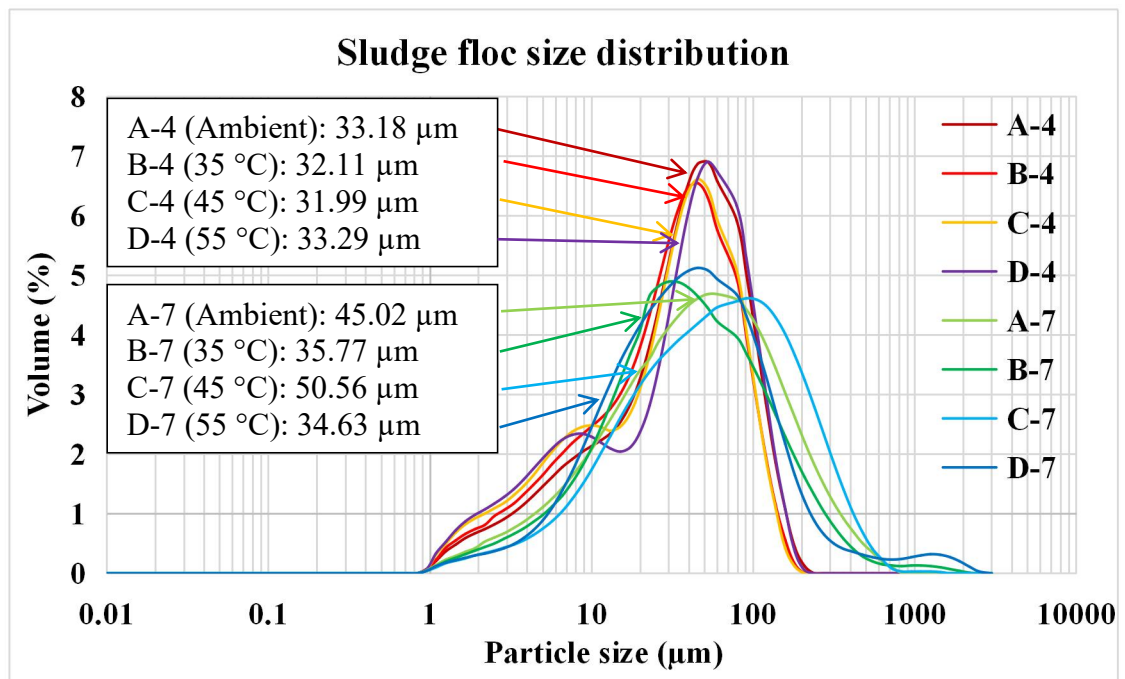
**Figure 4.2: Comparison of MLSS and MLVSS concentration in AnMBRs of Different Operational Temperatures and pH Values.**

#### **4.1.3 Effect of Operational Temperature and pH on Microbial Floc Size in Hybrid Membrane Anaerobic Bioreactors**

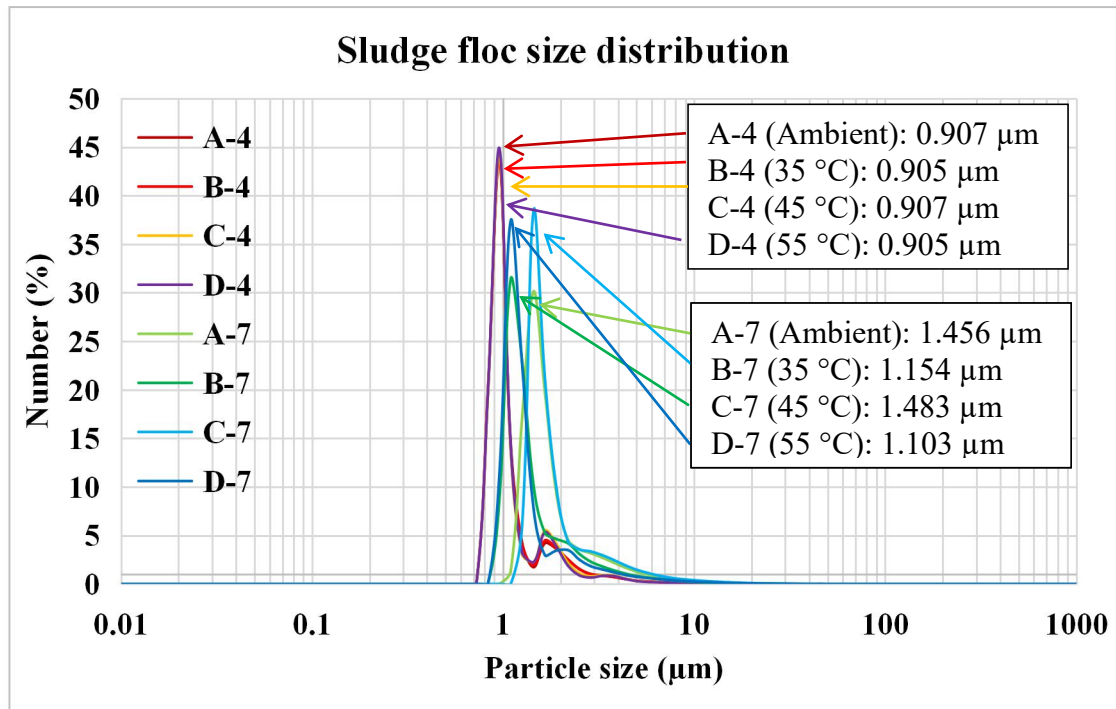
Sludge flocs make up a large proportion of biomass while the properties of sludge flocs influence the membrane fouling capability in MBRs (Shen et al., 2015). As an important indicator of the membrane fouling rate of MBRs, the particle size distribution of sludge flocs based on volume and number distributions were examined and shown in Figures 4.3 and 4.4.

The higher COD removal efficiency in all the AnMBRs under pH 4.3 related to the smaller floc size in the activated sludge content as shown in Figures 4.3 and

4.4. According to Naik et al. (2014), microorganisms in smaller floc have more surface area to undergo biological activity which then enhanced the biodegradation process in the anaerobic digestion. Among all the AnMBRs, C-7 which had the lowest treatment efficiency also having the biggest floc size in both the volume and number. The larger floc size for the AnMBRs with controlled pH may be due to the pH variation in the activated sludge which causes the flocculation and adhesion phenomena thus modifies the cell morphology and structure (Yu & Fang, 2003).



**Figure 4.3: Sludge floc sizes distribution of membrane anaerobic bioreactors based on volume distribution.**



**Figure 4.4: Sludge floc sizes distribution of membrane anaerobic bioreactors based on number distribution.**

#### **4.1.4 Membrane Fouling Control in Anaerobic Membrane Bioreactors of Different Operational Temperatures and pH Values**

