THE PERFORMANCE STUDY OF MEMBRANE BIOREACTOR (MBR) TREATING SYNTHETIC WASTEWATER

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Chemical Engineering

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DECLARATION

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

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"THE PERFORMANCE STUDY OF MEMBRANE BIOREACTOR (MBR) TREATING SYNTHETIC WASTEWATER"** was prepared by **NG SHIONG CHAN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (HONS) Chemical Engineering at Universiti Tunku Abdul Rahman.

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ABSTRACT

Membrane bioreactor (MBR) is one of the applications of membrane technology in wastewater treatment. Submerged MBR, in which the membranes are directly submerged in the aeration tank, has received significant attention because of their advantages over the conventional activated sludge process such as reduced footprint and excellent effluent quality. In this study, the performance of MBR in treating synthetic wastewater was investigated using laboratory-scale MBR at different organic loading rates of 0.37, 0.53 and 0.93 g COD/g MLSS·d; hydraulic retention times (HRTs) of 4, 2.58 and 1.3 hours and mixed liquor suspended solids (MLSS) concentrations ranging between 2 442.5 and 9 920 mg/L. The results demonstrated high treatment efficiencies for chemical oxygen demand (COD), turbidity and total suspended solids (TSS) under all conditions. The COD removal efficiencies under all operating conditions were higher than 92 %. The change in influent F/M ratios did not show any particular trend but the COD removal in the bioreactor decreased slightly with decreasing HRT and MLSS concentration. The MBR was able to retain almost all particles, producing an effluent with turbidity lower than 0.1 NTU and with negligible TSS at all conditions. All the effluents treated using the existing MBR complied with the effluent discharge standards to Malaysian inland waters. A secondary study was carried out on filtration performance, with respect to changes in fluxes and water productivity, under different conditions namely intermittent permeation with off time of 30 s, 1 min and 2 min; backwash with backwashing duration of 15 s, 30 s and 1 min; and combination of backwashing and intermittent permeation to mitigate the fouling problem in the MBR. Longer duration of off time and backwashing produced better result of flux improvement when the off time was shorter than 2 min and backwashing was shorter than 1 min. In contrast, the back-pumping of more filtrate for longer backwash duration or longer off time in intermittent permeation caused water productivity to decrease drastically (below 80%). The optimum fouling control conditions were determined based on the ability to produce the maximum amount of water with sustainable membrane operation. With the decrease in flux at a considerably low percentage, 4.69% (low fouling tendency) and higher efficiency of water production (89.92%), the combination method was more desirable compared to the others and was proven to be capable of overcoming the shortage of existing cleaning techniques such as low filtrate productivity in backwashing and lower flux improvement efficiency in intermittent permeation.

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LIST OF SYMBOLS / ABBREVIATIONS

ASP	Activated Sludge Process
BOD	Biochemical Oxygen Demand
CASP	Conventional Activated Sludge Process
COD	Chemical Oxygen Demand
DO	Dissolve Oxygen (mg/L)
F/M	Food to Mass ratio
FS	Flat Sheet
HF	Hollow Fibre
HRT	Hydraulic Retention Time (h)
MBR	Membrane Bioreactor
MF	Microfiltration
MLSS	Mixed Liquor Suspended Solids (mg/L)
MT	(Multi)tubular
NF	Nanofiltration
OLR	Organic Loading Rate
PE	Polyethylene
PES	Polyethersulfone
PP	Polypropylene
PEG	Polyethylene glycol
PVDF	Polyvinylidene Fluoride
RO	Reverse Osmosis
SBR	Sequential Bioreactor
SEM	Scanning Electron Microscope
SRT	Sludge Retention Time (h)
TSS	Total Suspended Solids
UF	Ultrafiltration
WEF	Water Environment Federation

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CHAPTER 1

INTRODUCTION

1.1 Background

In ancient Rome, homes were not connected to a collection system that removed wastewater from individual households. Instead, the streets themselves were the collection point for waste materials that were washed out to open sewers. It was not until the 19th century that the big cities began to understand the importance of reducing the pollutants in the wastewater. In the 1850s, the highly concentrated population and the unsanitary conditions resulted in an outbreak of life-threatening diseases. The cholera outbreak in London was found to be caused by sewage contamination of a pump well known as the Broad Street Pump Affair (Rao, 2006). Besides, bacteria discovery and the cause of many waterborne diseases such as typhoid fever, cholera, and dysentery led to great developments and evolution in wastewater technologies.

The membrane bioreactor (MBR) is an emerging advanced wastewater treatment that has been applied in an increasing number of locations around the world due to its numerous advantages over conventional biological treatment (Stephenson, Simon, Jefferson & Brindle, 2000; Yang, Cicek & Llg, 2006). It comprises of a suspended growth-activated sludge biological treatment coupled with membrane equipment where the membranes are used for liquid or solid separation that is traditionally accomplished using secondary clarifiers. There are two types of the membrane equipment: in-pipe cartridge systems that are located external to the bioreactor and immersed systems that are designed for installation within the bioreactor. However, immersed membrane technologies using the hollow-fibre or flat-sheet membranes are the most popular for MBR applications due to their ability to operate at lower pressure (Water Environment Federation (WEF), 2006).

The advantages of MBR include reduced footprint, excellent effluent quality and less sludge handling (Al-Malack, 2006; Mohammed, Birima, Mohd Noor, Muyibi & Idris, 2008). The potential for operating the MBR at very high solid retention times allows high biomass concentration and retention of microorganisms such as nitrifying bacteria in the bioreactor. Consequently, higher strength wastewater can be treated and lower sludge production is obtained (Muller, Stouthamer, Verseveld & Eikelboom, 1995). This system is also capable of handling high fluctuations in influent handling, and the effluent can be reused directly for non-potable purposes due to high-quality final effluent where the effluent solids concentrations are less than 1 mg/L (WEF, 2006).

Since MBR is a relatively new technology, many researches have been conducted on its process performance in relation to membrane characteristics, operational parameters, sludge characteristic and etc. The performance of MBR process is often related to the membrane fouling since it is the key element which constrains the performance. According to Gao et al. (2009), the major factors affecting the process performance include not only conventional factors such as biological and reactor kinetic parameters, but also the parameters of membrane separation. The biochemical kinetic parameters include: sludge retention times (SRT), hydraulic retention time (HRT), sludge concentration, volumetric loading rate, and specific sludge loading rate. The membrane separation parameters are membrane characteristics such as membrane material, pore size and its configuration (Gao et al., 2009).

1.2 Problem Statement

With increasing worldwide pressure on the demand for clean water, membrane bioreactor has become intensively popular in wastewater treatment and reclamation. MBR has many advantages over the conventional activated sludge process such as small foot print and high effluent quality. However, MBR is not applied in any wastewater treatment plant in Malaysia. Malaysia produces 3.2 million cubic metres of domestic sludge yearly, but facilities to treat and dispose of this sludge are limited. Currently, the sewage treatment plants with excess capacity are being used to treat septic tank sludge (Indah Water, 2011). MBRs may be an alternative for the treatment facility to increase its capacity as it can be directly integrated to existing activated sludge process (ASP) that is widely used by Indah Water. Therefore, it is important to study the practicality of the MBR. In this experiment, a MBR is constructed and the factors that affect the performance of MBR in obtaining higher quality of effluent are investigated. Since fouling is one of the key elements that constraints MBR performance, a secondary study has been carried out under different conditions namely backwash; intermittent permeation and combination of backwashing and intermittent permeation to investigate the effect of different cleaning techniques on filtration performance, with respect to changes in fluxes (fouling tendency) and water productivity.

1.3 Objectives

The objectives of this study are listed as follows:

1. To develop a laboratory scale aerobic MBR for synthetic wastewater treatment.
2. To investigate the performance of the aerobic MBR for synthetic wastewater under different operation conditions.
3. To investigate the effect of different cleaning techniques on filtration performance, with respect to changes in fluxes (fouling tendency) and water productivity.

4. To compare the quality of the effluent treated with MBR with Effluent Standards A and Standard B under the Environmental Quality (Sewage and Industrial Effluents) Regulations of 1979.

1.4 Scope of Study

This study was to investigate the performance of the MBR in treating synthetic wastewater using different parameters such as MLSS, HRT and organic loading. Besides, a secondary study was conducted to investigate the effect of different cleaning techniques on filtration performance.

The membrane modules were made and a laboratory scale membrane bioreactor was installed to treat synthetic wastewater. The pore size, inner and outer diameter was examined using the Scanning Electron Microscope (SEM). The efficiency of COD removals, turbidity, pH and total suspended solids (TSS) of effluent under different parameters were compared in order to investigate the impacts of each parameter on the MBR performance. Finally, the quality of the effluent was compared with the Effluent Standards A and Standard B under the Environmental Quality (Sewage and Industrial Effluents) Regulations of 1979.

On the other hand, the MBR was tested using different cleaning techniques, namely backwash; intermittent permeation; and combination of backwash and intermittent permeation. The results, with respect to changes in fluxes (fouling tendency) and water productivity, were compared and the optimal condition to control the fouling was determined.

CHAPTER 2

LITERATURE REVIEW

2.1 General

As shown in Figure 2.1, wastewater treatment is a process of removing the contaminants from wastewater where physical, chemical and biological processes are involved in removing physical, chemical and biological contaminants (Singh, 2009). It is usually classified into four levels: preliminary where gross solid are removed, primary where physical operation is used to remove settleable materials, secondary where most of the organic matter are removed and tertiary or advanced treatment where specific pollutants (toxic or non-biodegradable compounds) or pollutants that were not sufficiently removed in the secondary treatment are removed (Sperling, 2007; Metcalf & Eddy, 2004).

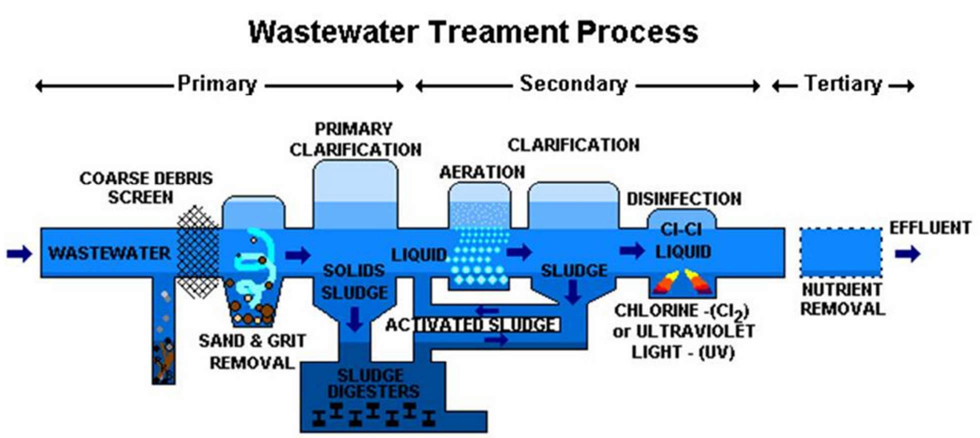


Figure 2.1: Wastewater Treatment Process

Biological treatment used for wastewater treatment can be divided into two main categories: suspended growth and attached growth processes. The most common suspended growth process used for municipal wastewater treatment is the activated-sludge process (Figure 2.2), while the most common aerobic attached growth process used is the tricking filter (Figure 2.3).

Figure 2.2: Activated Sludge Process

Figure 2.3: Tricking Filter

With increasing worldwide pressure on the demand for clean water, new ideas or advanced wastewater treatments have been introduced. The changing nature of the wastewater to be treated, emerging health and environmental concerns, the problem of industrial wastes and the impact of new regulations have accelerated the needs on replacing the conventional wastewater treatment technologies (Metcalf &

Eddy, 2004). Miserez, ,Philips and Verstraete (1999) reported that a number of new technologies for the advanced treatment of wastewater treatment have recently been developed. The performance of membrane bioreactor that is applied to advance wastewater treatment was summarised by Yamamoto in his paper (Yamamoto, 2001). Another advanced wastewater treatment technology, pressure-driven membrane filtration using reverse osmosis and nanofiltration was discussed by Rautenbach and Vobenkaul (2001). Its potential and limitations were discussed by taking availability, safety with respect to product, quality and costs into account.

2.2 Conventional Activated Sludge Process (CASP)

Activated sludge process is a typical type of suspended growth biological treatment system and the most widely used biological process for the treatment of organic and industrial wastewater. Figure 2.4 shows the flow diagram of an activated sludge wastewater treatment.

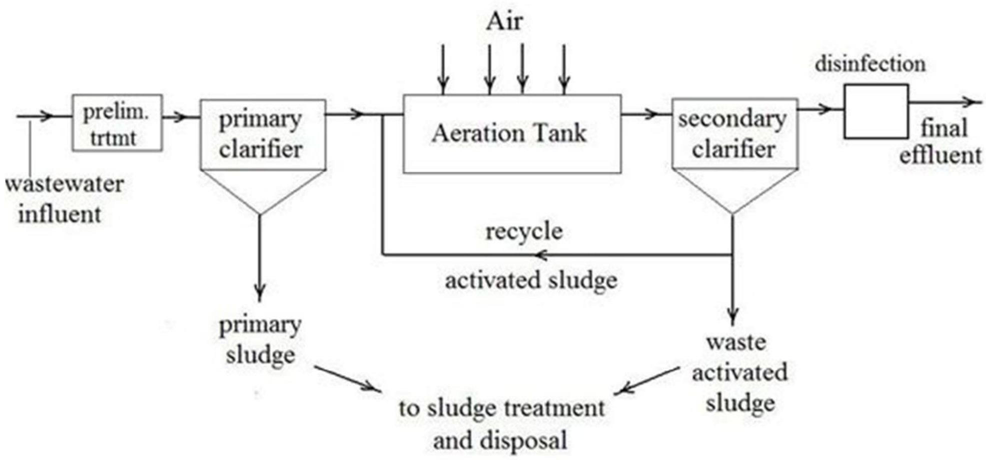


Figure 2.4: Flow Diagram of Conventional Activated Sludge Wastewater Process (CASP)

One of the advantages of CASP is its capability in handling high loading rate using relatively short hydraulic residence time (Noyes, 1994). In typical CASP, the organic loading rates range from 0.5 to 1.5 kg BOD /m^3/day with hydraulic retention of 1 to 2 hours with BOD removal of 60 to 70% (D'souza & Killedar, 2008). However, the process is limited by operational problems such as foaming.

2.3 Membranes and Membrane Separation Process

A membrane is a porous filtration medium which allows some physical or chemical components to pass more readily through it than others (Judd, 2006). Membranes range from the coarsest membrane, associated with microfiltration (MF) which rejects particulate matter or suspended solids in the size range of about 0.08 to 10 µm to the most selective membrane, associated with reverse osmosis (RO) which is capable of rejecting singly charged ions such as sodium. The sizes of molecular solids and salts to be rejected by RO are usually in the range of 0.00025 to 0.003 µm (Wang, Pereira & Hung, 2009).

The four key membrane separation processes are RO, nanofiltration (NF), ultrafiltration (UF) and MF. Figure 2.5 shows different type of membrane separation processes and their separation capabilities.

2.4 Membrane Bioreactor (MBR)

As mentioned in Chapter 1, the membrane bioreactor (MBR) is an emerging advanced wastewater treatment and an alternative to the conventional activated sludge system (CASP). It consists of two components: suspended growth bioreactor for biochemical reactions and membrane separator for solid-liquid separation (Wang et al., 2009). The system has been used for treatment in industrial and municipal applications. Dijk and Roncken (1997) reported that the membrane bioreactor has been applied at full scale successfully for concentrated wastewater such as industrial waste and landfill leachate. It was reported by Liu, Zhao, Chen and Zheng (2010) that over 50 MBR plants have been successfully built for hospital wastewater treatment in China between 2001 and 2009. According to them, MBR technology exhibits a more efficient system at removing pathological microorganism compared to conventional wastewater treatment system. Due to the increasing stringent regulations and strategies, it is believed that the MBR application areas will continue to widen and significant increase of MBR plant capacity will occur in the future (Yang et al., 2006).

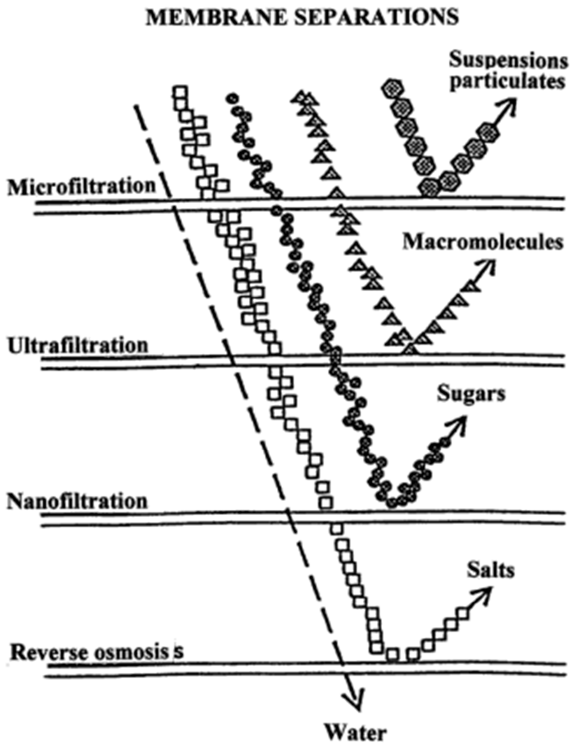


Figure 2.5: Separation Capabilities of MF, UF, NF and RO

2.4.1 MBR Process

The membrane separator of MBR replaces the clarifier in CASP. Thus, it is important that the membrane has a reasonable strength and capable of maintaining a high throughput of permeate with high degree of selectivity. The two major types of membranes used in the application of MBR treatment are microfiltration and ultrafiltration. The membranes are bundled into "modules" where they are connected to a permeate pump and either submerged or located outside the activated sludge bioreactor. The permeate pump pulls the effluent into the membrane modules by creating a vacuum and the solids are left behind in the bioreactor (Wang et al., 2009). Figure 2.6 shows a typical membrane process system with membrane modules submerged in the bioreactor.