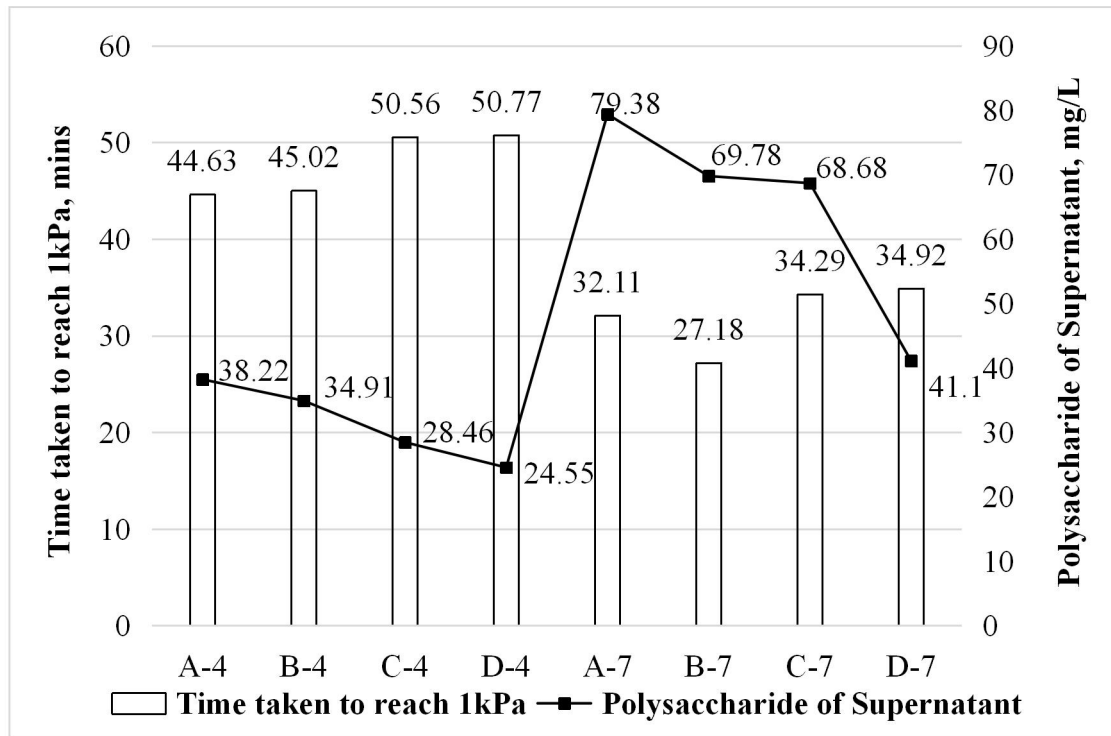
In this research, the membrane fouling rate was identified by the time taken for the pressure in the membrane filtration system to reach 1 kPa with a fixed flux of about 5 L/(m<sup>2</sup>.h). The results were tabulated in Table 4.2 and plotted in Figure 4.5 along with the concentrations of polysaccharide and protein of the supernatant and the removal efficiency of polysaccharide and protein. As shown in Figure 4.5, the time taken to reach the threshold, 1 kPa was longer when the concentration of the polysaccharide in the supernatant is lower. Because of its large size and gelling characteristics, polysaccharides may lead to higher fouling tendencies. The multiple blocks in polysaccharides promote gelation through cross-linked chains of polysaccharides. The membrane surface may be attached with thin, impermeable gels formed by polysaccharides thus severely increase filtration resistance (Meng et al., 2017).

According to Figure 4.5, the results of A-7 and C-7 biased to the trend as abovementioned. This may be because of the larger floc size in the biomass of A-7 and

C-7 which decreased the fouling propensity of these two AnMBRs. The reduction of floc size considerably rise the attractive specific interaction energy causing smaller flocs to increase susceptibility to adhere to the membrane surface. According to Shen et al. (2015), smaller flocs form denser cake layer compared to the larger flocs, which associated with higher specific cake resistance.

**Table 4.2: Performance of anaerobic membrane bioreactors of Different Operational Temperatures and pH Values against membrane fouling.**

Parameter	A-4	B-4	C-4	D-4
Polysaccharide of Supernatant, mg/L	38.22 ± 9.07	34.91 ± 5.38	28.46 ± 7.67	24.55 ± 5.25
Protein in Supernatant, mg/L	2213 ± 283	2059 ± 316	1866 ± 317	1823 ± 202
Removal efficiency of polysaccharide, %	97.35 ± 1.96	95.04 ± 3.25	97.54 ± 1.65	96.76 ± 3.14
Removal efficiency of protein, %	97.35 ± 1.55	92.57 ± 1.78	96.57 ± 1.8	98.51 ± 1.19
Time taken to reach 1 kPa, mins	44.63 ± 4.03	45.02 ± 6.24	50.56 ± 2.16	50.77 ± 6.86
	A-7	B-7	C-7	D-7
Polysaccharide of Supernatant, mg/L	79.38 ± 12.94	69.78 ± 14.73	68.68 ± 18.88	41.10 ± 7.41
Protein in Supernatant, mg/L	5214 ± 751	5125 ± 664	5064 ± 596	4855 ± 768
Removal efficiency of polysaccharide, %	78.53 ± 1.32	82.96 ± 2.63	85.28 ± 0.84	88.50 ± 1.72
Removal efficiency of protein, %	72.55 ± 3.86	76.78 ± 3.60	66.58 ± 3.06	70.98 ± 3.66
Time taken to reach 1 kPa, mins	32.11 ± 3.85	27.18 ± 3.17	34.29 ± 3.38	34.92 ± 3.88



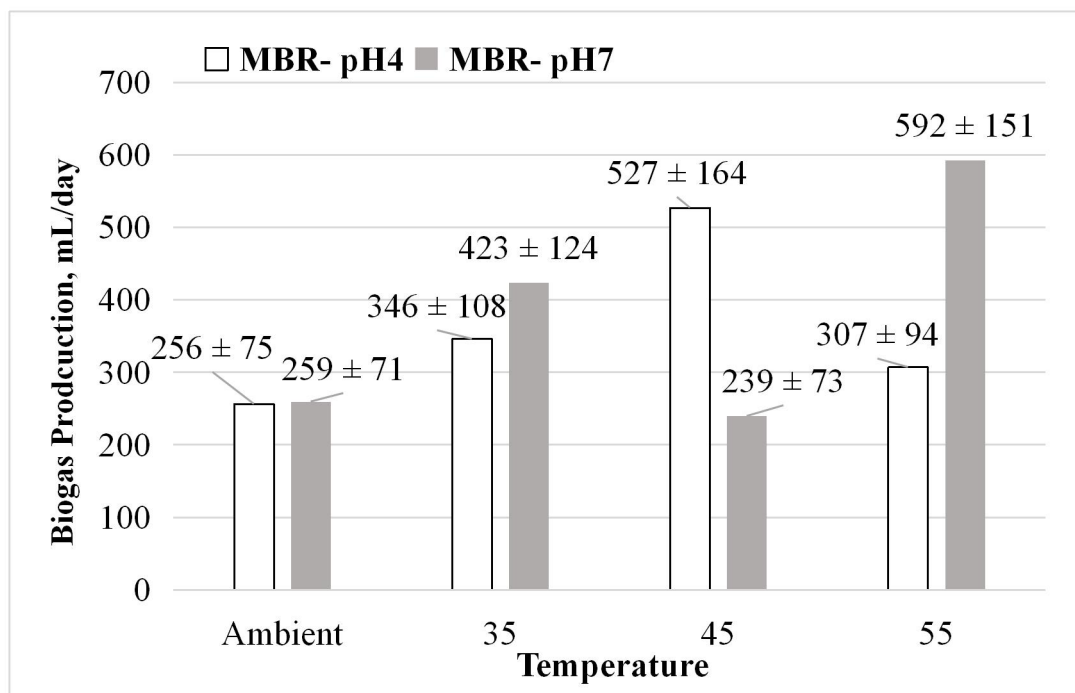
**Figure 4.5: Performance of anaerobic membrane bioreactors of Different Operational Temperatures and pH Values against membrane fouling.**

#### **4.1.5 Comparison of Biogas Production in Anaerobic Membrane Bioreactors of Different Operational Temperatures and pH Values**

During anaerobic digestion, anaerobic microbes convert organic matter in POME into biogas through anaerobic biodegradation process (Chen et al., 2016; Zhang, Hu and Lee, 2016). In this study, biogas production from the AnMBRs was measured and plotted in Figure 4.6. The AnMBR with the operational temperature of 55 °C (D-7) which had its pH value controlled around 6.7 achieved the highest biogas production which was  $592 \pm 151$  mL/day. Performance of anaerobic digestion was susceptible to the operational temperature and pH value. According to Zhou et al. (2016), the organic matter degradation rate and biogas production were the highest at pH 7. At pH 7, methanogenic bacteria were more active to degrade VFAs to produce methane. In addition, a suitable increment of operational temperature can accelerate hydrolysis of cellulose and hemicellulose into comparatively biodegradable components. Under higher temperature, the link between polysaccharide and lignin

would break and make the degradation of cellulose and hemicellulose easier for the bacteria. As such, the rise of temperature in the bioreactors improves biodegradability and biogas production (Liu et al., 2017).

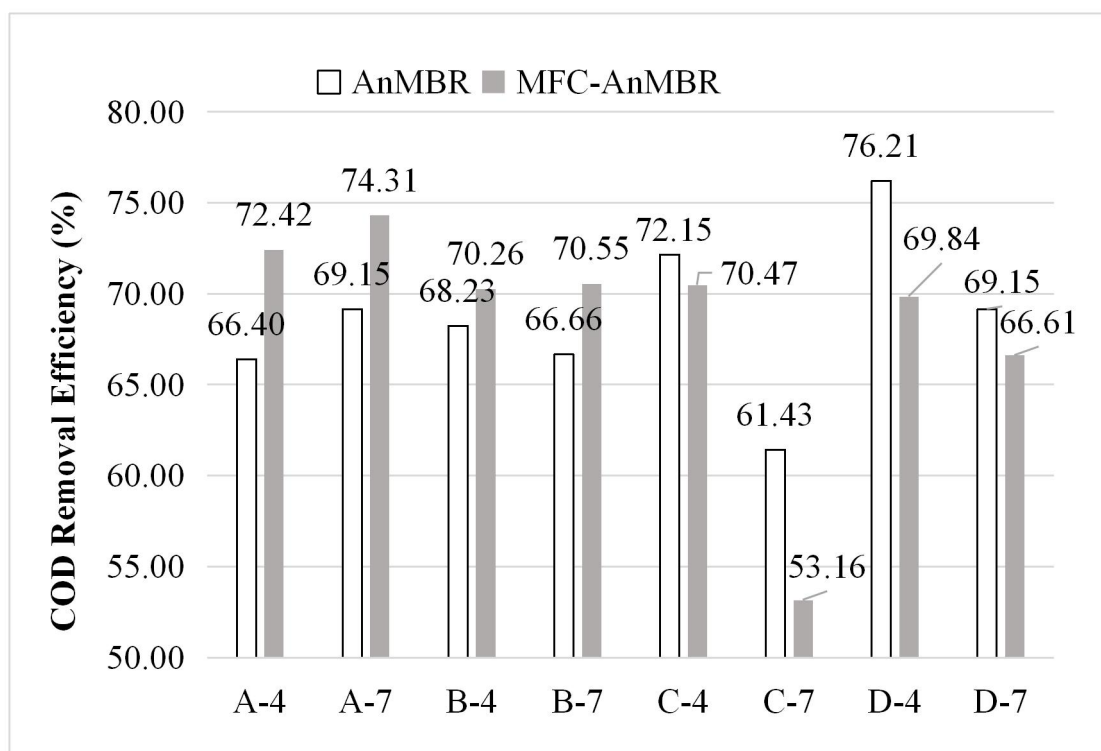
Based on Figure 4.6, the biogas production among the AnMBRs follows the trend proposed above except for C-7 (45 °C) and D-4 (55 °C) which showed significantly lower biogas production. For C-7, the reason behind the inhibition of biogas production was the excessive pressure created due to the blockage of the biogas outlet which causes reduction of treatment efficiency and bacteria growth rate. In addition, adjusted pH of the anaerobic digestion in the AnMBRs may cause different effects on the bacteria and archaea co-exist in the bioreactors which may lead to variations to the common trend (Zhou et al., 2016). Temperature change could bring out changes in the microbial communities in the digestion. According to Tian et al. (2018), the metabolic pathway of the biomass changes from mesophilic to thermophilic above 45 °C. Hence, the productivity of anaerobic digestion was relatively stable at mesophilic regime compared to the thermophilic regime (above 55 °C). In conclusion, operations of AnMBRs under optimum pH (~7) improves biogas production.



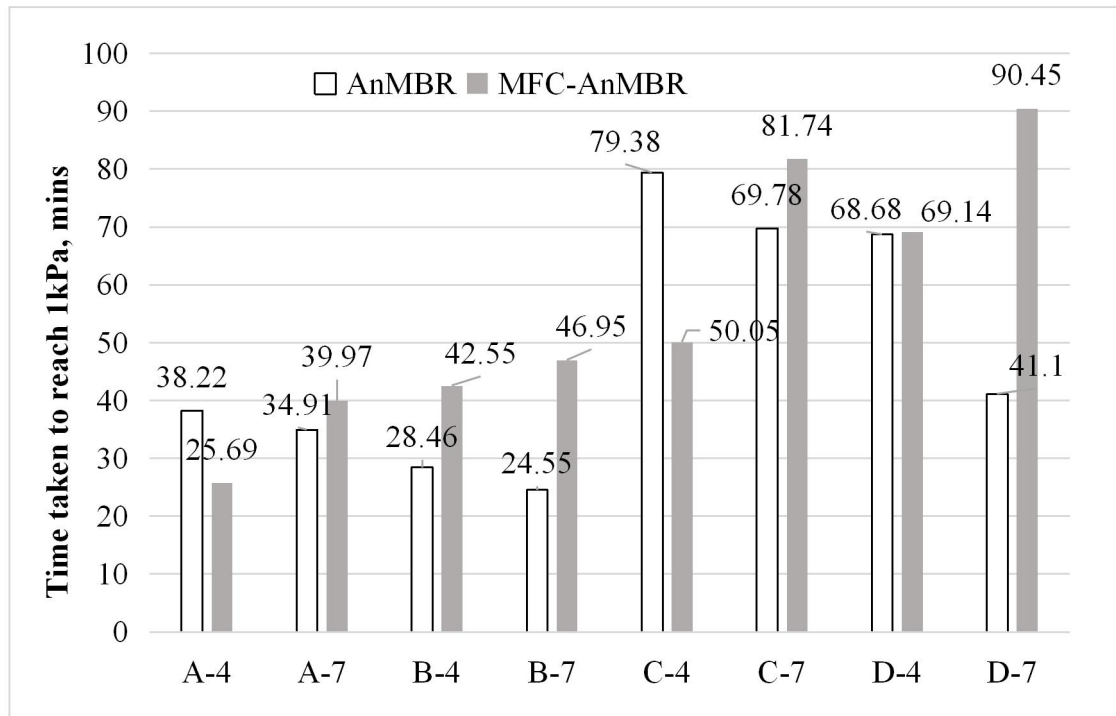
**Figure 4.6: Comparison of biogas production in anaerobic membrane bioreactors of Different Operational Temperatures and pH Values.**