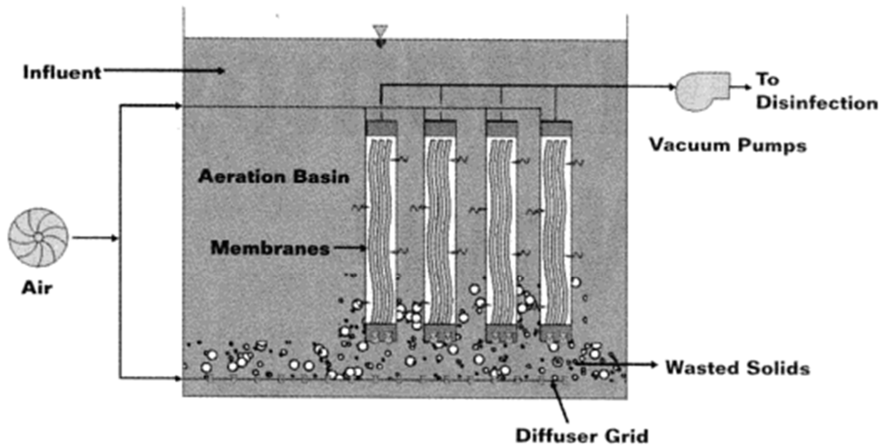


Figure 2.6: Membrane Process System with Membrane Modules Submerged in the Bioreactor

2.4.2 MBR Configurations

There are two configurations of MBR: submerged membrane system where the membrane unit submerged in the aeration tank and external membrane system where the membrane is located outside the aeration tank (Forster, 2003). Figure 2.7 and Table 2.1 shows the schematic diagrams and the advantages and disadvantages of the two types of reactor designs.

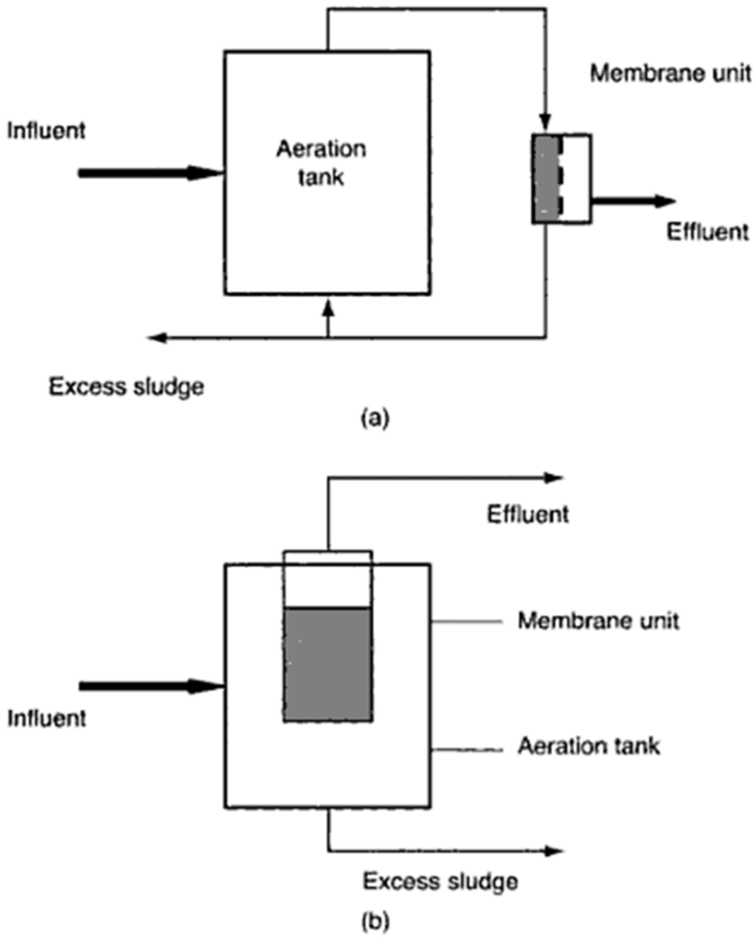


Figure 2.7: Schematic Diagram of Membrane Bioreactor: (a) External Membrane System and (b) Submerged Membrane System

Table 2.1: Advantages and Disadvantages of MBR Configuration

Item	Submerged MBR	External MBR
Aeration cost	High	Low
Liquid pumping cost	Low	High
Flux	Lower	Higher
Operating cost	Lower	Higher
Capital cost	Higher	Lower
Footprint	Higher footprint	Lower
Cleaning	Less frequent	More frequent

2.4.3 Advantages and Disadvantages of MBR

Several researchers reported that the MBR offers significant advantages. These includes complete solid-liquid separation, production of high quality effluent, capability of handling wide fluctuations in influent quality and small footprint (Santos, Judd & Ma, 2011; Visvanathan, Ben & Parameshwaran, 2000).

The potential for operating the MBR at very high solid retention times (SRT) allows high biomass concentration and complete retention of slow-growing microorganisms such as nitrifying bacteria in the bioreactor. The biomass concentration in MBR can be up to 20 to 30 g/L (Cervantes, Pavlostathis & Haandel, 2006; Gao et al., 2009). Since the biomass concentration is high, high organic loading rate can be tolerated. Consequently, higher strength wastewater can be treated and lower sludge production is obtained (Muller et al., 1995). The volume of the reactor can be reduced as a higher biomass concentration can be stored in the bioreactor. Due to high-quality final effluent where the effluent solids concentrations are <1 mg/L, the effluent can be reused directly for non-potable purposes (WEF, 2006).

The low sludge production in the MBR due to the long SRT results in less sludge handling (Al-Malack, 2006; Mohammed et al., 2008). Chaize and Huyard (1991) reported that the sludge production was greatly reduced if the sludge age was between 50 to 100 days for treatment of domestic wastewater. Another study was also in agreement with Chaize and Huyard where they found that the sludge production was decreased by a factor of two or three and concluded that reduction of overall operating costs was highly possible (Gander, Jefferson & Judd, 2000a).

However, it was also reported that the implementation of MBR treatment has been scarce due to high membrane cost and high energy consumption for membrane operation (Visvanathan et al., 2000). Another limitation is membrane fouling which reduces the productivity and shorten the membrane life. In order to prevent membrane fouling, chemical cleaning has to be carried out frequently, leading to the increase in operation and maintenance costs (Jeison & Lier, 2007).

2.5 Water Quality

2.5.1 Influent Quality

The influent to an MBR can be any wastewater stream that is treatable using an activated sludge process varying with geographical location and composition. Typical COD values for domestic waste range from 0.2 to 1 g/L. In a comparative study of polyvinylidene fluoride (PVDF) and polyethersulfone (PES) flat sheet membranes in submerged MBRs, Zhu et al. and his team (2009) reported a removal efficiency of 89 to 97 % in treating wastewater with COD concentrations of 400 to 1 000 mg/L. It has also been reported that MBR can be used to treat high strength industrial wastewater containing alcohols and sulfur compounds in a petrochemical company (Pitre, Enegess & Unterman, 1999). Besides, it is also used to treat leachate in France where the influent wastewater quality has high levels of organic and inorganic compounds (COD level more than 2 500 mg/L) (Beaubien, Trouve, Urbain, Amar & Manem, 1994).

2.5.2 Effluent Quality

The effluent quality must always comply with the standards set by the local authority. Under the Environmental Quality (Sewage and Industrial Effluents) Regulations of 1979, there are two effluent standards: Standard A and Standard B. Standard A is more stringent and generally applicable to activities and industries that are sited within or in the near vicinity of catchment areas. Standard B is generally applicable to both industrial and development activities throughout the country. Table 2.2 shows the partial parameters for Standard A and Standard B.

Table 2.2: Parameters for Standard A and Standard B

Parameters	Unit	Standards A	Standards B
Temperature	ºC	40	40
pH value	-	6.0-9.0	5.5-9.0
BOD at 20 ºC	mg/L	20	50
COD	mg/L	50	100
Suspended Solids	mg/L	50	100

The effluent from the MBR is in general free of solids and macrocolloidal materials. The effluent quality is often less than 1 mg/L in total suspended solids with low levels of COD (less than 100 mg/L) (Beaubien et al., 1994; WEF, 2006). A mean permeate COD of about 20 mg/L has been reported by Chiemchaisri, Wong, Urase and Yamamoto (1992) using hollow fibre membranes in an activated sludge process for domestic sewage. Table 2.3 summarises a typical effluent quality produced from a municipal MBR facility.

Table 2.3: Typical Municipal MBR Effluent Quality (WEF, 2006)

Parameter	Values
BOD	< 5 mg/L
TSS	< 1 mg/L
Total phosphorus	< 0.5 mg/L
Turbidity	< 0.2 NTU

2.6 Operating Parameters in MBR

2.6.1 Biological Kinetic Parameters

2.6.1.1 Mixed Liquor Suspended Solids (MLSS)

Mixed liquor suspended solids (MLSS) is the concentration of suspended solids in the aeration tank and commonly referred to as the crude measure of the biomass within the tank. Typically, the operating MLSS for the MBR ranges between 8 000 and 12 000 mg/L. Theoretically, the higher the MLSS concentration in the aeration tank, the greater the efficiency of the process as there is a greater biomass concentration to utilise available COD or nutrient (Gray, 1989). Innocenti, Bolzonella, Pavan and Cecchi (2002) reported that increasing the MLSS of the MBR from 4 000 to 9 000 mg/L resulted in the decrease of sludge production rate by 84 %. In contrast, Davies, Le and Heath (1998) used an immersed MBR at an average MLSS of 1 600 mg/L and reported that the bioreactor produced a very high quality effluent. A very high MLSS (more than 12 000 mg/L) has been shown to reduce membrane flux and lead to high aeration energy requirement. This is due to the deposition of sludge on the surface of membrane and higher aeration rate is needed to scour the membrane surface (Sven, Djamila & Thomas, 2007).

2.6.1.2 Sludge Retention Time (SRT)

Sludge retention time (SRT) is the average time the activated sludge solids are in the system. SRT is one of the most critical parameters for activated sludge design as it affects the treatment process performance and sludge production. High SRT allows high biomass concentration and complete retention of slow-growing microorganisms such as nitrifying bacteria in the bioreactor. As a result, the sludge production is low and effluent quality is high. According to Innocenti et al. (2002), the effluent quality was found to improve when the SRT values were increased. Cicek, Suidan, Ginestet and Audic (2001) also reported that the reduction of efficiency in the MBR performance was due to the washout effect resulted from low SRT. In the experiment, a decrease in nitrification rate was observed at very low SRT (2 days) due to a partial loss of nitrifying microorganisms.

2.6.1.3 Hydraulic Retention Time (HRT)

Hydraulic retention time (HRT), τ, is the average time spent by the influent liquid in the aeration tank of the activated sludge process (Bitton, 2011). The influence of HRT on the MBR performance has been investigated by several researchers. In the investigation on the influence of HRT on the organic pollutant removal, Ren, Chen, Wang and Hu (2005) proposed that high COD removal could be achieved through adjusting the HRT. From their results, the highest COD removal was 97.3 % at an HRT of 2 hours and 91.1 % at an HRT of 1 hour. This shows that higher HRT value usually results in better removal performance. Another study conducted by Aline, Geraldo and Sant'Anna, (2007) was also in agreement with Ren et al. where the COD removal in a MBR treating petroleum refinery wastewater increased with an increase of HRT (as shown in Figure 2.8).

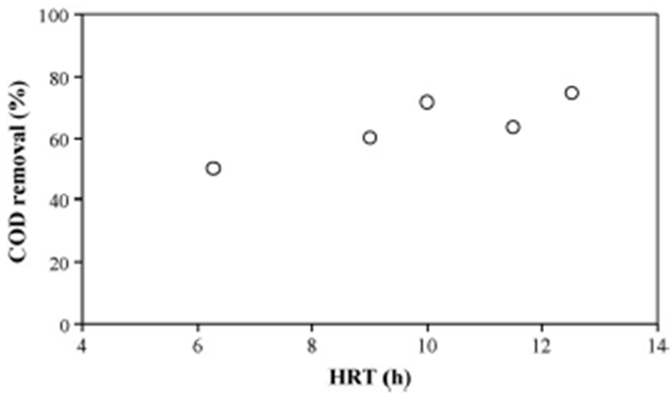


Figure 2.8: Effect of HRT on COD Removal in an MBR Treating Petroleum Refinery Wastewater (Reference: Aline et al., 2007)

2.6.1.4 Organic Loading Rate (OLR)

The organic loading rate (OLR), also known as food to mass ratio (F/M ratio), is the relationship between the load of COD (or bacterial 'food') entering the aeration plant, and the 'mass' of bacteria in the aeration tank available to treat the incoming COD. Treatment of industrial wastewater using a laboratory scale MBR was conducted by Sakrabani1, Mohammed and Pae1 (2001) to investigate the quality of effluent produced. The effluent quality was determined at different sludge age and F/M ratio. The change in sludge age and F/M ratio did not show any particular trend. The effluent produced was free of suspended solids and COD removal percentage was over 75% throughout the experiments. Sakrabanil et al. (2001) concluded that the system proved to be one, which can excellently treat wastewater of any type producing effluent of high purity and a reduced quantity of sludge. A shock loading experiment conducted by Al-Malack (2007) also showed that the performance of MBR was not significantly affected by increasing the OLR. In his report, the phenol and chromium were found to have short-term detrimental effect on the process performance and the COD removal efficiency was found to resume to its original values when the toxicants were ceased. Similarly, another research showed that the effluent COD in the MBRs were within 10 mg/L (above 90 % removal rate) regardless of organic loadings (Wu, Yi & Fane, 2011).

2.6.2 Membrane Separation Parameters

2.6.2.1 Membrane Materials

Polymeric membrane materials such as polyvinylidene fluoride (PVDF), polyether sulfone (PES), polyethylene (PE) and polypropylene (PP) are usually used in the wastewater treatment. Each type of material has its own specific features, physical properties and chemical resistance that will affect the design and operation of MBR.

PVDF is commonly used in MBR study due to its high mechanical strength, thermal stability and chemical resistance compared with other polymeric materials.

Benzinger, Parekh and Eichelberger (1980) evaluated the thermal stability and chemical stability of a commercial Kynar PVDF ultrafiltration membrane using spiral-wound modules at a higher temperature. During continuous operation at 85.6 °C, while keeping the pressure constant for 7 months, no evidence of thermal degradation was observed on the PVDF membrane. The membrane material also showed to have an excellent stability to harsh chemicals such as acids, strong oxidants and many organic solvents in the study on the effect of different types of acids, bases, and oxidants onto PVDF membrane.

Compared to PVDF, there are very few applications of PES membranes in MBR experiments as PES is relatively new in the market. Recent studies have shown that the performance of PES membrane was superior to PVDF membrane. Mocé-Llivina, Jofre and Muniesa (2003) reported that higher filtration rate and slower clogging rate could be achieved using PES when compared to PVDF (Mocé-Llivina et al., 2003). In another experiment, two types of membranes, PVDF and PES, were used in submerged flat sheet MBRs to treat domestic wastewater (Zhu et al., 2009). The MBRs were run under the same reactor structure and the same membrane pore size of 0.45 µm. The experimental results showed that the MBR with PVDF membrane achieved the COD removal efficiencies of 89-98% while 93-97% in MBR with PES membrane. On top of that, the flux of MBR using PVDF membrane was found to have decreased quickly and was washed twice. The high removal efficiency and fine capability in PES membrane proved its superiority to PVDF.

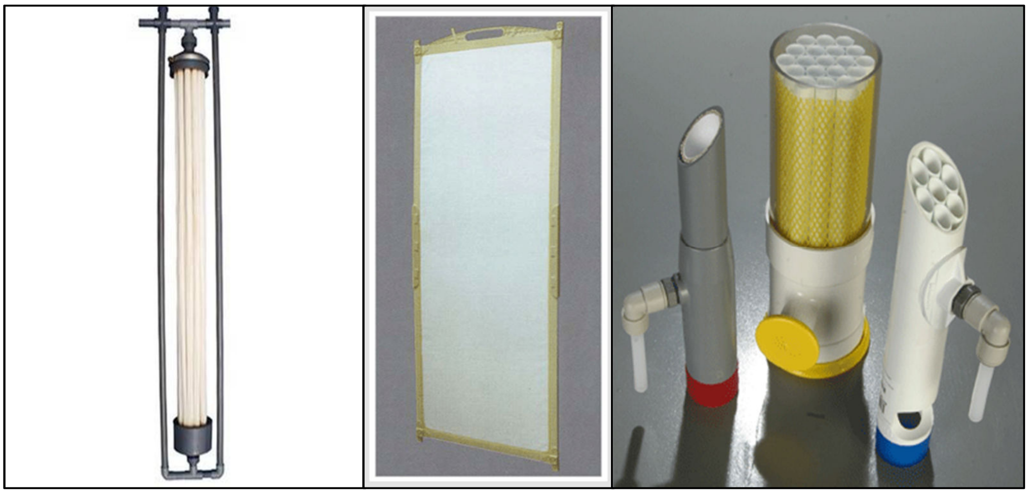
2.6.2.2 Membrane Configurations

Types of membrane configurations that are commonly used in MBR technologies are: flat sheet (FS), hollow fibre (HF) and (multi)tubular (MT) (Figures 2.9(a), (b), (c)). Flat sheet membranes comprise a series of flat membrane sheets and support plates. The hollow fibre membranes consist of a bundle of hundreds to thousands of hollow fibre membranes. In tubular systems, the membranes are cast on the inside of a support tube and then placed into a pressure vessel. Table 2.4 shows the various benefits and limitations of each membrane configuration

Table 2.4: Membrane Configurations

Configurations	Cost	Turbulence promotion	Backflushable
FS	High	Fair	No
MT	Very high	Very good	No
HF	Very low	Very poor	Yes

HF modules are generally less expensive to manufacture, allow high membrane density and tolerate vigorous back flushing. The influence of different configurations has been studied by several investigators. Gunter and Krauth (1998) discussed the relative merits of FS and HF membranes and demonstrated the superior hydraulic performance attainable from the FS in their report. On the other hand, Hai, Yamamoto and Fukushi (2005) conducted a comparative study of FS and HF membranes of the same pore size (0.4 μm) and found the FS membrane to foul slightly more than the HF membrane and the permeability was not recovered following cleaning with water.



(a) (b) (c)

Figure 2.9: (a) Hollow Fibre Module (b) Flat Sheet Membrane (c) Tubular Membrane

2.7 Membrane Fouling

MBR has become more and more popular due to its enormous advantages over the conventional treatment technologies. These include high COD removal efficiency due to its capability in maintaining high biomass concentration in relatively small reactor. Besides, rapidly decreasing membrane cost is another important driving force for the widespread of the application of MBR (Judd, 2006). However, membrane fouling in MBR remain the most challenging issues faced in the MBR development and may hinder its widespread application.

Membrane fouling has been investigated since the early MBRs and remains one of the most challenging issues faced in the MBR development as it decreases permeate flux and membrane lifespan. To prevent the membrane from fouling, regular membrane cleaning needs to be carried out. If the membrane fouling is severe and irreversible, replacement of membrane is required. All these will lead to an increase in operational and maintenance cost (Jeison and Lier, 2007). Several physical and chemical methods have been proposed for reducing fouling in the microfiltration such as increasing tangential fluid velocity, backwash with pure water or air, sparging air bubbles or introducing turbulent flow into the filter channel, adjusting the pH or ionic concentration of the suspension, and membrane surface polishing (Belfort, Davis & Zydney, 1994; Hwang, Chan & Tung, 2009). In general, increasing the shear stress on the membrane surface is commonly believed to be an efficient method for reducing fouling on the membrane surface. However, increasing the shear stress may lead to high cost as higher aeration will need to be applied. Therefore, a suitable backwash and intermittent permeation may enhance the sustainability of membrane by alleviating membrane internal clogging as well as surface fouling at a very reasonable cost.

Roh, Shin and Kim (2005) suggested that both backwashing and intermittent permeation are suitable cleaning techniques for permeate flux improvement. The results showed that backwashing cause an increase in the permeate flux at about 112 %, from 422 $L/m^{2}\cdot h$ to 897 $L/m^{2}\cdot h$. On the other hand, the intermediate permeation increases the permeate flux at about 63 %. The research team suggested that a longer duration of backwashing produced higher flux improvement. Another research team, Hwang et al. (2009), supported their results by concluding that an increase in backwash duration led to higher productivity, when the duration was shorter than 2 minutes.

In the experiment carried out by Chin, Lim, Chiang and Fane (2009) on the hybrid low pressure membrane photoreactor for the removal of bisphenol A in a suspension of TiO_2, the membrane bioreactor was run at an intermittent permeation of 5 minutes running and 2 minutes relaxation. From their result, 38% of the TiO_2 was found on the membrane surface after 5 hours of continuous filtration compared to 7% of TiO_2 for the intermittent permeation. This indicated that intermittent permeation should be more effective in reducing and preventing fouling on membrane compare with continuous filtration. The advantages of intermittent permeation have also been reported by Hong, Bae, Tak, Hong and Randall (2002) and Howell, Chua and Arnot (2004) during the operation of their MBR. Hong et al suggested that the use of intermittent permeation could be economically feasible for controlling fouling in small scale MBR processes treating wastewater with high fouling potentials.

CHAPTER 3

METHODOLOGY

3.1 Experimental Setup

3.1.1 Preparation of Synthetic Wastewater

In this study, the synthetic wastewater employed was prepared with COD concentrations between 500 and 1 450 mg/L. The synthetic wastewater was used to provide a source of carbon, nitrogen, phosphorus and trace metals required for biomass growth. The composition of the synthetic wastewater is shown in Table 3.1.

Table 3.1: Composition of the Synthetic Wastewater

Compound	Concentration (mg/L)
Bactopeptone	188
Sucrose	563
KH_2PO_4	250
NH_4Cl	172
$MgSO_4$	49
$NaHCO_3$	14.7
$FeCl_3$	11.3

3.1.2 Activated Sludge

The sludge was collected from the aeration tank of a wastewater treatment plant in a food processing plant at Shah Alam. Then, it was acclimatized with influent synthetic wastewater for four weeks to allow the changes in morphological, behavioural, physical and biochemical traits of the biomass. The acclimatization process was carried out at ambient temperature (26-30 °C) with aeration of 23 hours and settling of 1 hour. Aeration was provided to maintain dissolved oxygen (DO) concentration above 5 mg/L. The pH was adjusted between 7 and 8 using NaOH or HCl solution. Variation of MLSS concentration was observed throughout the processes to verify the proper growth of microorganisms.

3.1.3 Membrane Bioreactor

A lab scale membrane bioreactor (Figure 3.1) was designed for the study. The reactor was made of transparent acrylic sheet having the dimensions of 0.2 m (length) × 0.35 m (height) × 0.12 m (width). The working volume was 6.5 L, while the total tank volume was 8.4 L. Two polyether sulfone (PES) hollow fibre (HF) membrane modules were submerged in the reactor. A peristaltic pump was used to extract permeate from the MBR. The MBR was aerated by the air pump through stone diffusers to minimize the cake formation on the membrane surface, agitation and supply oxygen for biomass growth.

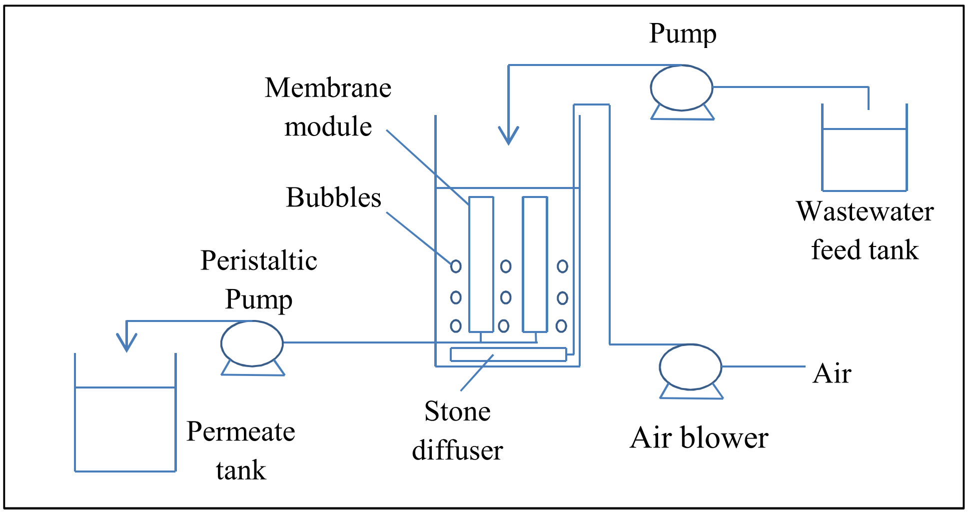


Figure 3.1: Schematic Diagram of the MBR System

3.1.4 Fabrication of PES Hollow Fibre Membranes

The hollow fibre membranes were fabricated by Universiti Teknologi Malaysia (UTM) using dope solution that consisted of 13.86 wt% PES, 60.33 wt% N-methyl-pyrrolidone (NMP), 17.58 wt% poly(ethylene glycol) (PEG) and 8.22 wt% water by the dry-jet-wet-spinning technique described elsewhere (Ismail, Mustaffar, Illias & Abdullah, 2005). The PES powders were initially dried and dispersed slowly into NMP solvent. Then, the dope solution was stirred at high speed to ensure the homogeneity. Before the spinning, the dope solution was degassed under vacuum for 3 hours. The spinning system used is schematized in Figure 3.2.

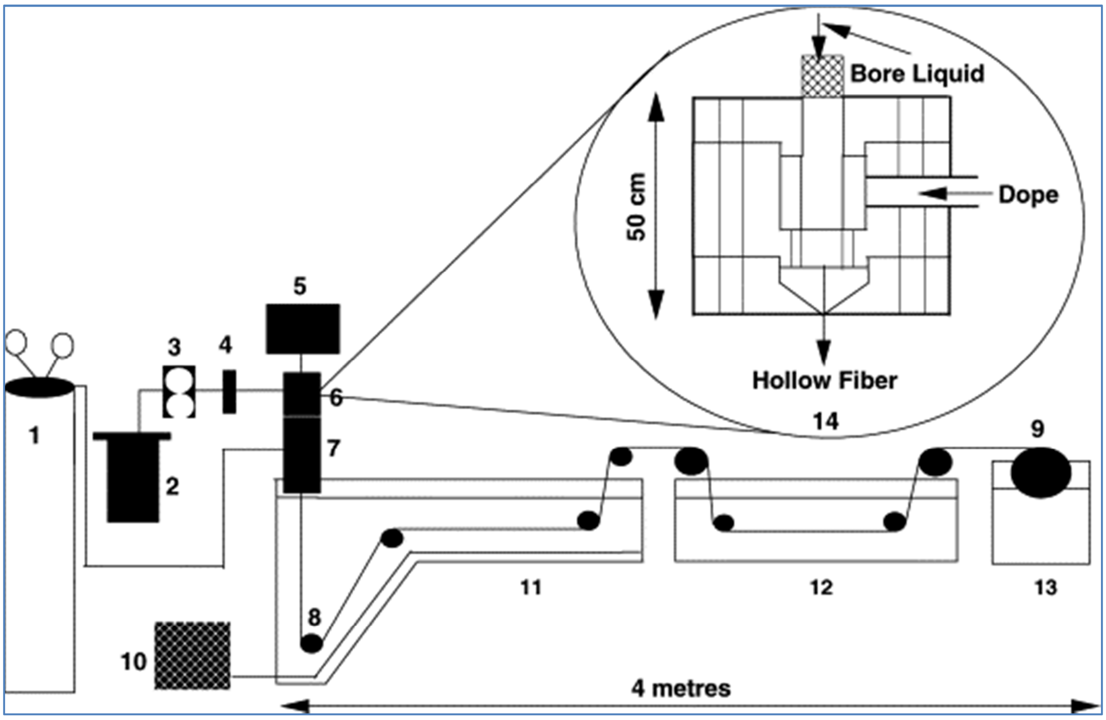


Figure 3.2: Schematic Diagram of Hollow Fibre Spinning System: (1) Nitrogen Cylinder; (2) Dope Reservoir; (3) Gear Pump; (4) On-Line Filter, 7 mm; (5) Syringe Pump; (6) Spinneret; (7) Forced Convective Tube; (8) Roller; (9) Wind-Up Drum; (10) Refrigeration/Heating Unit; (11) Coagulation Bath; (12) Washing/Treatment Bath; (13) Wind-Up Bath; (14) Schematic Spinneret

3.1.5 Membrane Module

Few HF membrane modules, each with forty hollow fibre membranes were constructed for the MBR experiment. Two membrane modules were used in every study and others were served as a backup. In the module configuration, a bundle of fibres were first bent to a “U” shape and the tip ends were inserted into a PVC pipe (3 cm long). Roughly one quarter of the pipe was filled with epoxy glue to hold the fibres in place (first layer) followed by the second layer of epoxy glue after the first layer was dried and hardened. Then, the epoxy glue was allowed to dry for another two days. After that, approximately 1 cm of the pipe from bottom was sawed off, leaving behind the final working module of around 24 cm (2 cm long pipe with 22 cm long fibres). Figure 3.3 shows the schematic diagram of the module.

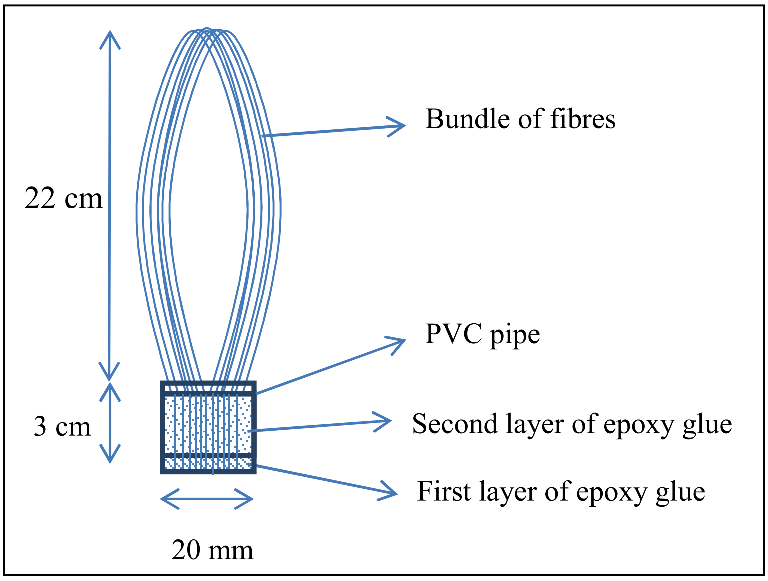


Figure 3.3: Schematic of Membrane Module

3.2 Experimental Study

3.2.1 Experiment 1: Effect of Food to Mass Ratio (F/M) on MBR System Performance

The effluent quality was investigated for different food to mass ratios (F/M) or organic loading rates (OLR). Three samples of synthetic wastewater with different COD concentrations (550 ± 50, 800 ± 50 and 1 400 ± 50 mg/L) were prepared to give different F/M ratios. The effects of organic loading on membrane performance were determined by holding HRT and MLSS concentration constant. The HRT was maintained at 4 hours with MLSS concentration maintained at 9 000 ± 1 000 mg/L. Equation 3.1 was used to calculate the F/M ratio with constant flow rate of 39 L/d (calculations shown in Appendix A) and Table 3.2 shows different F/M ratios under different COD concentrations. The COD concentrations in the effluent were measured to assess the removal efficiency and MBR performance. Other parameters such as dissolved oxygen (DO), pH and turbidity were also measured. Finally, the effluent water quality was compared with the Effluent Standards A and Standard B under the Environmental Quality (Sewage and Industrial Effluents) Regulations of

1979. The sludge characteristics such as MLSS and SVI were measured at each run to verify the proper growth of microorganisms.

$$\mathrm{F/M\ ratio} = \frac{\mathrm{COD\ (g/L)} \times \mathrm{wastewater\ flow\ rate\ (L/d)}}{\mathrm{MLSS\ (g/L)} \times \mathrm{tank\ volume\ (L)}} \tag{3.1}$$

Table 3.2: F/M Ratio at Different COD Concentrations

COD concentrations (mg/L)	F/M ratio (g COD/g MLSS·d)
550	0.37
800	0.53
1 400	0.93

3.2.2 Experiment 2: Effect of HRT on MBR System Performance

The MBR was investigated for three different HRTs including 1.30, 2.58 and 4 hours. From Equation 3.2, the influent flow rate, Q_i was determined (calculations shown in Appendix A). Table 3.3 shows the influent flow rate at different HRTs. For every HRT, the average COD concentration of synthetic wastewater was 800 ± 50 mg/L and MLSS concentration was maintained at about 8 800 ± 1 200 mg/L. The COD concentrations in the effluent were measured to assess the removal efficiency and MBR performance. Other parameters such as DO, pH and turbidity were also measured. Finally, the effluent water quality was compared with the Effluent Standards A and Standard B under the Environmental Quality (Sewage and Industrial Effluents) Regulations of 1979. The sludge characteristics such as MLSS and SVI were measured at each run to verify the proper growth of microorganisms.

$$HRT = \frac{V}{Q_i} \tag{3.2}$$

Where,

V= volume of the aeration tank

Q_i= flow rate of the influent wastewater into the aeration tank.

Table 3.3: Influent Flow Rate at Different HRTs

HRT (hours)	Flow rate (L/d)
4.00	39.00
2.58	60.50
1.30	120.00

3.2.3 Experiment 3: Effect of Mixed Liquor Suspended Solids (MLSS) on MBR System Performance

Besides HRT, the MBR was also investigated using three different MLSS concentrations which were less than 4 000, between 4 000 to 6 000 and above 7 000 mg/L. In every MLSS concentration, the average COD concentration of synthetic wastewater was 800 ± 50 mg/L and HRT was maintained at four hours. The MLSS concentration was adjusted accordingly based on the amount of sludge wastage. The COD concentrations in the effluent were measured to assess the removal efficiency and MBR performance. Other parameters such as DO, pH and turbidity were also measured. Finally, the effluent water quality was compared with the Effluent Standards A and Standard B under the Environmental Quality (Sewage and Industrial Effluents) Regulations of 1979. The sludge characteristics such as MLSS and SVI were measured at each run to verify the proper growth of microorganisms.