#### 4.1.6 Assessment of Performance of Anaerobic Membrane Bioreactors Integrated with MFC

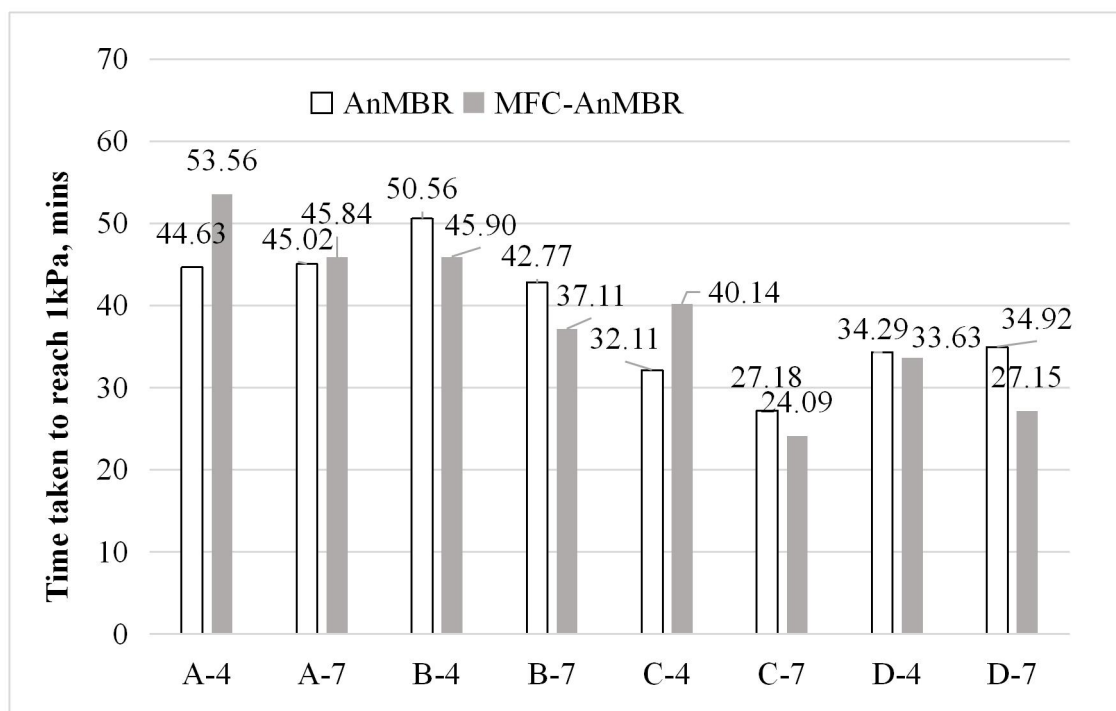
The hybrid anaerobic bioreactors were incorporated with MFC where the effluent from MFC was used to feed into anaerobic membrane bioreactors in order to determine the performance of the combined system. The comparison between AnMBRs and MFC-AnMBRs in terms of COD removal efficiencies, polysaccharide concentration before membrane filtration process and performances of membrane fouling control were plotted in Figures 4.7, 4.8 and 4.9 respectively. In this study, the integration of MFC into the AnMBRs did not contribute to much improvement but also shows declination as regards to COD removal efficiency and membrane fouling control. The declination of the performance of the integrated system was due to the sensitivity of anaerobic microorganisms to the environmental conditions such as the change in feedstock from raw POME to supernatant of MFC. The changes of the feedstock for the AnMBRs takes time to stabilize hence the performance of MFC-AnMBRs may be affected during this start-up period as a stability of microbes' community is yet achieved.



**Figure 4.7: Comparisons of COD removal efficiencies in AnMBRs and MFC-AnMBRs.**



**Figure 4.8: Comparison of polysaccharide concentration in supernatant of AnMBRs and MFC-AnMBRs before cross flow filtration.**



**Figure 4.9: Performance of AnMBRs and MFC-AnMBRs towards membrane fouling control.**

## 4.2 Economic Appraisal

Formally, the major concern which inhibit the widespread of membrane bioreactors was the capital expenditure (CAPEX) which includes the costly membrane modules. Although membrane costs have dropped over the past few years, capital expenditure (CAPEX) and operational expenditure (OPEX) which associated with membrane filtration process still depreciate membrane bioreactors eventually. Most energy is consumed by membrane tank biogas recycling blower or membrane tank sludge feeding pump representing up to 75 % of the total energy demand in AnMBR (Dvořák et al., 2016). Recent studies had showed the overall cost benefits of MBR over conventional activated sludge (CAS) technology despite the higher OPEX for the MBR based on an immersed hollow fibre (iHF) membrane. Through determination of the net present value (NPV) to account for all costs over the full life of the installation, that the MBR offered an overall cost benefit through the substantially reduced CAPEX for circumstances where land costs were high and enhanced nutrient removal was required. In general, there have been very few studies that have calculated the costs associated with operating AnMBRs, particularly with those that treat industrial wastewaters (Dvořák et al., 2016). Table 4.3 and 4.4 show the costing for this final year project which provides the basic cost estimation for industrial scale anaerobic membrane bioreactor.

**Table 4.3: Final year project costing.**

<b>Material</b>	<b>Cost (RM)</b>	<b>Operational Requirement</b>	<b>Cost (RM)</b>
PAC (1 kg)	3.87	Electricity (Heating)	0.78
PES membrane (100 units)	69.66		
Sodium Bicarbonate Powder (2 kg)	1.55		
<b>Sub-total (RM)</b>	<b>75.08</b>		<b>0.78</b>
<b>Total (RM)</b>			<b>75.86</b>

**Table 4.4: Calculation of electricity bill for heating.**

<b>AnMBRs</b>	<b>Ambient</b>	<b>35 °C</b>	<b>45 °C</b>	<b>55 °C</b>
C <sub>p</sub> , Specific heat of POME (J/kg °C)	4374.89 (bin Khalid, Lin and Fei, 1998)			
ΔT, Temperature difference (°C)	-	10	20	30
E, Heat Energy required (kJ/kg POME)	-	43.75	87.50	131.25
*Let 1 kWh = 1000 W x 3600 s = 3.6 MJ				
Energy factor of the heating elements	0.5			
E, Heat Energy required (kWh/kg POME)	-	0.02431	0.0486	0.0729
Medium voltage general industrial tariff (sen/ kWh)	33.7 (Tenaga Nasional Berhad, 2017)			
Heating cost (sen/kg POME)	-	0.82	1.64	2.46
Density of POME (kg/m <sup>3</sup> )	700 (Hassan, Kee and Al-Kayiem, 2013)			
Hydraulic retention time (days)	4			
AnMBRs size (m <sup>3</sup> )	1x10 <sup>-3</sup>			
Flow rate ( m <sup>3</sup> /day)	2.5x10 <sup>-4</sup>			
Flow rate (kg/ day)	0.175			
Heating cost (sen/ day)	-	0.144	0.287	0.431
Experiment duration (days)	90			
Subtotal cost for heating (sen)	-	12.96	25.92	38.88
<b>Total cost for heating (RM)</b>	<b>RM 0.78</b>			

## CHAPTER 5

### CONCLUSION AND RECOMMENDATIONS

#### 5.1 Conclusion

The AnMBR which operated under thermophilic condition, 55 °C and without pH modification, D-4 shows the best treatment performance among others AnMBRs in terms of COD removal efficiency. Anaerobic digestion of POME under thermophilic condition have been frequently reported to have higher substrate degradation and COD removal. The increment of operational temperature increases the biomass growth rate which subsequently accelerates the process of hydrolysis which involves the disruption and solubilization of complex organic substances in POME to soluble substrates. Surprisingly, the performance of the AnMBRs with controlled pH around 6.7 does not show a significant improvement as regards to COD removal efficiency. The deterioration of COD removal efficiency even though optimum pH is maintained within these AnMBR may be due to increase of pressure within the bioreactors after an unexpected production of foam clogging the biogas outlets. The increases of MLVSS contents in the AnMBRs leads to the better removal efficiency of COD as the MLVSS is directly proportional to the microbial growth rate. The concentration of the polysaccharide in the AnMBRs strongly affects the membrane fouling capability. Because of its large size and gelling properties, polysaccharides may lead to higher fouling tendencies. The multiple blocks in polysaccharides promote gelation through cross-linked chains of polysaccharides. Thin impermeable gels were formed and attached on the membrane surface thus severely increase filtration resistance. Performance of anaerobic digestion was susceptible to the operational temperature and pH value. The organic matter degradation rate and biogas

production were the highest at pH 7. At pH 7, methanogenic bacteria were more active to degrade VFAs to produce methane. Besides, a suitable increment of operational temperature can accelerate hydrolysis of cellulose and hemicellulose into comparatively biodegradable components. In this study, the integration of MFC into the AnMBRs did not contribute to much improvement but also shows declination as regards to COD removal efficiency and membrane fouling control. The declination of the performance of the integrated system was due to the sensitivity of anaerobic microorganisms to the environmental conditions. The introduction of foreign species into the AnMBRs takes time to stabilize hence the performance of MFC-AnMBRs may be affected during this start-up period for a newly formed microbes community.