3.2.4 Experiment 4: Effect of Continuous, Backwash, Intermittent Permeation and Combination Operation Mode (Backwash and Intermittent Permeation) on MBR System Performance

The filtration performance was investigated by running the MBR in four operation modes, namely continuous, intermittent permeation, backwash and combination of backwash and intermittent permeation. For the continuous mode, the system was run continuously without backwash or stopping duration. For the second mode, three different stopping or membrane relaxation durations (30 s, 1 min and 2 min) were adopted with a running time of 8 minutes to study the effect of intermittent permeation (Figure 3.4).

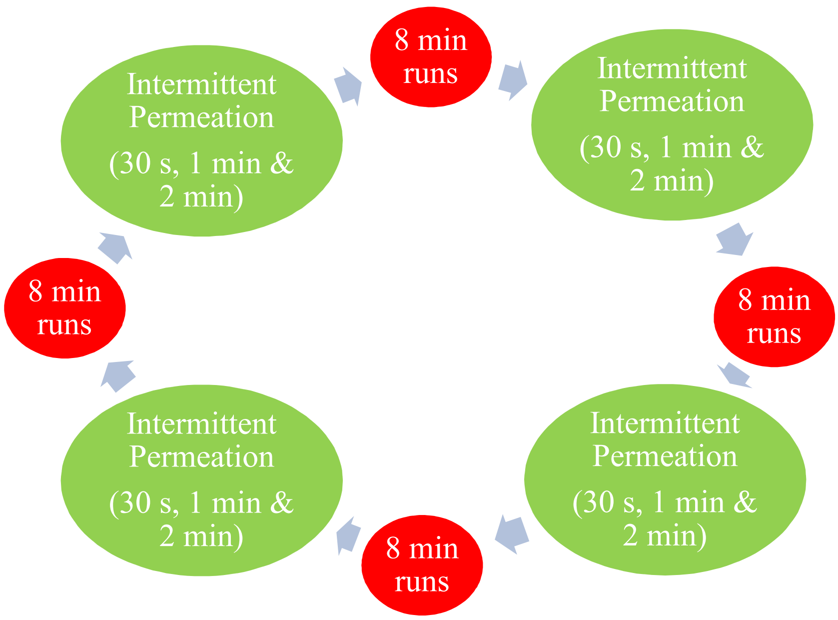


Figure 3.4: Operation Cycle Diagram for Intermittent Permeation

Similarly, three different backwash durations (15 s, 30 s and 1 min) were also applied with a running time of 8 minutes to investigate the effect of backwash on MBR filtration performance (Figure 3.5).

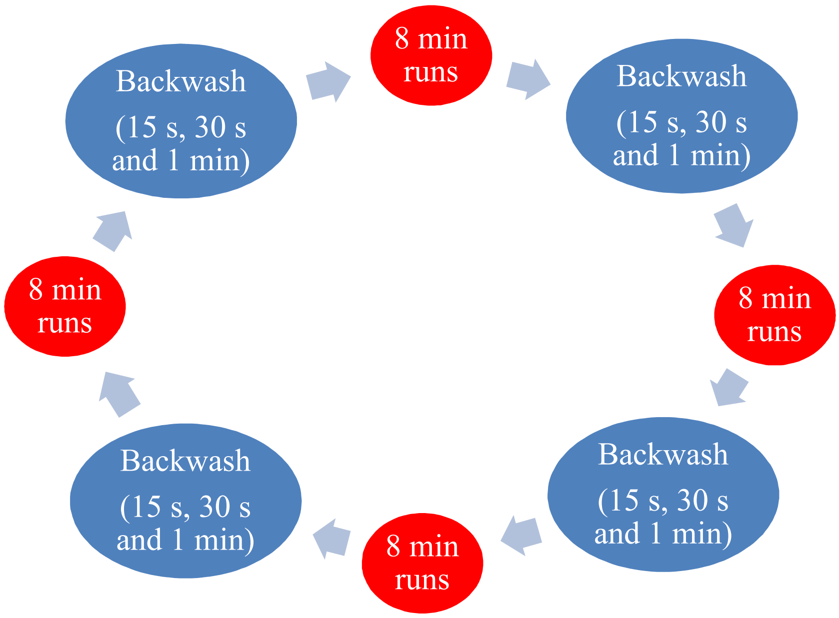


Figure 3.5: Operation Cycle Diagram for Backwash

The filtration performance was also investigated by running the system using combination mode of both backwash and intermittent permeation. In this mode (Figure 3.6), the system underwent three cycles of intermittent permeation mode where it ran for 8 minutes and stopped for 30 seconds. After the three cycles, a backwash of 30 seconds duration was conducted and the cycles were repeated. The HRT was maintained at 1 hour with MLSS concentration maintained above 10 000 mg/L. The duration for each operation mode was set to be 2 hours. Throughout the two hours operation, the filtrate was collected every 8 minutes and the volume was measured in order to determine the change of permeate flux across the time and the efficiency of water production.

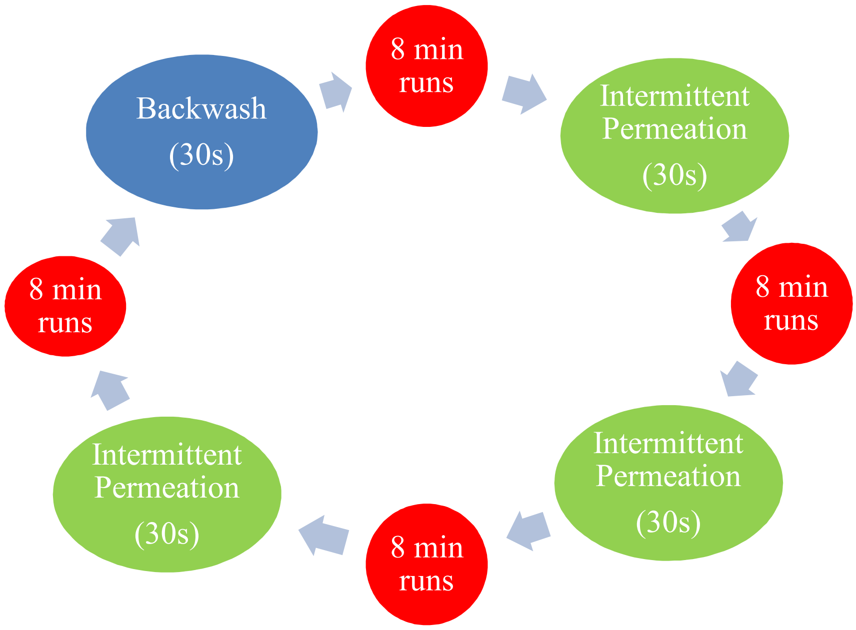


Figure 3.6: Operation Cycle Diagram for Combination Mode

3.3 Analytical Analysis

3.3.1 Membrane Characterization by Scanning Electron Microscope (SEM)

SEM (Hitachi S-3400N) was used to examine the membrane characteristics including pore size, inner and outer diameter, and morphology of the hollow fibres membranes used in this study that were prepared by Universiti Teknologi Malaysia (UTM). The membrane samples were immersed in liquid nitrogen for a few minutes, then broken and deposited on a copper holder. All samples were coated with Au/Pt in vacuum before being analysed with the SEM. The SEM micrographs of cross section and outer surface of hollow fibre membranes were taken at various magnifications from 70 k to 50 k with an accelerating voltage of 15 kV.

3.3.2 Chemical Oxygen Demand (COD) Test

Chemical Oxygen Demand (COD) was used as a measure of oxygen requirement of a sample that is susceptible to oxidation by a strong chemical oxidant. The COD test was performed using the closed reflux colorimetric method (Standard 5520 D). In the test, the samples, standards and blanks were heated at 150 ˚C in a closed reactor for two hours in the presence of acid dichromate solution. The tubes were then cooled and measured either at 420 (low range) or 610 nm (middle range). When a sample was digested, the dichromate ion oxidized organic components in the sample. This resulted in the change of chromium from the hexavalent (chromate) state to the trivalent (chromic) state. Both of these chromium species were coloured and absorb in the visible region of the spectrum. For low level of COD, the decrease in chromate was used for analysis, while for the higher values the chromic ion was measured directly.

The equipments used to carry out the analysis test were DRB200 Reactor and DR2800 spectrophotometer. The DRB200 Reactor was used to heat the samples, standard and blank. On the other hand, the DR2800 spectrophotometer was used to measure the COD concentration. Other materials and apparatus include:

- Tensette pipette, 0.1 – 1 mL + tips
- COD vials rack
- COD vials
- Paper towel
- Beaker

3.3.3 Mixed Liquor Suspended Solids (MLSS) Test

The Mixed Liquor Suspended Solids (MLSS) Test was used to determine the total amount of organic and mineral suspended solids, including microorganisms, in the mixed liquor. The MLSS test was performed using the Standard Method 2540 D. In the test, a well-mixed measured sample was filtered through a filter paper and the residue retained on the filter was dried to a constant weigh at 103 to 105 ˚C. The increase in weight of the filter represents the total suspended solids. The materials and apparatus used for this test were:

- Filter paper
- Measuring cylinder
- Pipette, 10 mL
- Analytical balance
- Oven
- Desiccator
- Buchner flask and funnel
- Vacuum pump

3.3.4 Sludge Settling

The sludge settling was conventionally described using the Sludge Volume Index (SVI). The SVI can be calculated using Equation 3.3. The settled sludge volume is determined using Method 2710 D. In the test, 1 000 mL of samples was allowed to settle in a measuring cylinder for 30 minutes. After 30 minutes, the settled sludge volume was measured.

$$\mathrm{SVI} = \frac{\text{Settled sludge volume (mL/L)} \times 1000}{\text{Suspended solids (mg/L)}} \tag{3.3}$$

- SVI = 100 mL/g is considered a good settling sludge
- SVI > 150 mL/g are typically associated with filamentous growth (Metcalf and Eddy, 2003)

3.3.5 Other Analytical Analysis

Table 3.4 shows other analytical analysis used in the experiments.

Table 3.3: Analysis of Various Parameters

Parameters	Analytical Equipments
pH	Hanna pH 211 microprocessor-based pH and temperature bench meter
DO	Waterproof DO 300 hand-held meter
Turbidity	Waterproof TN100 turbidimeter
Total Suspended Solids	Oven (Standard Method 2540 D)

3.4 Membrane Cleaning

Membranes were cleaned on a regular basis (every ten days or prior to each experimental run) to prevent fouling and ensure that the desired system filtration capacity was achieved. The module was dismantled from the MBR system and flushed with water tap to remove any residual from membrane surface. Then, the unit was soaked completely in a cleaning tank with approximately 2 000 mg/L sodium hypochlorite (NaOCl) for 6 to 24 hours. Finally, the membrane was rinsed with water to remove the chemical residual before it was reinstalled on the reactor.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Membrane Characterisation

4.1.1 SEM Observation of Cross Sectional and External Membrane Surface

Figures 4.1, 4.2 and 4.3 show the partial cross sectional view, sponge-like cross section and membrane surface of the PES membrane, respectively. Figure 4.1 indicates that the membrane was asymmetric membranes as the membrane was observed to consist of extremely thin surface layer which was supported on a much thicker and porous structure. As shown in the Figure 4.3 (b), the SEM revealed that the membranes were typical MF membrane with the pore sizes in the range of 99.2 to 147 nm. Its outer diameter was around 1.18 to 1.21 mm and inner diameter was around 646 to 677 µm. Porous surface and sponge-like cross section could also be obviously observed from Figures 4.1 and 4.2. Table 4.1 shows the membrane characteristics of the PES membrane used in this study.

Table 4.1: Membrane Characteristics of PES Membrane

Items	Characteristic
Material	Polyether sulfone (PES)
Actual pore size	0.0992 – 0.147 μm
Outer surface area	0.00165 m^2/fibre
Length	0.44 m/fibre
Total outer surface area	0.066 m^2/module
Membrane manufacturer	Universiti Teknologi Malaysia (UTM)

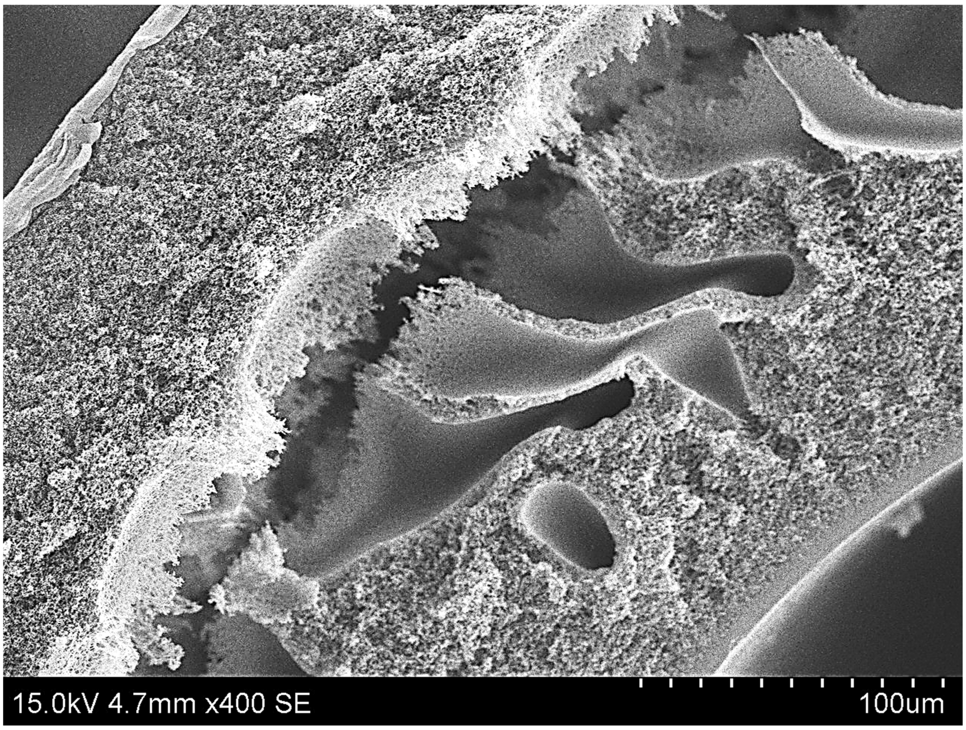


Figure 4.1: Partial Cross Sectional View of PES Membrane

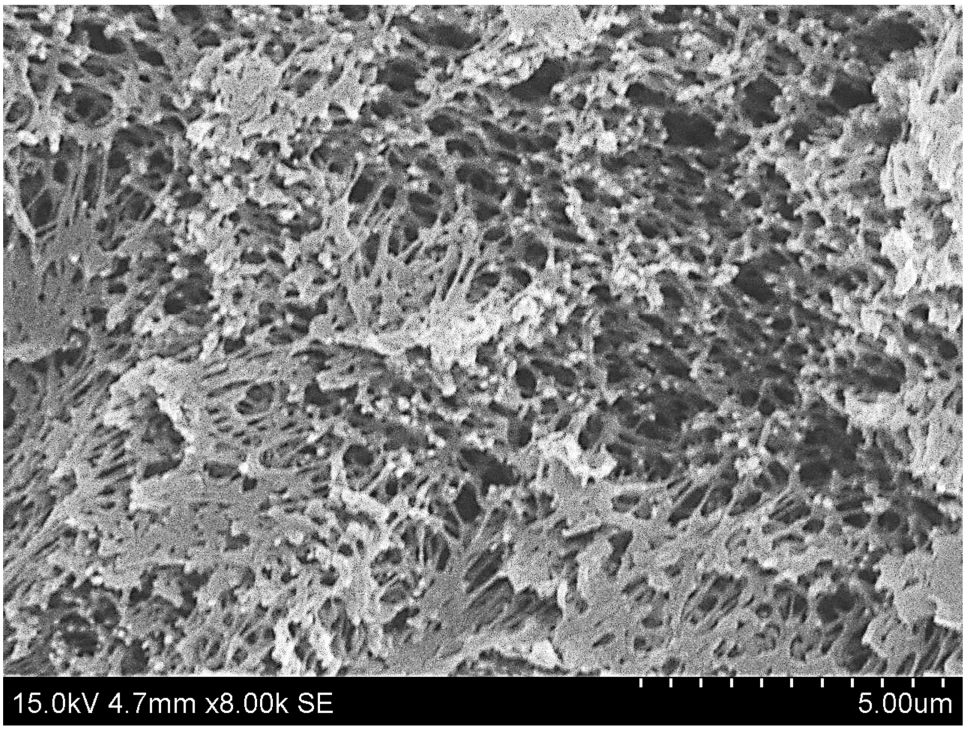
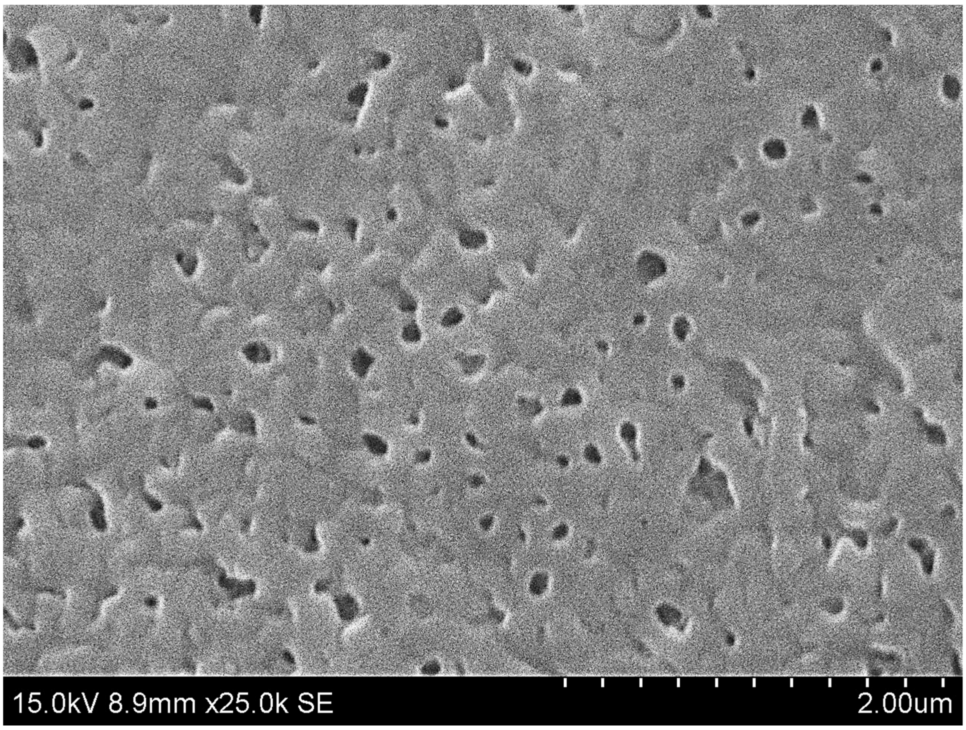
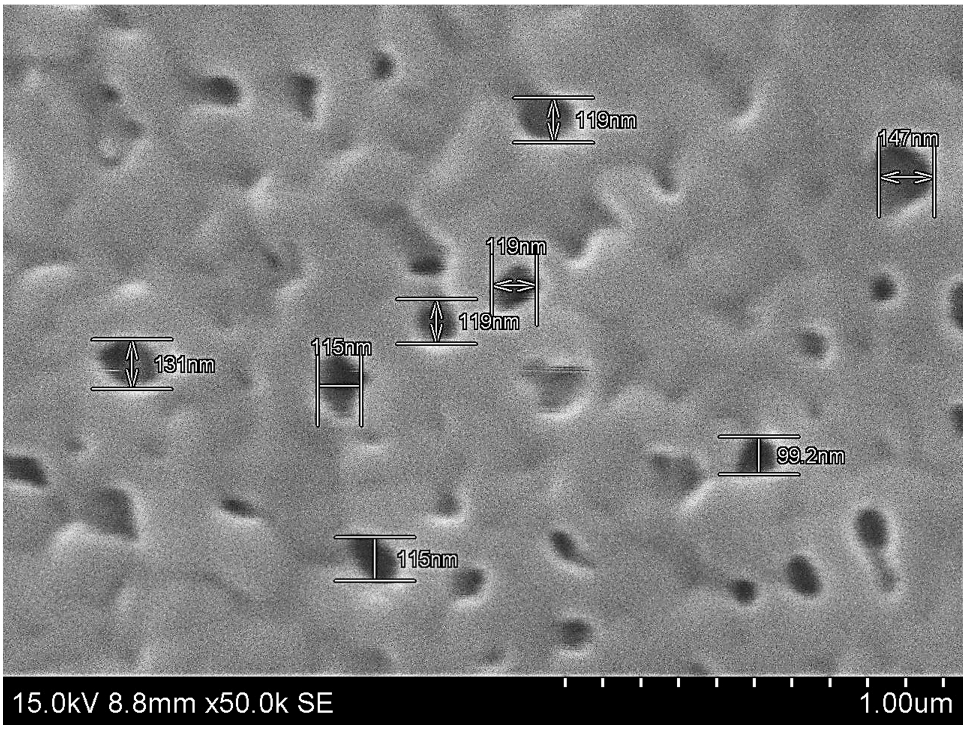


Figure 4.2: Sponge-like Cross Sectional of PES Membrane



(a)



(b)

Figure 4.3: (a) PES Membrane Surface (b) Pore Size Measurements on the PES Membrane Surface

4.2 MLSS and COD Variations During Acclimatization

The initial MLSS of the sludge was 3 390 mg/L and was allowed to acclimatize. Figure 4.4 shows the MLSS variation during acclimatization. During the acclimatization, pH was monitored regularly to range between 7 to 8 and aeration was provided to maintain the DO concentration above 5 mg/L. Starting from day 7, the surfactant of the system was filtered and the COD was examined regularly. The initial COD was 172 mg/L and the MLSS was observed to fluctuate, indicating that the system has yet to achieve stability. After 4 weeks, the COD dropped to 35 mg/L and the MLSS reached above 7 000 mg/L. The relative low COD showed that the system had stabilized. The system was then started to be used for investigating different parameters.

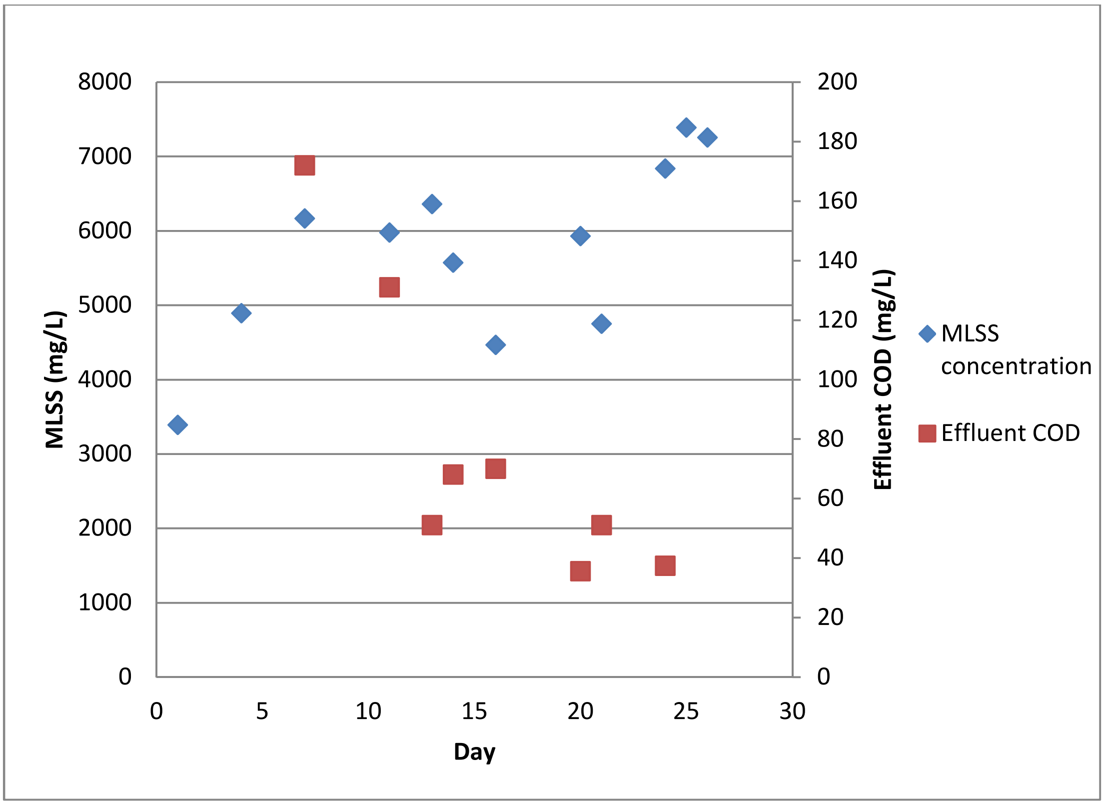


Figure 4.4: MLSS Variation During Acclimatization

4.3 Membrane performance

4.3.1 COD removal

The MBR system removed COD at a high rate under all operating conditions. In Experiment 1, three samples of synthetic wastewater with different F/M ratios were introduced into the system. Despite fluctuations in the influent F/M ratio, the MBR effluent COD was less than 40 mg/L and the COD removal under all operating conditions was greater than 94 % as illustrated in Figure 4.5. This result was in accordance with Zhu et al. (2009), who investigated the performance of submerged PES membrane bioreactor to treat domestic wastewater and reported COD removal efficiencies of 93 to 97%, despite large fluctuations in influent conditions.

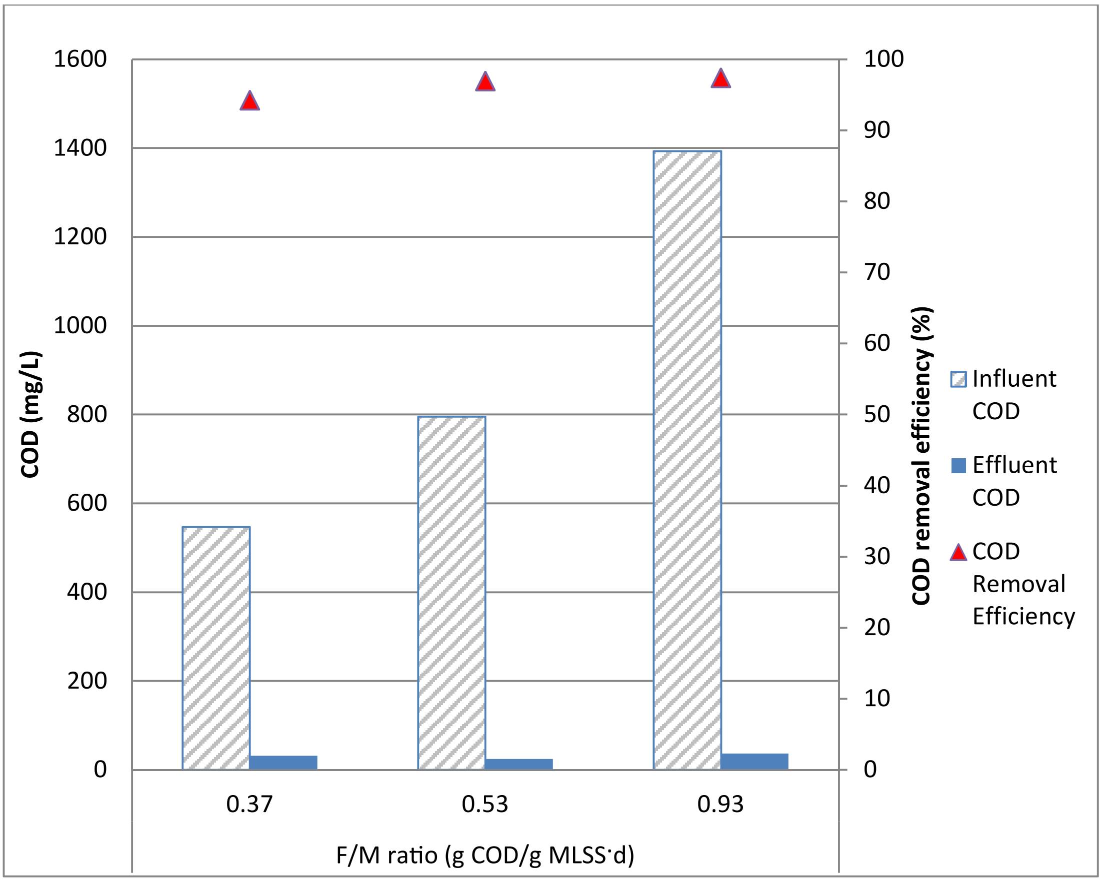


Figure 4.5: Experiment 1: Effect of Food to Mass Ratio (F/M) in MBR System Performance

From the results presented above, the change in F/M ratio has no effect on the COD efficiency and the system was proved to excellently treat wastewater of any type producing effluent with low COD. This finding was in agreement with Fan, Urbain, Qian and Manem (1996) and Stefan and Walter (2001). The former reported that the COD effluent was always low and extremely stable despite fluctuation in the influent COD. The latter used MBR in treating urban wastewater and found that the COD of the filtrate did not exceed 30 mg/L although the COD in the influent was varying between 400 and 900 mg/L. One of the reasons was because upon the addition of organic substrates, biomass responded immediately with increased respiration activity (Fan et al., 1996). Another reason was due to the fact that, as a large organic load of the wastewater resulted in a high biomass production, the system could react immediately to alternating substrate concentrations in the feed stream (Stefan & Walter, 2001).

In Experiment 2, the variation of effluent COD and removal efficiency at different HRT conditions is illustrated in Figure 4.6. The average COD concentration of effluent were 24.5, 38 and 57.5 mg/L and the average reductions of COD were 96.9 %, 95.1 % and 92.5 % when the HRTs were 4, 2.58 and 1.3 hours, respectively. This result agreed with the results reported by Ren et al. (2005) and Naghizadeh, Mahvi, Mesdaghinia and Alimohammadi (2011). In the removal of organic pollutants and analysis of MLSS–COD removal relationship at different HRTs in a submerged membrane bioreactor, Ren and his team reported COD removal rate of 89.3 - 97.3 % at HRT of 2 hours and 80 - 91.1 % at HRT of 1 hour. On the other hand, Naghizadeh et al. (2011) studied the performance of hollow fibre microfiltration membranes immersed in a bioreactor for removal of COD, TSS and turbidity from municipal wastewater and the removal efficiencies obtained were above 96 % at HRT of 4 hours.

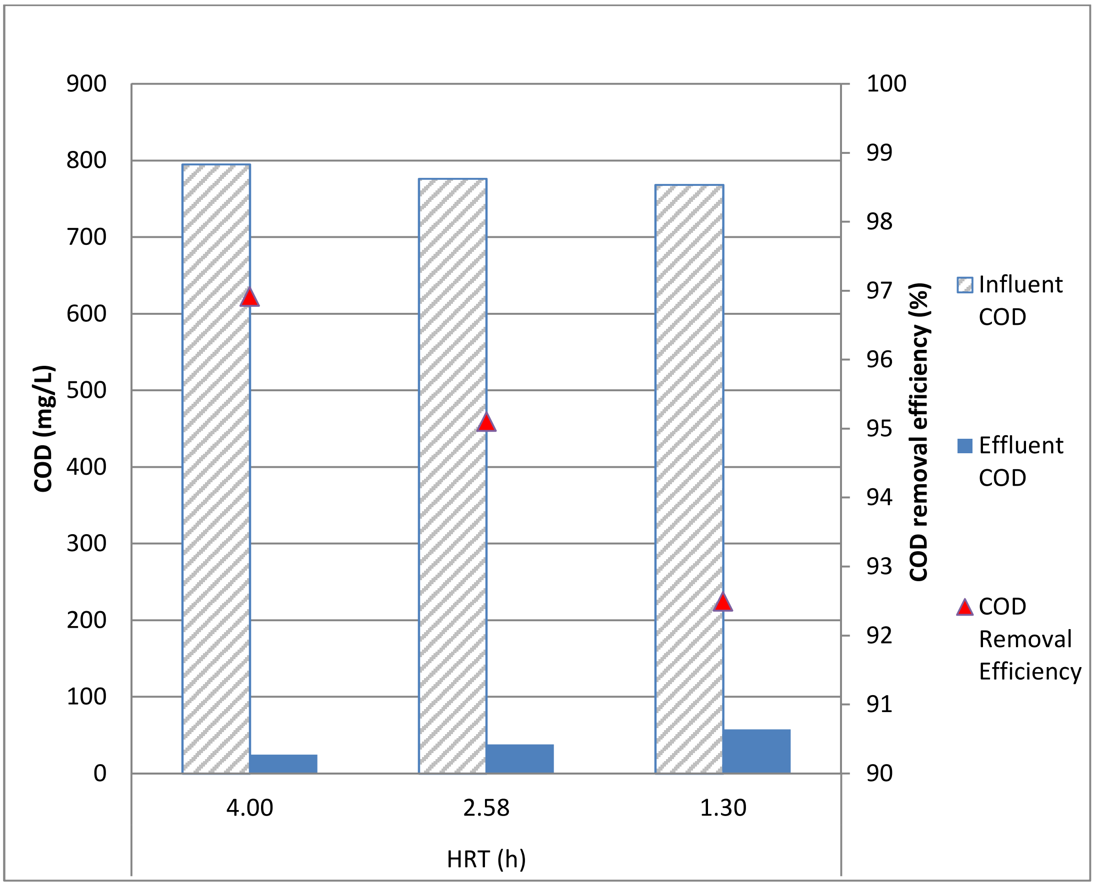


Figure 4.6: Experiment 2: Effect of HRT in MBR System Performance

The slight decrease in removal efficiency at short retention times (1.3 and 2.58 hours) might be due to insufficient time available for the substrate to transfer from liquid to biomass. Besides, another possible cause of the lower COD removal efficiency at short HRTs might be due to high oxygen consumption by the biomass. It can be seen from Figure 4.7 that the dissolve oxygen level dropped rapidly to less than 4 mg/L at both HRTs of 2.58 and 1.30 hours, while the dissolved oxygen remained almost constant at a level above 5 mg/L throughout the experiment at HRT of 4 hours. Due to the low dissolve oxygen available, the respiration activity decreased and resulted in poorer removal performance.