## 5.2 Recommendations

The modification of the pH value to around 7 as well as the integration of MFC were proven to improve the performance of AnMBRs by previous researches. However, there were some unforeseen factors which affects the results of this study to comply with the following trend. Some workable recommendations are suggested to enhance the performance of AnMBR which are shown as follows:

- i) Enclosed anaerobic bioreactor should be made bigger in consideration to the foam produced while sodium bicarbonate was added into the system. The biogas pipe should not be clogged by the foam in order to obtain more accurate results.
- ii) Slow stirring should be applied to maintain homogeneous mix in the bioreactor all the time. Vigorous stirring should be avoided to prevent obstruction of biofloc formation.
- iii) Sufficient start-up period should be provided in order to obtain accurate and precise data about the performance of the anaerobic bioreactor. The organic loading rate of the bioreactors should be increased steadily from a relative lower amount to prevent deterioration of the performance.

## REFERENCES

- Aghamohammadi, N., bin Abdul Aziz, H., Isa, M.H. and Zinatizadeh, A.A., 2007. Powdered activated carbon augmented activated sludge process for treatment of semi-aerobic landfill leachate using response surface methodology. *Bioresource Technology*, 98(18), pp.3570-3578.
- Ahmad, A.L., Chong, M.F., Bhatia, S. and Ismail, S., 2006. Drinking water reclamation from palm oil mill effluent (POME) using membrane technology. *Desalination*, 191(1-3), pp.35-44.
- Ahmed, Y., Yaakob, Z., Akhtar, P. and Sopian, K., 2015. Production of biogas and performance evaluation of existing treatment processes in palm oil mill effluent (POME). *Renewable and Sustainable Energy Reviews*, 42, pp. 1260-1278.
- Aida Isma, M.I., Idris, A., Omar, R. and Putri Razreena, A.R., 2014. Effects of SRT and HRT on Treatment Performance of MBR and Membrane Fouling. *International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering*, 8(6) pp. 488-492.
- bin Khalid, K., Lin, E.S.M. and Fei, C.K., Microwave Drying of Palm Oil Mill Effluent.
- BioEnergy Consult, 2015. *Properties and uses of POME*. [online] Available at: <<http://www.bioenergyconsult.com/tag/what-is-pome/>> [Accessed 23 June 2016].
- Bitton, G., 1998. *Formula handbook for environmental engineers and scientists*. [e-book] Canada: Wiley. Available at: Google Books <[https://books.google.com.my/books?id=7PDS6jb8XtkC&pg=PA166&lpg=PA166&dq=ratio+of+mlvss+to+mlss&source=bl&ots=Q-kpHf5czH&sig=BOLIXagsQn1qKG\\_62364OQqZEcM&hl=en&sa=X&ved=0ahUKEwjV-rfggfSAhURSo8KHWSJBXIQ6AEIbTAQ#v=onepage&q=ratio%20of%20mlvss%20to%20mlss&f=false](https://books.google.com.my/books?id=7PDS6jb8XtkC&pg=PA166&lpg=PA166&dq=ratio+of+mlvss+to+mlss&source=bl&ots=Q-kpHf5czH&sig=BOLIXagsQn1qKG_62364OQqZEcM&hl=en&sa=X&ved=0ahUKEwjV-rfggfSAhURSo8KHWSJBXIQ6AEIbTAQ#v=onepage&q=ratio%20of%20mlvss%20to%20mlss&f=false)> [Accessed 28 March 2017].
- Chai, H.Y., 2016. Performance Of Anaerobic Hybrid Membrane Bioreactors Incorporated With Different Sizes Of Powdered Activated Carbon And Biogas Production In Treating Palm Oil Mill Effluent.
- Chen, C., Guo, W., Ngo, H., Lee, D., Tung, K., Jin, P., Wang, J. and Wu, Y., 2016. Challenges in biogas production from anaerobic membrane bioreactors. *Renewable Energy*, 98 (2016), pp. 1-15.

- Chen, C., Guo, W., Ngo, H.H., Chang, S.W., Nguyen, D.D., Nguyen, P.D., Bui, X.T. and Wu, Y., 2017. Impact of reactor configurations on the performance of a granular anaerobic membrane bioreactor for municipal wastewater treatment. *International Biodeterioration & Biodegradation*, 121, pp.131-138.
- Choong, Y.Y., Chou, K.W. and Norli, I., 2017. Strategies for improving biogas production of palm oil mill effluent (POME) anaerobic digestion: A critical review. *Renewable and Sustainable Energy Reviews*.
- Deng, L., Guo, W., Ngo, H.H., Du, B., Wei, Q., Tran, N.H., Nguyen, N.C., Chen, S. and Li, J., 2016. Effects of hydraulic retention time and biofloculant addition on membrane fouling in a sponge-submerged membrane bioreactor. *Bioresource Technology*, 210, pp. 11-17.
- Ding, G.T., Yaakob, Z., Takriff, M.S., Salihon, J. and Rahaman, M.S., 2016. Biomass production and nutrients removal by a newly-isolated microalgal strain *Chlamydomonas sp* in palm oil mill effluent (POME). *International Journal of Hydrogen Energy*, 41(8), pp. 4888-4895.
- Düppenbecker, B., Engelhart, M. and Cornel, P., 2017. Fouling mitigation in anaerobic membrane bioreactor using fluidized glass beads: Evaluation fitness for purpose of ceramic membranes. *Journal of Membrane Science*, 537, pp.69-82.
- Dvořák, L., Gómez, M., Dolina, J. and Černín, A., 2016. Anaerobic membrane bioreactors—a mini review with emphasis on industrial wastewater treatment: applications, limitations and perspectives. *Desalination and Water Treatment*, 57(41), pp.19062-19076.
- Fan, J., Ji, F., Xu, X., Wang, Y., Yan, D., Xu, X., Chen, Q., Xiong, J. and He, Q., 2015. Prediction of the effect of fine grit on the MLVSS/MLSS ratio of activated sludge. *Bioresource technology*, 190, pp.51-56.
- Ferrer, J., Pretel, R., Durán, F., Giménez, J.B., Robles, A., Ruano, M.V., Serralta, J., Ribes, J. and Seco, A., 2015. Design methodology for submerged anaerobic membrane bioreactors (AnMBR): A case study. *Separation and Purification Technology*, 141, pp.378-386.
- Gao, D., Tao, Y. and An, R., 2012. Digested sewage treatment using membrane-based process at different hydraulic retention times. *Desalination*, 286, pp. 187-192.
- Gkotsis P.K., Banti D.C., Peleka E.N., Zouboulis A.I., and Samaras P.E., 2014. Fouling Issues in Membrane Bioreactors (MBRs) for wastewater treatment: Major Mechanisms, Prevention and Control Strategies. *Processes*, 2, pp. 795-866.