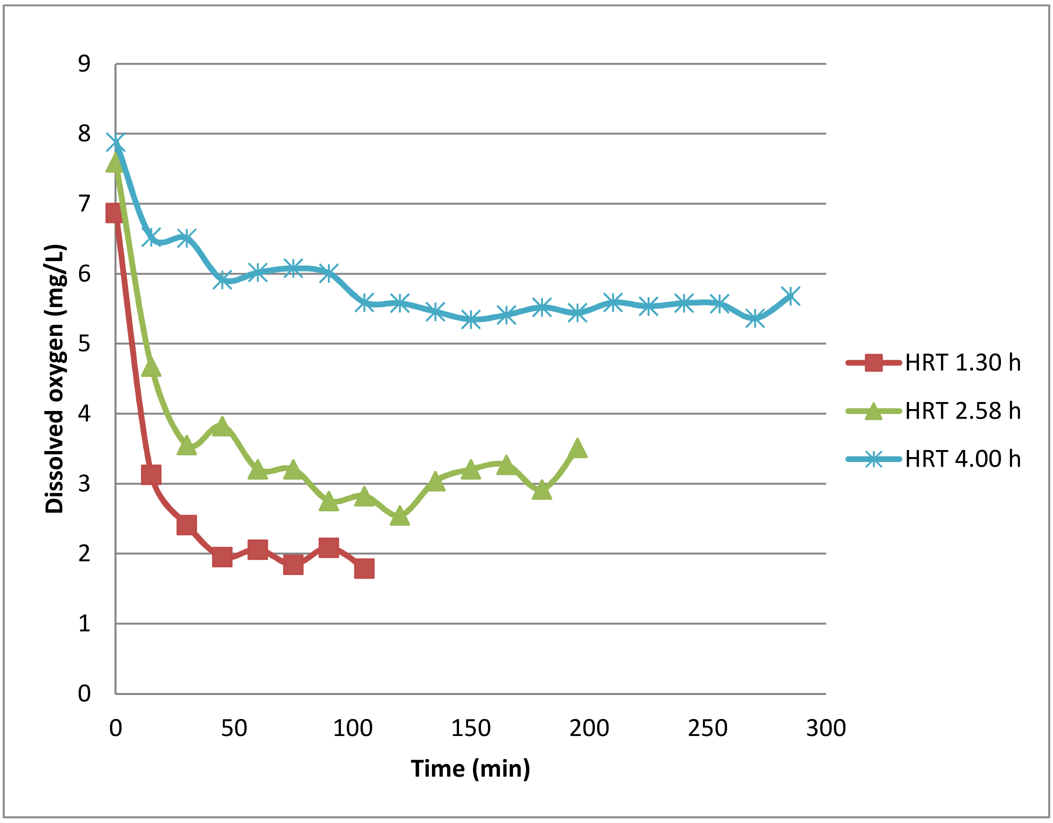


Figure 4.7: DO Levels in Experiment 2: Effect of HRT on MBR System Performance

From the results presented above it can be concluded that higher HRT resulted in better removal efficiency. Aline et al. (2007) carried out a study using a MBR treating petroleum refiner wastewater at different HRTs and they reported that the COD removal increased with an increase of HRT. Similarly, Meng, Shi, Yang and Zhang (2007) investigated the effect of HRT on membrane fouling and biomass characteristics in submerged membrane bioreactor and the results showed that the removal efficiencies of COD decreased slightly as HRT decreased accompanied with a drop in biomass activity and dissolved oxygen concentration in sludge suspension.

In Experiment 3, Figure 4.8 demonstrates that the COD removal efficiency increased slightly as the MLSS concentrations increased from 2 442.5 to 9 920 mg/L. At lower MLSS (2 442.5-3 085 mg/L), the average COD concentration of effluent was 42.5 mg/L and the average reduction of COD was 94.8 %. As the MLSS increased to above 7 000 mg/L (8 680-9 920 mg/L), the average COD of effluent was 24.5 mg/L and the average reduction of COD was 96.9 %. The slight increase in the average reduction of COD was attributed to the increase in biomass activity as the biomass concentration increased. The results of the experiments showed that high MLSS system was favourable as greater COD removal efficiency could be achieved. The high biomass concentration also allows high organic loading rate to be tolerated as the biomass activity is high (Muller, 1995). Consequently, higher strength wastewater can be treated and lower sludge production is obtained. Davies et al. (1998) used an immersed MBR operating at an average mixed liquor suspended solids (MLSS) of 16 000 mg/L and hydraulic retention time (HRT) of 4.5 hours. They reported that the MBR produced a very high quality effluent with typical BOD value of 4 mg/L. On the other hand, Al-Malack (2007) concluded that increasing the MLSS concentration was found to increase the COD removal efficiency in the investigation on the performance of an immersed membrane bioreactor in treating synthetic municipal wastewater at different MLSS concentrations of 3 000, 5 000, 10 000 and 15 000 mg/L.

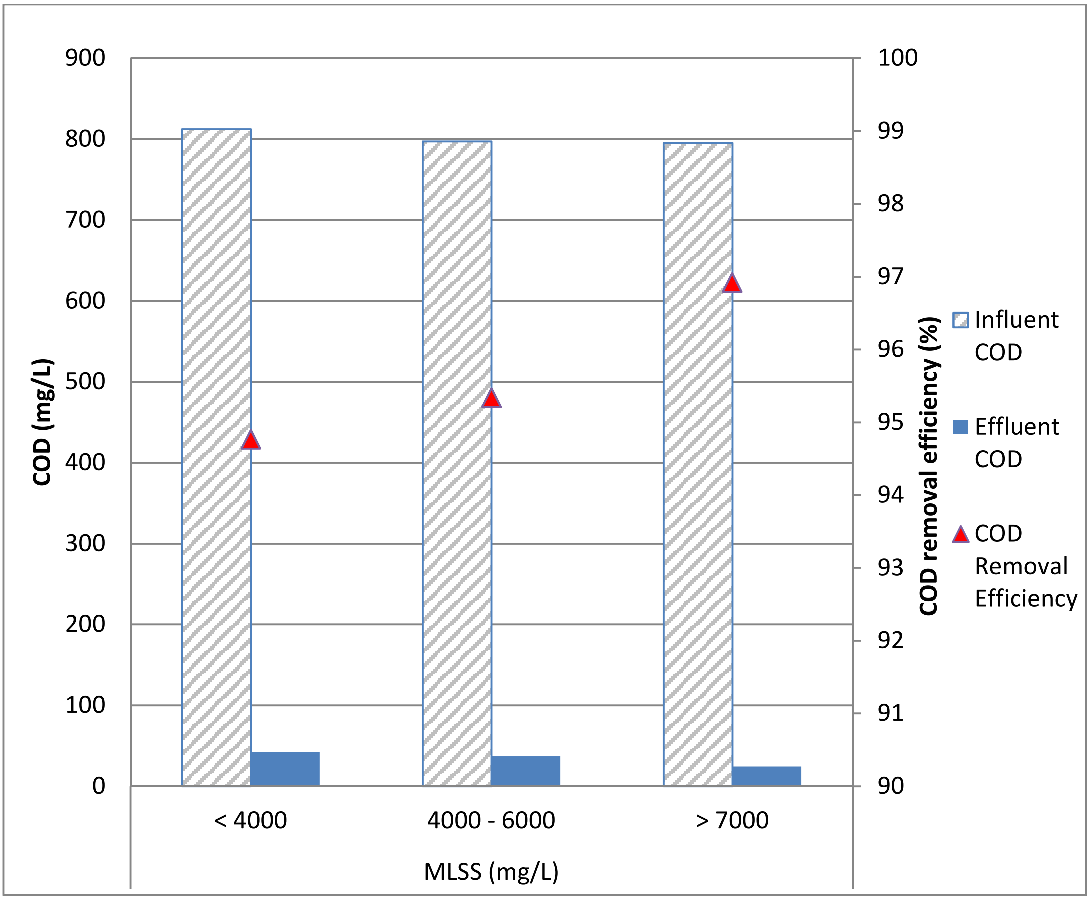


Figure 4.8: Experiment 3: Effect of Mixed Liquor Suspended Solids (MLSS) in MBR System Performance

Overall, the COD levels of all effluents from Experiments 1 and 3 complied with the Standard A of the effluent discharge standards to Malaysian inland waters (maximum permitted value for COD is 50 mg/L). On the other hand, the discharges from Experiment 2 complied with Standard B of the effluent discharge standards to Malaysian inland waters (maximum permitted value for COD is 100 mg/L).

4.3.2 Turbidity Removal

Turbidity levels of effluent samples were measured in all the experiments conducted and results are presented in Figure 4.9. The average amounts of turbidity under all operating conditions were below 0.1 NTU. This low turbidity showed that the total suspended solids (TSS) levels in the effluents were low or negligible, probably because of the perfect retention of microorganisms and particles in the MBR.

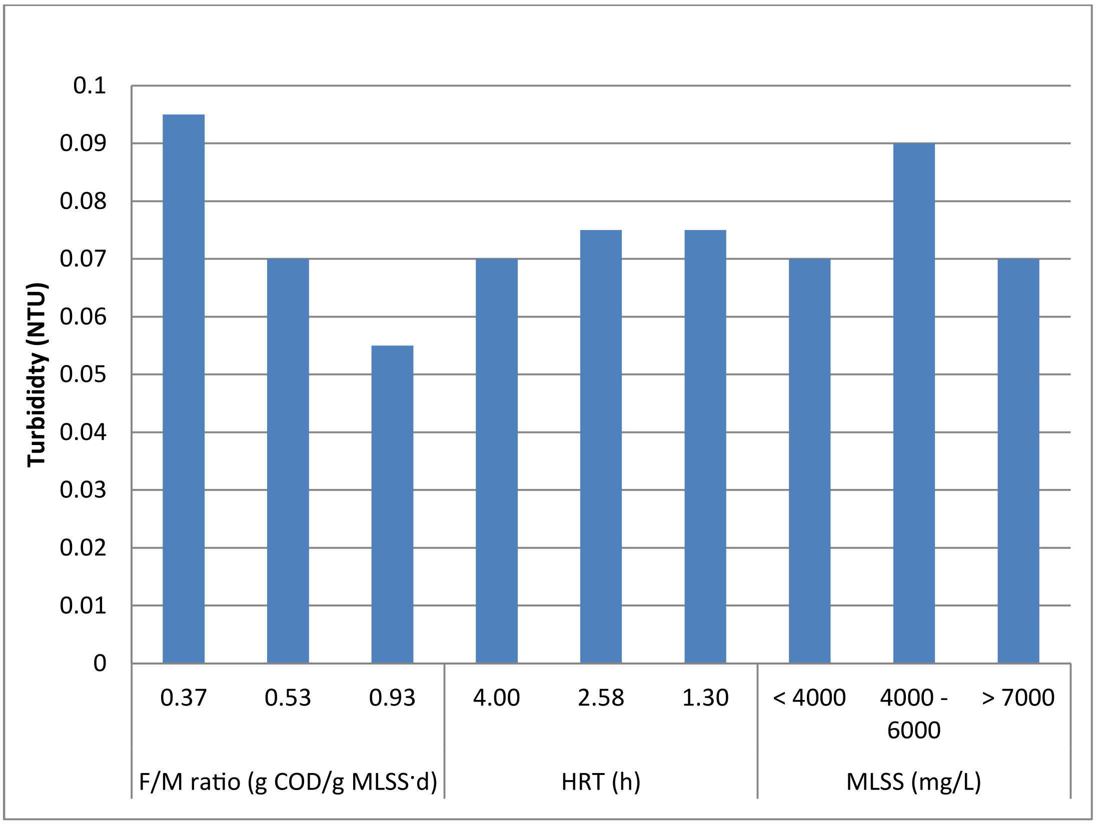


Figure 4.9: Turbidity Levels of Effluent Samples Measured in Experiment 1, 2 & 3

These results were in good agreement with previously published reports such as that of Adham, DeCarolis and Pearce (2004), who compared various MBRs manufactured by different companies. They concluded that the Zenon MBR effluent on-line turbidity performance did not exceed 0.5 NTU at any time and reported that turbidity of effluent under all operating conditions was close to the accepted standard for potable water. On the other hand, Naghizadeh et al. (2010) reported high turbidity and total suspended solids removal in their study in treating municipal wastewater. According to their findings, the TSS removal efficiency and the effluent turbidity under all conditions were more than 99% and less than 0.3 NTU, respectively.

The results of Figure 4.9 clearly indicated that the MBR system produced an effluent stream with excellent quality and had a high ability to remove TSS and turbidity compared to the CASP. Investigations conducted by researchers such as Harper et al. (2006) had proved that the effluent TSS concentration was much lower than the level of TSS in other conventional wastewater treatment processes. Furthermore, the results were far better than that required in the Standard A and B of the effluent discharge standards to Malaysian inland waters (maximum permitted values for TSS are 50 mg/L and 100 mg/L, respectively).

4.3.3 Influent and Effluent pH

The pH values of influent and effluent samples for each operating condition were measured and results are illustrated in Figure 4.10.

The pH values of the influent, ranging from 5.51 to 5.99, indicated that the influent was slightly acidic. This was probably due to the presence of potassium dihydrogen phosphate (KH_2PO_4) and iron (III) chloride ($FeCl_3$), which were added in the preparation of synthetic wastewater. On the other hand, the pH of the effluent were between 6.20 and 6.93, slightly higher than the influent pH due to the COD degradation by biomass. However, it is still slightly below 7 due to the release of carbon dioxide by the biomass from respiration. Overall, all effluent pH values complied with the effluent discharge standards to Malaysian inland waters for pH (6.0-9.0).

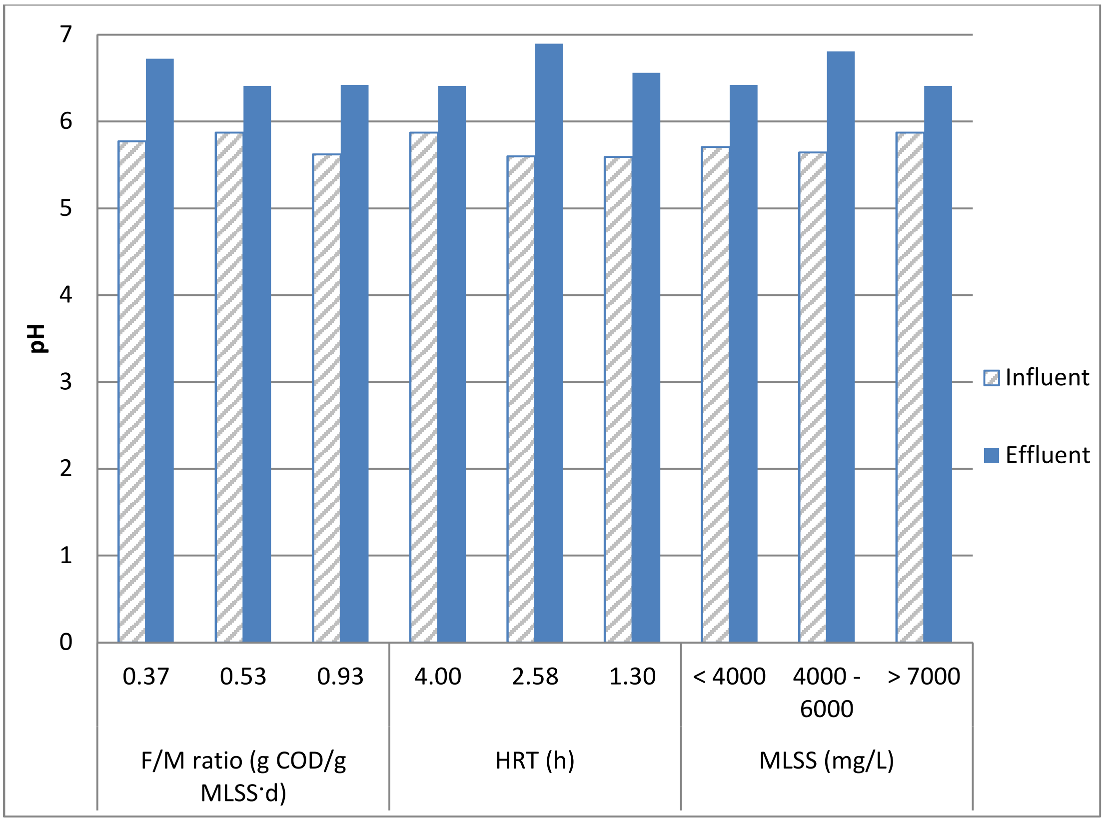
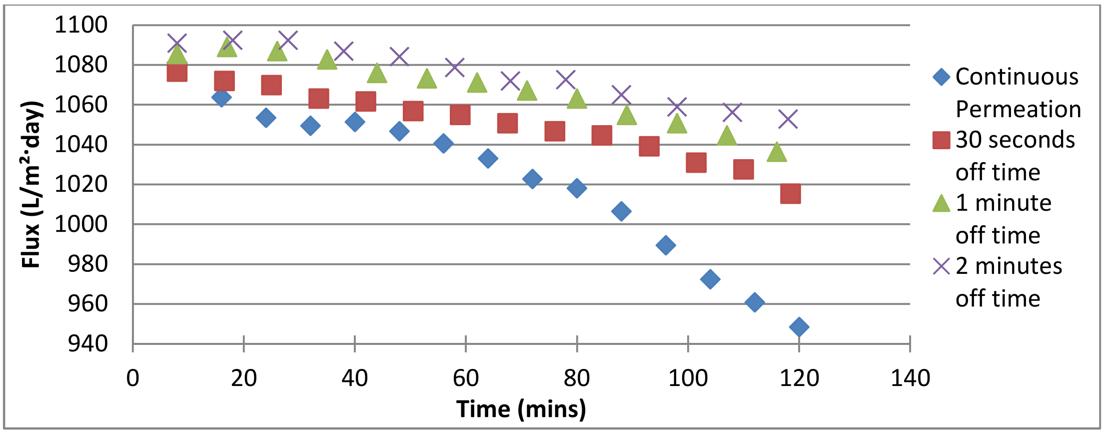


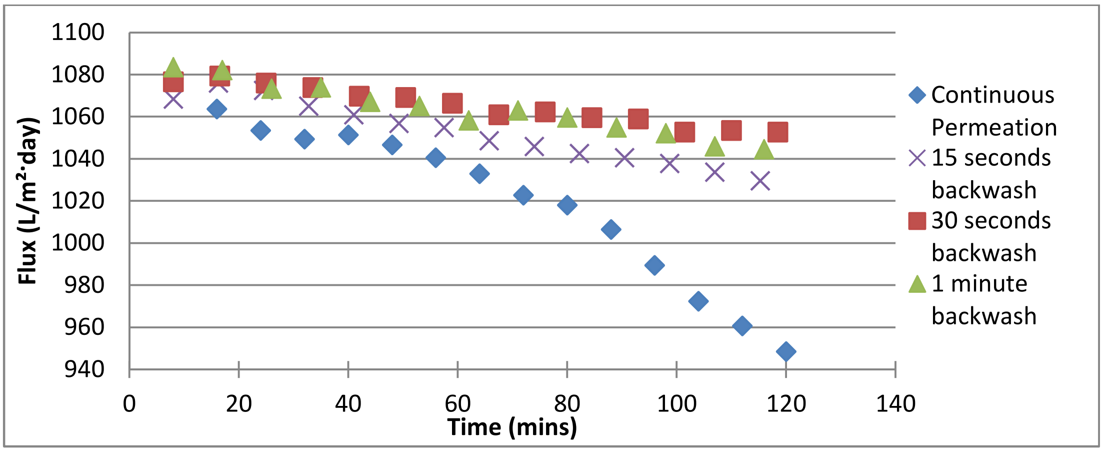
Figure 4.10: pH Values of Influent and Effluent Samples for Each Operating Condition

4.4 Filtration Performance

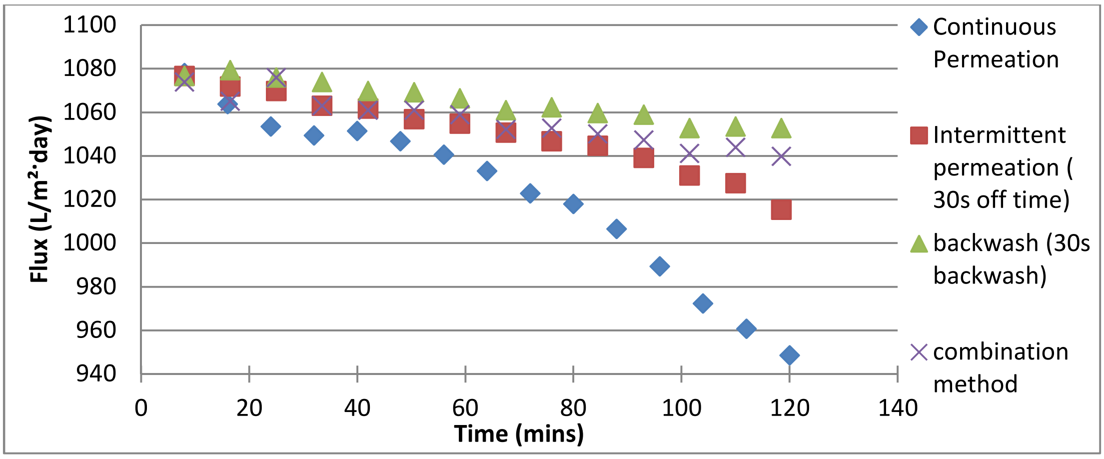
The filtration performance was investigated by running the MBR in four operation modes, namely continuous, backwash, intermittent permeation and combination of backwash and intermittent permeation. The flux profile for each operation is shown in Figure 4.11. On the other hand, the reduction in flux and efficiency in water production were calculated (calculations shown in Appendix A) and the results are summarised in Figure 4.12.



(a)

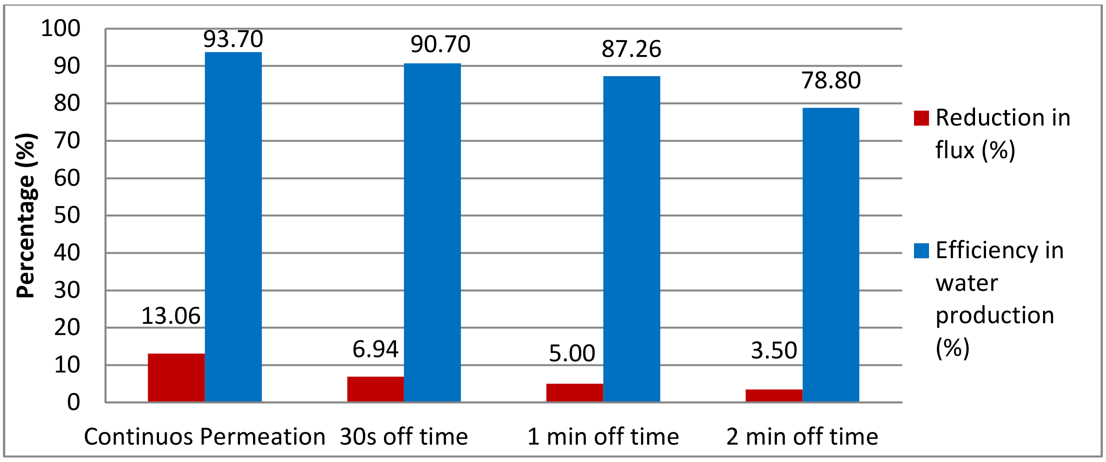


(b)

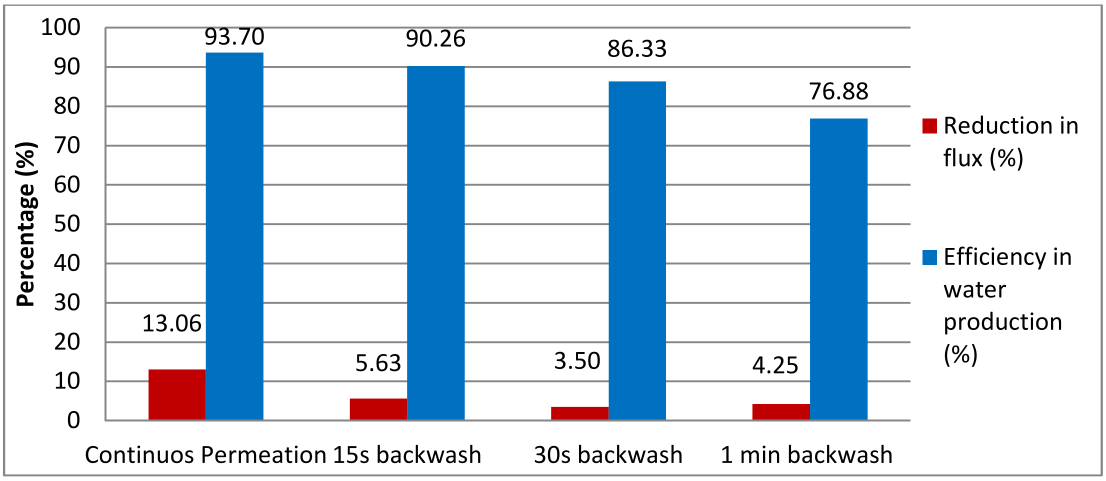


(c)

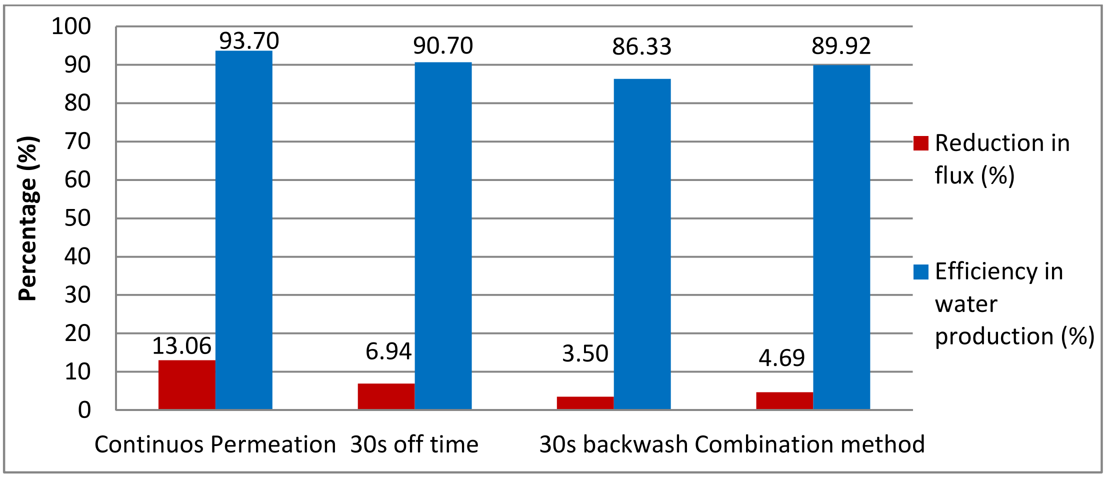
Figure 4.11: Flux Profile – (a) Continuous Permeation and Intermittent Permeation at Different Off Time, (b) Continuous Permeation and Backwash at Different Backwash Durations, (c) Comparison of Continuous Permeation, Intermittent Permeation, Backwash and Combination Method



(a)



(b)



(c)

Figure 4.12: Filtration Performance - (a) Continuous Permeation and Intermittent Permeation at Different Off Time, (b) Continuous Permeation and Backwash at Different Backwash Durations, (c) Comparison of Continuous Permeation, Intermittent Permeation, Backwash and Combination Method

4.4.1 Continuous Permeation

In Figure 4.11, the flux was observed to decrease more rapidly for continuous permeation without backwashing and intermittent stopping. After 2 hours, the flux for continuous permeation was 948.41 $L/m^2 \cdot d$, which was much lower compared to the system with backwash or intermittent permeation (1 015.23-1 052.73 $L/m^2 \cdot d$). The large value of decrease in flux (13.06 %) implied a greater fouling tendency in continuous permeation as compared to the others. This might be attributed to internal clogging and deposition as the suspended solids could not be removed from the membrane.

4.4.2 Intermittent Permeation

The effect of intermittent permeation was investigated and the results are presented in Figures 4.11 (a) and 4.12 (a). In this case, the permeation was stopped for 30 s, 1 min and 2 min for every 8 min of operation. It was observed that the flux decreased to lesser extent as the off time increased and the fluxes were higher than the continuous permeation under all intermittent permeation conditions. The reductions in fluxes were, respectively, 6.9 %, 5.0 % and 3.5 % for 30 s, 1 min and 2 min off time, while the decrease in fluxes was 13.06 % for continuous permeation.

The results clearly proved that intermittent permeation improved the flux and longer off time caused lower deposits and internal clogging. When suction was stopped and no permeate was collected, there was a period for the aeration to exert shear rate on the membrane surface to facilitate the detachment of suspended solids on membrane. As the off time increased, the period for the aeration to exert shear rate increased, more suspended solids were able to be removed from the membrane, preventing an accumulation of suspended solids, internal clogging and deposition on the membrane. The advantages of intermittent permeation have been reported by Hong et al. (2002). Hong et al. suggested that the use of intermittent suction operation could be economically feasible for controlling fouling in small-scale MBR processes treating wastewater with high fouling potentials.

Although intermittent operations were found to reduce the fouling tendency of the membrane, it resulted in a decrease in water production. Figure 4.12 (a) clearly illustrated the efficiency of water production decreased as the off time increased.

4.4.3 Backwash

Figure 4.11 (b) depicts the time course of the filtration flux under various backwash durations. Without backwash, the flux declined very quickly. However, the flux attenuation could be significantly retarted by periodic backwash operations. In each filtration-backwash cycle, permeate was pumped in reverse and inside out scheme, dislodging the internal and external foulants. Since some fouled particles were washed away from the membrane by the periodic backwash, the filtration flux could be enhanced due to decrease in filtration resistance.

Comparing the results shown in Figure 4.12 (b), the flux increased as the backwash duration increased from 15 s to 30 s. The reductions in flux were, 5.6 %, 3.5 % for backwash duration of 15 s and 30 s, respectively. This was expected since the fouled particles had more opportunities to be washed away from the membrane pores during longer backwash. The results were in good agreement with the work of Roh et al. (2005) which reported that longer duration of backwashing encouraged higher flux improvement.

However, as the backwash duration increased further, the flux no longer experienced any improvement, probably due to irreversible fouling which was not removable through backwash. One of the explanations for these phenomena might be due to the operating conditions at high flux (HRT 1 hour) and high MLSS concentrations (more than 10 000 mg/L). As mentioned by Sven et al. (2007), the sludge would deposit on the surface of the membrane easier, if the MLSS increased.

A shorter HRT increased the flux and the concentration of dissolved organic matter in reactor, resulting in acceleration of membrane fouling and increases irreversible fouling, causing backwash less effective (Jeong, Cha, Yoo & Kim, 2007; Li, 2008).

Figure 4.12 (b) depicted the efficiency of water production for continuous permeation and different backwash durations. Comparing the results of different backwash durations, the water production efficiency decreased when the backwash duration increased. This was because more filtrate needs to be pumped back for a longer backwash, and thus reduce the water production rate.

4.4.4 Combination of Intermittent Permeation and Backwash

By comparing both techniques (Figure 4.12 (c)), backwash was more efficient in reducing fouling than intermittent permeation (lower reduction in flux). In contrast, intermittent permeation permitted higher water productivity compared to backwash. Therefore, an experiment was carried out in order to investigate the possibility of overcoming the shortcomings in both intermittent permeation and backwash by combining both techniques. In this case, the permeation was stopped for 30 s followed by a filtration of 8 min. After 3 cycles of on-off operation, a backwash of 30 s was conducted followed by a filtration of 8 min and the cycles of on-off were repeated. Through the combination, it should be possible to optimize the system to obtain maximum production of water with sustainability of membrane operation.

The results are illustrated in Figures 4.11 (c) and 4.12 (c). From the results, the decrease in flux was 4.69 %, which was considerably low and the efficiency of water production was 89.92%. The results showed a significant improvement in flux through combination method when compared to the intermittent permeation (6.94 % reduction in flux) and continuous permeation (13.06 % reduction in flux). When the filtration was stopped at regular time interval before being resumed, particles deposited on the membrane surface tended to diffuse back to the reactor. This phenomena being increased by the continuous aeration applied during the resting period. While the intermittent permeation helped to maintain a membrane surface free from fouling, backwashing suppressed the fouling tendency even more by dislodging the internal and external foulants.

Though the combination method had a slightly higher percentage in flux reduction compared with the backwash system, it exhibited a much better water productivity. This was due to the fact that integration of intermittent operation into backwash operation had reduced the backwash cycle, and hence less filtrates needed to be pumped back.

The choices of the cleaning methods might be different for each wastewater treatment plant depending on their specifications. In this experiment, the optimum conditions were determined based on the ability in producing the maximum amount of water with sustainable membrane operation. The combination method was more desirable compared to the other methods due to its capabilities in reducing the fouling tendency, meanwhile producing a substantial amount of water. This method was also proven to be capable of overcoming the shortage of existing cleaning techniques such as low filtrate productivity in backwashing and lower flux improvement efficiency in intermittent permeation. In comparison between intermittent permeation and combination method, the latter showed a greater performance as it had lower fouling tendency, and could maintain almost similar water productivity as the former (less than 1 % in difference). On the other hand, the combination method also successfully mitigated the low water productivity in backwash by slightly improving the efficiency of water production from 86.33 % to 89.92 %, which was almost equivalent to the efficiency of water production in intermittent permeation.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

A membrane bioreactor and a completely mixed activated sludge system were operated at different conditions namely: F/M ratios of 0.37, 0.53 and 0.93 g COD/g MLSS·d; HRTs of 4, 2.58 and 1.3 hours; and MLSS concentrations ranging between 2 442.5 and 9 920 mg/L treating synthetic wastewater. A satisfactory effluent quality was obtained and COD removal efficiencies were higher than 92 % under all operating conditions. The change in the influent F/M ratio did not show any particular trend, but the COD removal in the bioreactor decreased slightly with decreasing HRT and MLSS concentration. The MBR was able to retain almost all particles, producing an effluent with turbidity lower than 0.1 NTU and with negligible TSS at all conditions. All results were found to comply with the effluent discharge standards to Malaysian inland waters.

In terms of filtration performance, backwashing and intermittent permeation were suitable cleaning techniques for permeate flux improvement. Longer duration of off time and backwashing produced better result of flux improvement when the off time was shorter than 2 min and backwashing was shorter than 1 min. In contrast, the back-pumping of more filtrate for longer backwash duration or longer off time in intermittent permeation caused water productivity to decrease drastically (below 80%). By combining the backwashing and intermittent permeation technique, an optimum condition was obtained where the reduction in flux was considerably low at 4.69 % with water production efficiency of 89.92%. This method was proven to be capable of overcoming the shortage of existing cleaning techniques such as low filtrate productivity in backwashing and lower flux improvement efficiency in intermittent permeation.

It can be concluded that MBR technology is able to produce excellent quality permeate, suitable for various water reuse application. It has a number of significant benefits for the treatment of municipal wastewater over the conventional activated sludge system. By integrating a suitable cleaning technique to the system, maximum production of water with sustainable membrane operation is possible, hence mitigating the fouling problem. Due to its capabilities in handling wastewater of any strength and completely retention of particles, the membrane bioreactor is recommended for application in high strength municipal wastewater treatment plants that are subjected to various concentrations of COD.

5.2 Recommendations

- Fouling was a severe problem faced during the experiments. Due to the limitation of funding and time, the study of fouling in this research was only focused on filtration performance using different cleaning techniques with different durations. The effect of the trans-membrane pressure (TMP) and air flow rate on fouling should be investigated as a future study.
- A microbiological aspect of the sludge in the MBR can be highlighted in the future study.
- This report only covered the preliminary study on the membrane performance under different operating conditions. This study can be continued by conducting a cost benefit analysis.
- It is recommended to scale up the existing MBR to pilot scale MBR.
- Further membrane characterization such as pore size distribution and surface porosity can be carried out to investigate the effects of membrane characteristics on membrane performance and filtration performance.