- Global Industry Analysts Inc., 2012. *Global MBR market forecast to reach \$888 million by 2017*. [online] Available at: <[http://ac.els-cdn.com/S0958211812700174/1-s2.0-S0958211812700174-main.pdf?\\_tid=4af567b2-33c6-11e6-8469-00000aabb0f27&acdnat=1466083923\\_77e4ea a05299b8c664b0d01568a53936](http://ac.els-cdn.com/S0958211812700174/1-s2.0-S0958211812700174-main.pdf?_tid=4af567b2-33c6-11e6-8469-00000aabb0f27&acdnat=1466083923_77e4ea a05299b8c664b0d01568a53936)> [Accessed 18 June 2016].
- Gouveia, J., Plaza, F., Garralon, G., Fdz-Polanco, F. and Pena, M., 2015. A novel configuration for an anaerobic submerged membrane bioreactor (AnSMBR). Long-term treatment of municipal wastewater under psychrophilic conditions. *Bioresource Technology*, 198, pp. 510-519.
- Habib, R., Asif, M.B., Iftekhhar, S., Khan, Z., Gurung, K., Srivastava, V. and Sillanpää, M., 2017. Influence of relaxation modes on membrane fouling in submerged membrane bioreactor for domestic wastewater treatment. *Chemosphere*, 181, pp.19-25.
- Helmenstine A.M., 2017. Equation for the Reaction Between Baking Soda and Vinegar. [online] Available at: <<https://www.thoughtco.com/equation-for-the-reaction-of-baking-soda-and-vinegar-604043>> [Accessed 2 April 2018]
- Han, S.S., Bae, T.H., Jang, G.G. and Tak, T.M., 2005. Influence of sludge retention time on membrane fouling and bioactivities in membrane bioreactor system. *Process Biochemistry*, 40, pp. 2393-2400.
- Hassan, S., Kee, L.S. and Al-Kayiem, H.H., 2013. Experimental study of palm oil mill effluent and oil palm frond waste mixture as an alternative biomass fuel. *Journal of Engineering Science and Technology*, 8(6), pp.703-712.
- Hoek, M.V.E. and Tarabara, V.V., 2013. *Encyclopedia of membrane science and technology*. New Jersey: John Wiley & Sons, Inc.
- Hong, H., Lin, H., Mei, R., Zhou, X., Liao, B. and Zhao, L., 2016. Membrane fouling in a membrane bioreactor: A novel method for membrane surface morphology construction and its application in interaction energy assessment. *Journal of Membrane Science*, 516, pp. 135-143.
- Hu, Y., Wang, X.C., Ngo, H.H., Sun, Q. and Yang, Y., 2017a. Anaerobic dynamic membrane bioreactor (AnDMBR) for wastewater treatment: A review. *Bioresource technology*.
- Hu, Y., Yang, Y., Wang, X.C., Ngo, H.H., Sun, Q., Li, S., Tang, J. and Yu, Z., 2017b. Effects of powdered activated carbon addition on filtration performance and dynamic membrane layer properties in a hybrid DMBR process. *Chemical Engineering Journal*, 327, pp.39-50.
- Indonesia-Investments, 2016. *Palm Oil*. [online] Available at: <<http://www.indonesia-investments.com/business/commodities/palm-oil/item166>> [Accessed 15 July 2016].

- Iorhemen, O.T., Hamza, R.A. and Tay, J.H., 2016. Membrane bioreactor (MBR) technology for wastewater treatment and reclamation: membrane fouling. *Membranes*, 6(2), p.33.
- Jo, S.J., Kwon, H., J, S.Y., Lee, C.H. and Kim, T.G., 2016. Comparison of microbial communities of activated sludge and membrane biofilm in 10 full-scale membrane bioreactors. *Water Research*, 101, pp. 214-225.
- Judd, S., 2008. The status of membrane bioreactor technology. *Trends in Biotechnology*, 26(2), pp. 109-116.
- Judd, S.J., 2017. Membrane technology costs and me. *Water research*, 122, pp.1-9.
- Karmakar, S., Kundu, K. and Kundu, S., 2010. Design and development of microbial fuel cells. [pdf] Available at: <<http://www.formatex.info/microbiology2/1029-1034.pdf>> [Accessed 7 March 2017].
- Kim, K., Yang, W., Ye, Y., LaBarge, N. and Logan, B.E., 2016. Performance of anaerobic fluidized membrane bioreactors using effluents of microbial fuel cells treating domestic wastewater. *Bioresource Technology*, 208, pp. 58-63.
- Kimura, K., Miyoshi, T., Naruse, T., Yamato, N., Ogyu, R. and Watanabe, Y., 2008. The difference in characteristics of foulants in submerged MBRs caused by the difference in the membrane flux. *Desalination*, 231, pp. 268-275.
- Kong, H.F., 2017. Treatment Of Palm Oil Mill Effluent Using Combination Of Microbial Fuel Cell And Anaerobic Membrane Bioreactor.
- Kumar, S., Srivastava, N., Gupta, B.S., Kuhad, R.C. and Gomes, J., 2014. Lovastatin production by *Aspergillus terreus* using lignocellulose biomass in large scale packed bed reactor. *Food and Bioproducts Processing*, 92(4), pp.416-424.
- Lalia, B.S., Kochkodan, V., Hashaikeh, R. and Hilal, N., 2013. A review on membrane fabrication: Structure, properties and performance relationship. *Desalination*, 326, pp.77-95.
- Le-Clech, P., Chen, V. and Fane, A.G.T., 2006. Fouling in membrane bioreactors used in wastewater treatment. *Journal of Membrane Science*, 284(1-2), pp. 17-53.
- Le-Clech, P., Jefferson, B., Chang, I.S. and Judd, S.J., 2003. Critical flux determination by the flux-step method in a submerged membrane bioreactor. *Journal of Membrane Science*, 227, pp. 81-93.
- Li Y., Hu. Q., Chen C.H., Wang X.L., and Gao D.W., 2017. Performance and microbial community structure in an integrated anaerobic fluidized-bed membrane bioreactor treating synthetic benzothiazole contaminated wastewater. *Bioresource Technology*, 236, pp. 1-10.

- Liew, W.L., Kassim, M.A., Muda, K., Loh, S.K. and Affam, A.C., 2015. Conventional methods and emerging wastewater polishing technologies for palm oil mill effluent treatment: A review. *Journal of Environmental Management*, 149, pp. 222-235.
- Liu, C., Wachemo, A.C., Tong, H., Shi, S., Zhang, L., Yuan, H. and Li, X., 2017. Biogas production and microbial community properties during anaerobic digestion of corn stover at different temperatures. *Bioresource Technology*.
- Liu, J., Jia, X., Gao, B., Bo, L. and Wang, L., 2016. Membrane fouling behavior in anaerobic baffled membrane bioreactor under static operating condition. *Bioresource Technology*, 214, pp. 582-588.
- Ma, D., J, Z.H., Lay, C.H. and Zhou, D., 2016. Electricity generation from swine wastewater in microbial fuel cell: Hydraulic reaction time effect. *International Journal of Hydrogen Energy*, 41(46), pp. 21820-21826.
- Malaysia Palm Oil Board, 2014. *Oil Palm & The Environment (updated March 2014)*. [online] Available at: <<http://www.mpob.gov.my/palm-info/environment/520-achievements#Mill>> [Accessed 23 June 2017].
- Mao, C.L., Feng, Y.Z., Wang, X.J. and Ren, G.X., 2015. Review on research achievements of biogas from anaerobic digestion. *Renewable and sustainable energy reviews*. 45, pp. 540-555.
- Martinez-Sosa, D., Helmreich, B., Netter, T., Paris, S., Bischof, F. and Horn, H., 2011. Anaerobic submerged membrane bioreactor (AnSMBR) for municipal wastewater treatment under mesophilic and psychrophilic temperature conditions. *Bioresource Technology*, 102(22), pp. 10377-10385.
- Meabe, E., Deleris, S., Soroa, S. and Sancho, L., 2013. Performance of anaerobic membrane bioreactor for sewage sludge treatment: Mesophilic and thermophilic processes. *Journal of Membrane Science*, 446, pp. 26-33.
- Meng, F., Chae, S., Drews, A., Kraume, M., Shin, H. and Yang, F., 2009. Recent advances in membrane bioreactors (MBRs): Membrane fouling and membrane material. 43, pp. 1489-1512.
- Meng, F., Zhang, S., Oh, Y., Zhou, Z., Shin, H.S. and Chae, S.R., 2017. Fouling in membrane bioreactors: An updated review. *Water Research*, 114, pp. 151-180.
- Naik, L., Gebreegziabher, Z., Tumwesige, V., Balana, B.B., Mwirigi, J. and Austin, G., 2014. Factors determining the stability and productivity of small scale anaerobic digesters. *Biomass and Bioenergy*, 70, pp. 51-57.
- Najafpour G.D, Zinatizadeh A.A.L., Mohamed A.R., Hasnain Isa M., and Nasrollahzadeh H., 2006. High-rate anaerobic digestion of palm oil mill effluent in an upflow anaerobic sludge-fixed film bioreactor. *Process Biochemistry*, 41(2), pp. 370-379.

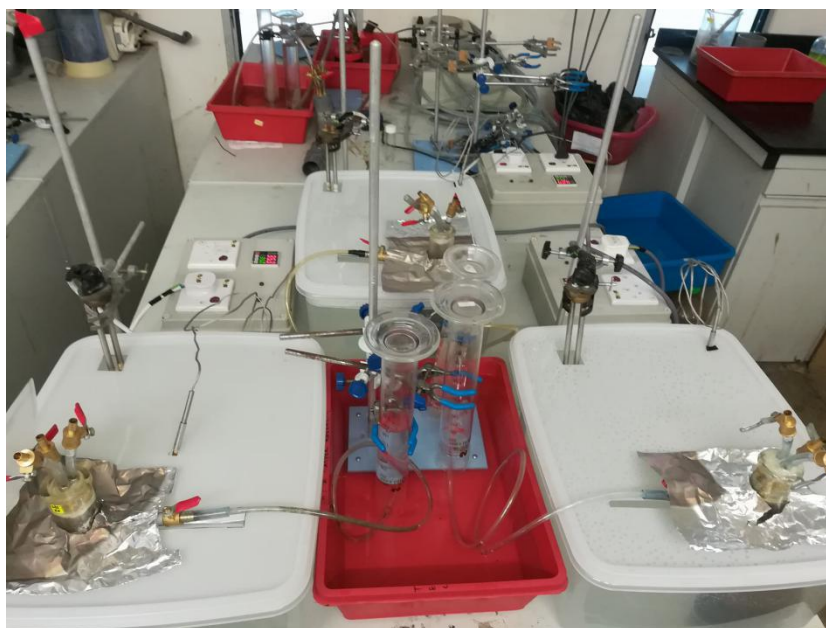
- Neoh, C.H., Yung, P.Y., Noor, Z.Z., Razak, M.H., Aris, A., Din, M.F.M. and Ibrahim, Z., 2017. Correlation between microbial community structure and performances of membrane bioreactor for treatment of palm oil mill effluent. *Chemical Engineering Journal*, 308, pp.656-663.
- Ng, C.A., 2008. The effect of powdered activated carbon and two-compartment configuration on membrane bioreactor performance. s.l: Nanyang Technological University.
- Nguyen, L.N., Hai, F.I., Nghiem, L.D., Kang, J., Price, W.E., Park, C. and Yamamoto, K., 2014. Enhancement of removal of trace organic contaminants by powdered activated carbon dosing into membrane bioreactors. *Journal of the Taiwan Institute of Chemical Engineers*, 45(2), pp.571-578.
- Ohimain, E.I. and Izah, S.C., 2017. A review of biogas production from palm oil mill effluents using different configurations of bioreactors. *Renewable and Sustainable Energy Reviews*, 70, pp.242-253.
- Ouyang, K. and Liu, J., 2009. Effect of sludge retention time on sludge characteristics and membrane fouling of membrane bioreactor. *Journal of Environmental Sciences*, 21, pp. 1329-1335.
- Peinemann, K.V. and Nunes, S.P., 2010. Membrane for water treatment. Volume 4. Great Britain: WILEY-VCH.
- Poh, P.E. and Chong, M.F., 2009. Development of anaerobic digestion methods for palm oil mill effluent (POME) treatment. *Bioresource Technology*, 100(1), pp.1-9.
- Pollice, A., Laera, G., Saturno, D. and Giordano, C., 2008. Effects of sludge retention time on the performance of a membrane bioreactor treating municipal sewage. *Journal of Membrane Sciences*, 317, pp. 65-70.
- Pulido, J.M.O., 2016. A review on the use of membrane technology and fouling control for olive mill wastewater treatment. *Science of the total environment*, 563, pp.664-675.
- Radjenović, J., Matošić, M., Mijatović, I., Petrović, M. and Barceló, D., 2008. Membrane bioreactor (MBR) as an advanced wastewater treatment technology. In *Emerging Contaminants from Industrial and Municipal Waste* (pp. 37-101). Springer Berlin Heidelberg.
- Sabia, G., Ferraris, M. and Spagni, A., 2013. Effect of solid retention time on sludge filterability and biomass activity: Long-term experiment on a pilot-scale membrane bioreactor treating municipal wastewater. *Chemical Engineering Journal*, 221, pp. 176-184.
- Said, M., Ahmad, A., Mohammad, A.W., Nor, M.T.M. and Abdullah, S.R.S., 2015. Blocking mechanism of PES membrane during ultrafiltration of POME. *Journal of Industrial and Engineering Chemistry*, 21, pp.182-188.

- Shen, L., Lei, Q., Chen, J.R., Hong, H.C., He, Y.M. and Lin, H.J., 2015. Membrane fouling in a submerged membrane bioreactor: Impact of floc size. *Chemical Engineering Journal*, 269, pp. 328-334.
- Shin, J.W., Pyeon, J.H., Son, S.M., Jeong, J.Y. and Park, J.Y., 2014. Performance evaluation of a field-scale pilot bioreactor for anaerobic treatment of palm oil mill effluent. *International Biodeterioration & Biodegradation*, 95, pp.89-92.
- Singh, R.P. and Heldman, D.R., 2014. Membrane Separation. Introduction to food engineering (Fifth Edition), pp. 645-674.
- Su, X., Tian, Y., Sun, Z., Lu, Y. and Li, Z., 2013. Performance of a combined system of microbial fuel cell and membrane bioreactor: Wastewater treatment, sludge reduction, energy recovery and membrane fouling. *Biosensors and Bioelectronics*, 49, pp. 92-98.
- Tabassum, S., Zhang, Y. and Zhang, Z., 2015. An integrated method for palm oil mill effluent (POME) treatment for achieving zero liquid discharge – a pilot study. *Journal of Cleaner Production*, 95, pp. 148-155.
- Tan, S.P., Kong, H.F., Bashir, M.J., Lo, P.K., Ho, C.D. and Ng, C.A., 2017. Treatment of palm oil mill effluent using combination system of microbial fuel cell and anaerobic membrane bioreactor. *Bioresource technology*, 245, pp.916-924.
- Tenaga Nasional Berhad, TNB., 2017. Electricity Pricing and Tariffs Rates. [online] Available at: <https://www.tnb.com.my/commercial-industrial/pricing-tariffs1/#commercial-tariffs> [4 April 2018].
- Tian, Y., Li, H., Su, X., Lu, Y., Zuo, W. and Zhang, J., 2015. In-situ integration of microbial fuel cell with hollow-fiber membrane bioreactor for wastewater treatment and membrane fouling mitigation. *Biosensors and Bioelectronics*, 64, pp. 189-195.
- Wang, Z., Wu, Z., Yu, G., Liu, J. and Zhou, Z., 2006. Relationship between sludge characteristics and membrane flux determination in submerged membrane bioreactors. *Journal of Membrane Science*, 284(1-2), pp. 87-94.
- Xiao, Y., Yaohari, H., De Araujo, C., Sze, C.C. and Stuckey, D.C., 2017. Removal of selected pharmaceuticals in an anaerobic membrane bioreactor (AnMBR) with/without powdered activated carbon (PAC). *Chemical Engineering Journal*, 321, pp.335-345.
- Xiong, Y., Harb, M. and Hong, P.Y., 2016. Characterization of biofoulants illustrates different membrane fouling mechanisms for aerobic and anaerobic membrane bioreactors. *Separation and Purification Technology*, 157, pp.192-202.
- Xu, Z., Zhao, M., Miao, H., Huang, Z., Gao, S. and Ruan, W., 2014. In situ volatile fatty acids influence biogas generation from kitchen wastes by anaerobic digestion. *Bioresource technology*, 163, pp.186-192.

- Yahaya S.M. and Lau S., 2013. Palm oil mill effluent (POME) from Malaysia palm oil mills: Waste or resource. *International Journal of Science, Environmental and Technology*, 2(6), pp. 1138-1155.
- Yu, H.Q. and Fang, H.H.P., 2003. Acidogenesis of gelatin-rich wastewater in an upflow anaerobic reactor: influence of pH and temperature. *Water Research*, 37(1), pp. 55-66.
- Yuniarto, A., Noor, Z.Z., Ujang, Z., Olsson, G., Aris, A. and Hadibarata, T., 2013. Bio-fouling reducers for improving the performance of an aerobic submerged membrane bioreactor treating palm oil mill effluent. *Desalination*, 316, pp. 146-153.
- Zhang, Q. Z., Hu, J. J. and Lee, D. J., 2016. Biogas from anaerobic digestion processes: research updates. *Renewable energy*, 98 (2016), pp. 108-119.
- Zhang, Q., Tan, G.H.V. and Stuckey, D.C., 2017. Optimal biogas sparging strategy, and the correlation between sludge and fouling layer properties in a submerged anaerobic membrane bioreactor (SAnMBR). *Chemical Engineering Journal*, 319, pp.248-257.
- Zhou, J., Zhang, R., Liu, F., Yong, X., Wu, X., Zheng, T., Jiang, M. and Jia, H., 2016. Biogas production and microbial community shift through neutral pH control during the anaerobic digestion of pig manure. *Bioresource technology*, 217, pp.44-49.

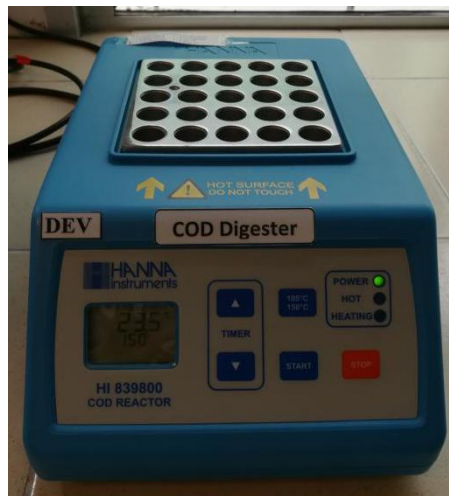
## APPENDICES

### Appendix A: Experimental Set-up



**Figure A1: Hybrid anaerobic bioreactors operated at ambient temperature, 35 °C, 45 °C, and 55 °C**

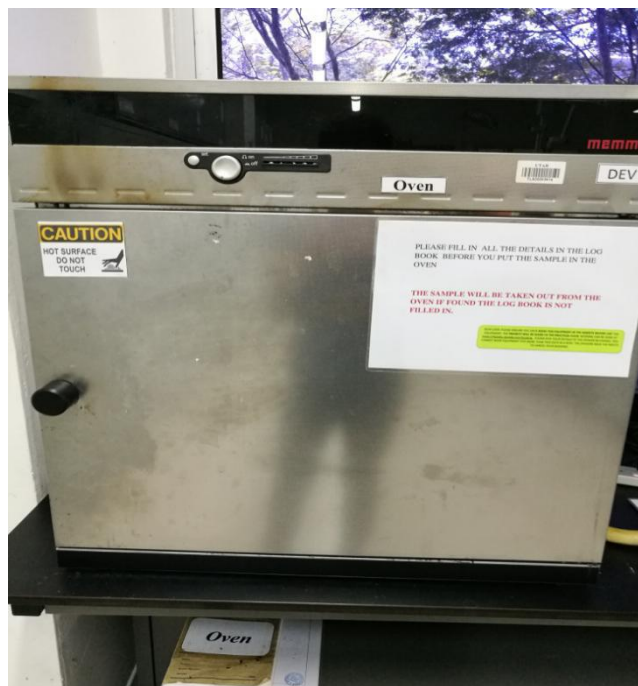
### Appendix B: Laboratory Analytical Instruments



**Figure B1: COD Reactor**



**Figure B2: UV-Vis Spectrophotometer (DR 6000)**



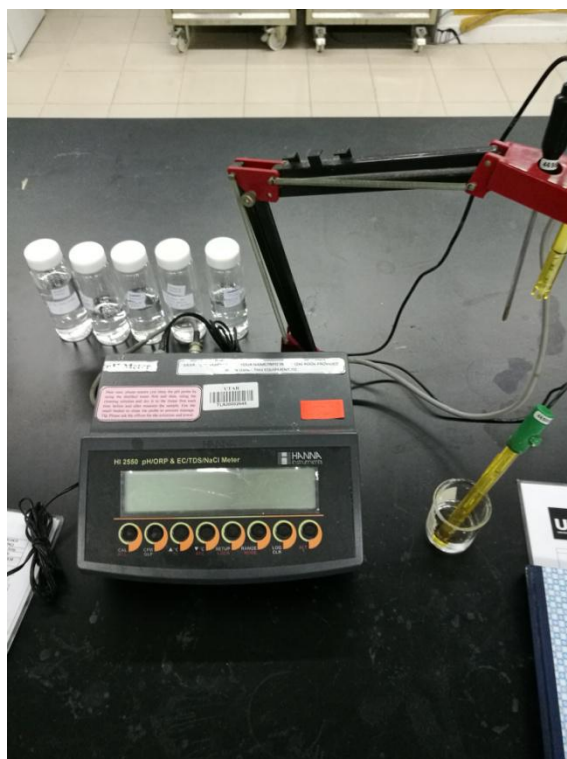
**Figure B3: Oven**



**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: Vortex Shaker**



**Figure B10: Desiccator**

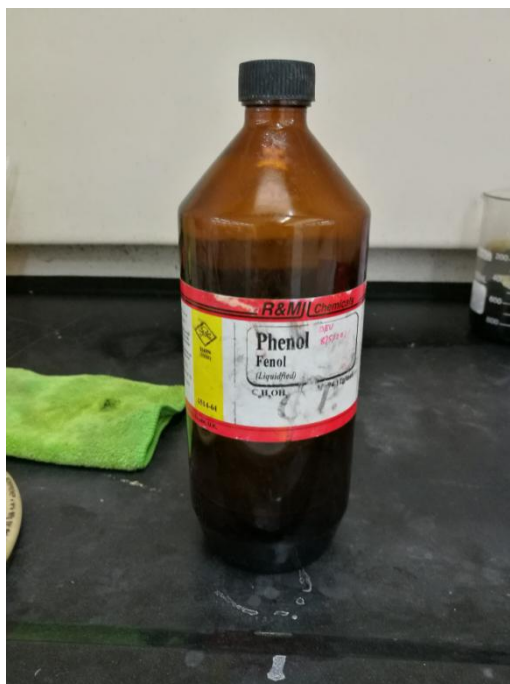
## Appendix C: Materials



**Figure C1: Powdered Activated Carbon (PAC)**



**Figure C2: Palm Oil Mill Effluent (POME)**



**Figure C3: Phenol**



**Figure C4: Glass Microfibre Filter**