- The study can be repeated by using different types of membrane materials, pore sizes or configurations in the future study. Eventually, it is aimed that the membrane type, pore size and configuration for MBR application treating various types of wastewater can be optimized.

REFERENCES

Adham, S., DeCarolis, J.F. & Pearce, W. (2004). Optimization of various MBR systems for water reclamation. *Desalination and Water Purification Research and Development Report*, 103.

Aline, F.V., Geraldo, L. & Sant'Anna, J. (2007). Is hydraulic retention time an essential parameter for MBR performance. *Journal of Hazardous Materials*, 150(1), 185-186.

Al-Malack, M.H. (2007). Performance of an immersed membrane bioreactor (IMBR). *Desalination*, 214, 112-127.

Arden, E., & Lockett, W.T. (1914). Experiment on the oxidation of sewage without the aid of filters. *Journal Society of Chemical Industries*, 33, 523.

Beaubien, A., Trouve, E., Urbain, V., Amar, D. & Manem, J. (1994). Membrane bioreactors offer new solution to old wastewater treatment problems. *Environment Solution*, 34-36.

Belfort, G., Davis, R.H. & Zydney, A.L. (1994). The behaviour of suspensions and macromolecular solutions in crossflow microfiltration. *Journal of Membrane Science*, 96, 1-58.

Benzinger, W.D., Parekh, B.S. & Eichelberger, J.L. (1980). High temperature ultrafiltration with Kynarpoly(vinylidene fluoride) membranes. *Separation Science and Technology*, 15(4), 1193–1204.

Bouhabila, E., Aim, R.B. & Buisson, H. (2001).Fouling characterisation in membrane bioreactors. *Separation and Purification Technology*, 22-23, 123-132.

Bitton, G. (2011). *Wastewater Microbiology*. New York: John Wiley & Sons.

Cervantes, F.J., Pavlostathis, S.G. & Haandel, A.C. (2006). *Advanced biological treatment processes for industrial wastewaters*. London: IWA Publishing.

Chaize, S. & Huyard, A. (1991). Membrane bioreactor on domestic wastewater treatment sludge production and modelling approach. *Water Science technology*, 23(10), 1591-1600.

Chang, I.S., Clech, P.L., Jefferson, B. & Judd, S. (2002). Membrane fouling in membrane bioreactors for wastewater treatment. *Journal of Environmental Engineering*, 128(11), 1018-1029.

Chang, M.C., Horng, R.Y., Shao H. & Hu, Y.J. (2006). Performance and filtration characteristics of non-woven membranes used in a submerged membrane bioreactor for synthetic wastewater treatment. *Desalination*, 191(1–3), 8–15.

Chiemchaisri, C., Wong, Y.K., Urase, T. & Yamamoto, K. (1992). Organic stabilization and nitrogen removal in membrane separation bioreactor for domestic wastewater treatment. *Water Science Technology*, 25, 231-240.

Chin, S.S., Lim, T.M., Chiang, K. & Fane, A.G. (2006). Hybrid low-pressure submerged membrane photoreactor for the removal of bisphenol A. *Desalination*, 202, 253-261.

Cicek, N., Suidan, M.T., Ginestet, P. & Audic, J.M. (2001). Impact of soluble organic compounds on permeate flux in an anaerobic membrane bioreactor. *Environmental Technology*, 24, 249-256.

Clark, H.W. & Adams, G.O. (1914). Sewage treatment by aeration and contact in tanks containing layers of slate. *Engineering Records*, 69, 158.

Davies, W.J., Le, M.S. & Heath, C.R. (1998). Intensified activated sludge process with submerged membrane microfiltration. *Proceedings of 19th International Conference, Vancouver, Canada*, 182-189.

Dijk, L.V. & Roncken, G.C.G. (1997). Membrane bioreactors for wastewater treatment: The state of the art and new developments. *Water Science and Technology*, 35, 35-41.

D'souza, J.I. & Killedar, S.G. (2008). *Biotechnology And Fermentation Process*. PUNE: NiraliPrakashan.

Fan, X.J., Urbain, V., Qian, Y. & Manem, J. (1996). Nitrification and mass balance with a membrane bioreactor for municipal wastewater treatment. *Water Science and Technology*, 34, 129-136.

Fang, H.H.P. & Shi, X. (2005). Pore fouling of microfiltration membranes by activated sludge. *Journal of Membrane Science*, 264, 161-166.

Forster, C.F. (2003). *Wastewater treatment and technology*. London: Thomas Telford Publishing.

Gander, M., Jefferson, S. & Judd, S. (2000a). Aerobic MBRs for domestic wastewater treatment: a review with cost considerations. *Separation and Purification Technology*, 18, 119-130.

Gander, M., Jefferson, S. & Judd, S. (2000b). Membrane bioreactors for use in small wastewater treatment plants: membrane materials and effluent quality. *Water Science technology*, 41, 205-211.

Gao, D.W., Fu, Y., Tao, Y., Wu, M.W., An, R. & Li, X.X. (2009). Current research and development of controlling membrane fouling in MBR. *Journal of Biotechnology*, 8, 2993-2998.

Gray, N.F. (1989). *Biology of wastewater treatment*. New York: Oxford University Press.

Gray, N.F. (1999). *Water technology: an introduction for scientists and engineers*. Burlington: Elsevier Butterworth Heinemann.

Gunter, B. & Krauth, K. (1998). Replacement of secondary clarification by membrane separation – results with plate and hollow fibre modules. *Water Science technology*, 38, 383-393.

Hai, F.I., Yamamoto, K. & Fukushi, K. (2005). Different fouling modes of submerged hollow-fibre and FS membranes induced by high strength wastewater with concurrent biofouling. *Desalination*, 180, 89-97.

Harper, W.F., Bernhardt, M. & Newfield, C. (2006). Membrane bioreactor biomass characteristics and microbial yield at very low mean cell residence time. *Journal of Water SA*, 32(2), 193–198.

Hong, S.P., Bae, T.H., Tak, T.M., Hong, S. & Randall, A. (2002). Fouling control in activated sludge submerged hollow fibre membrane bioreactors. *Desalination*, 143 (3), 219-228.

Howell, J.A., Chua, H.C. & Arnot, T.C. (2004). In situ manipulation of critical flux in a submerged membrane bioreactor using variable aeration rates, and effects of membrane history. *Journal of Membrane Science*, 242, 13-19.

Hwang, K.J., Chan, C.S. & Tung, K.L. (2009). Effect of backwash on the performance of submerged membrane filtration. *Journal of Membrane Science*, 330, 349-356.

Hwang, Z., Ong, S.L. & Ng, H.Y. (2010). Submerged anaerobic membrane bioreactor for low-strength wastewater treatment: Effect of HRT and SRT on treatment performance and membrane fouling. *Water Research*, 45, 705-713.

Indah Water. (2011). *Sludge treatment*. Retrieved from http://www.iwk.com.my/v/customer/sludge-treatment

Innocenti, L., Bolzonella, D., Pavan, P. & Cecchi, F. (2002). Effect of sludge age on the performance of a membrane bioreactor: influence on nutrient and metals removal. *Desalination*, 146, 467-474.

Ismail, A.F., Mustaffar, M.I., Illias, R.M. & Abdullah, M.S. (2005). Effect of dope extrusion rate on morphology and performance of hollow fibres membrane for ultrafiltration. *Separation and Purification Technology*, 49(1), 10-19.

Jeison, D. & Lier, J.B.V. (2007). Thermophilic treatment of acidified and partially acidified wastewater using an anaerobic submerged MBR: Factors affecting long-term operational flux. *Water Research*, 41, 3868-3879.

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

Judd, S. (2006). *The MBR book: principles and applications of membrane bioreactors in water and wastewater treatment*. United Kingdom: Elsevier Ltd.

Le-Clech, P., Jefferson, B. & Judd, S. (2003). Impact of aeration, solids concentration and membrane characteristics on the hydraulic performance of a membrane bioreactor. *Journal of Membrane Science*, 218, 117-129.

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

Lee, W., Jeon, J.H., Cho, Y., Chung, K.Y. & Min, B.R. (2005).Behaviour of tmp according to membrane pore size. *Proceedings of International Congress on Membrane and Membrane Processes (ICOM), Seoul, Korea*.

Li, N.N. (2008). *Advanced membrane technology and applications*. New Jersey: John Wiley & Sons. Inc.

Liu, Q.L., Zhao, Y.F., Chen, L.Y. & Zheng, F. (2010). Application of MBR for hospital wastewater treatment in China. *Desalination*, 250, 605-608.

Meng, Z., Yang, F. & Zhang, X. (2005). MBR focus: do nonwovens offer a cheaper option. *Filtration + Separation*, 42 (5), 28–30.

Meng, F.G., Shi, B.Q., Yang, F.L. & Zhang, H.M. (2007). Effect of hydraulic retention time on membrane fouling and biomass characteristics in submerged membrane bioreactors. *Bioprocess and Biosystems Engineering*, 30, 359-367.

Metcalft & Eddy (1930). *Sewerage and sewage disposal, a textbook*. New York: McGraw-Hill Book Co..

Metcalf & Eddy (2004). *Wastewater engineering, treatment and reuse*. New York: Mc-Graw-HillBook Co..

Miserez, K. ,Philips, S.& Verstraete, W. (1999). New biology for advanced wastewater treatment. *Water Science and Technology*, 40, 137-144.

Mocé-Llivina, L., Jofre, J. & Muniesa, M. (2003). Comparison of polyvinylidene fluoride and polyether sulfone membranes in filtering viral suspensions. *Journal of virological methods*, 109(1), 99-101.

Mohammed, T.A., Birima, A.H., Mohd Noor, M.J.M., Muyibi, S.A. & Idris, A. (2008). Evaluation of using membrane bioreactor for treating municipal wastewater at different operating conditions. *Desalination*, 221, 502-510.

Muller, E.B., Stouthamer, A.H., Verseveld, H.W.V. & Eikelboom, D.H. (1995). Aerobic domestic wastewater treatment in pilot plant with complete sludge retention by cross-flow filtration. *Water Research*, 29, 1179-1189.

Naghizadeh, A., Mahvi, A.H., Mesdaghinia, A.R. & Alimohammadi, M. (2011). Application of MBR technology in municipal wastewater treatment. *Arab Journal for Science and Engineering*, 36, 3-10.

Noyes, R. (1994). *Unit operations in environmental engineering*. United States of America: Noyes Publications.

Ozaki,N. & Yamamoto, K. (2001). Hydraulic effects on sludge accumulation on membrane surface in cross-flow filtration. *Water Research*, 35, 3137-3146.

Pitre, M.P., Enegess, D.N. & Unterman, R. (1999). Bioreactors: The new wave in wastewater treatment. *Environment Protection*, 10(9), 30-33.

Rao, S.V. (2006). *An introduction to water pollution*. India: The ICFAI University Press.

Rautenbach, R. & Vobenkaul, K. (2001). Pressure driven membrane processes - the answer to the need of a growing world population for quality water supply and waste water disposal. *Separation and Purification Technology*, 22-23, 193-208.

Ren, N.Q., Chen, Z.B., Wang, A.J. & Hu, D.X. (2005). Removal of organic pollutants and analysis of MLSS–COD removal relationship at different HRTs in a submerged membrane bioreactor. *International Biodeterioration & Biodegradation*, 55(4), 279-284.

Roh, S.H., Shin, H.J. & Kim, S.I. (2006). Backflushing, pulsation and in-line flocculation techniques for flux improvement in crossflow microfiltration. *Korean Journal of Chemical Engineering*, 23, 391-398.

Sakrabani1, R., Mohammed, A.A. & Pae1, J.H. (2001). Treatment of industrial wastewater using membrane bioreactors (MBR) - Effluent quality & sludge Characterization. *Proceedings of World Water and Environmental Resources Congress 2001, Environmental & Water Resources Institute (EWRI), Orlando, Florida, USA*.

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

Seo, G.T., Moon, B.H., Lee, T.S., Lim T.J. & Kim I.S. (2003). Non-woven fabric filter separation activated sludge reactor for domestic wastewater reclamation. *Water Science and Technology*, 47 (1), 133–138.

Singh, G. (2009). *Applied chemistry*. New Delhi: Discovery Publishing House PVT. LTD.

Sperling, M.V. (2007). *Wastewater characteristics, treatment and disposal*. United Kingdom: IWA Publishing.

Stefan, H. & Walter, T. (2001). Treatment of urban wastewater in membrane bioreactor at high organic loading rates. *Journal of Biotechnology*, 92, 95-101.

Stephenson, T., Simon, J., Jefferson, B. & Brindle, K. (2000). *Membrane Bioreactors for Wastewater Treatment*. London: IWA Publishing.

Sven, L.,Djamila, A.H. & Thomas, W. (2007). Polymeric compounds in activated sludge supernatant – characterization and retention mechanisms at a full-scale municipal membrane bioreactor. *Water Resources*, 41, 3894-3902.

Vigneswaran, S., Shim, W.G., Chaudhary, D.S. & Ben, A.R. (2004). Mathematical modeling of submerged membrane bioreactor (smbr) system used in wastewater treatment. *Proceedings of Water Environment – Membrane Technology Conference, Seoul, Korea.*

Visvanathan, C., Ben, A. &Parameshwaran, K. (2000). Membrane separation bioreactor for wastewater treatment. *Critical reviews in Environment Science and Technology*, 30(1), 1-48.

Wang, L.K., Pereira, N.C. & Hung, Y.T. (2009). *Advanced Biological Treatment Processes*. New York: Humana Press.

Wanner, J. (1994). *Activated sludge bulking and foaming control*. United States of America: Lewis Publishers.

Water Environment Federation (WEF) (2006). *Membrane Systems for Wastewater Treatment*. United States of America: The McGraw-Hill Companies.

Wu, B., Yi, S. & Fane, A.G. (2011). Microbial community developments and biomass characteristics in membrane bioreactors under different organic loadings. *Bioresource technology*, 102(13), 6808-6814.

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

Yamamoto, K. (2001). Membrane bioreactor: An advanced wastewater treatment/reclamation technology and its function in excess-sludge minimization. *Advances in Water and Wastewater Treatment Technology*, 229-237.

Yamanoi, I. & Kageyama, K. (2010). Evaluation of bubble flow properties between flat sheet membranes in membrane bioreactor. *Journal of Membrane Science*, 360, 102-108.

Yeo, Y. & Fane, A.G. (2004). Performance of individual fibres in a submerged hollow fibre bundle. *Proceedings of Water Environment – Membrane Technology Conference, Seoul, Korea.*

Zhu, T., Xie, Y.H., Jiang, J., Wang, Y.T., Zhang, H.J. & Nozaki, T. (2009). Comparative study of polyvinylidene fluoride and PES flat membranes in submerged MBRs to treat domestic wastewater. *Water Science Technology*, 59(3), 399-405.

APPENDICES

APPENDIX A: Sample Calculations

1. Food to Mass (F/M) Ratio Calculations

Referring to Table 3.2,

Influent COD concentrations = 550 mg/L
Mixed Liquor Suspended Solids (MLSS) concentration = 9 000 mg/L
Hydraulic retention times (HRT) = 4 hours
Tank volume, V = 6.5 liters

$$\text{Wastewater flow rate, } Q_i = \frac{V}{\text{HRT}} = \frac{6.5\ \text{L}}{4\ \text{h}} = 39\ \text{L/d}$$

$$\text{F/M ratio} = \frac{\text{COD (g/L)} \times \text{wastewater flow rate (L/d)}}{\text{MLSS (g/L)} \times \text{tank volume (L)}}$$

$$\text{F/M ratio} = \frac{0.55\ \text{(g/L)} \times 39\text{(L/d)}}{9\ \text{(g/L)} \times 6.5\ \text{(L)}}$$

$$\text{F/M ratio} = 0.37\ \text{g COD/g MLSS·d}$$

2. COD Removal Efficiency Calculations

Referring to Table B.1,

Influent COD = 787.20 mg/L

Effluent COD = 24.83 mg/L

$$\text{COD removal} = \frac{\text{Influent COD} - \text{Effluent COD}}{\text{Influent COD}} \times 100\%$$

$$\text{COD removal} = \frac{787.2\ \text{mg/L} - 24.83\ \text{mg/L}}{787.2\ \text{mg/L}} \times 100\%$$

$$\text{COD removal} = 96.85\ \%$$

3. Filtration Performance Calculations

Referring to Table B.4,

Initial flux = 1 090.91 $L/m^2 \cdot d$

Final flux = 948.41 $L/m^2 \cdot d$

Total volume of permeate = 11 244.5 mL

$$\text{Reduction in flux} = \frac{\text{Initial flux} - \text{final flux}}{\text{Initial flux}} \times 100\%$$

$$\text{Reduction in flux} = \frac{1\ 090.91 - 948.41}{1\ 090.91} \times 100\%$$

$$\text{Reduction in flux} = 13.06\%$$

$$\text{Effciency in water production} \\ = \frac{\text{Total volume of permeate}}{\text{Total volume of permeate with no fouling}} \times 100\%$$

$$\text{Effciency in water production} = \frac{11\ 244.5\ \text{mL}}{12\ 000\ \text{mL}} \times 100\%$$

$$\text{Effciency in water production} = 93.7\ \%$$

APPENDIX B: Results of Experiment 1, 2, 3 & 4

Table B.1: Experiment 1: Effect of Food to Mass Ratio (F/M) in MBR System Performance

	F/M ratio (g COD/g MLSS·d)						
	0.37		0.53			0.93	
Run	1	2	1	2	3	1	2
Influent COD (mg/L)	578.50	515.50	787.20	789.00	810.20	1 370.00	1 416.00
Effluent COD (mg/L)	33.50	30.00	24.83	24.50	24.17	35.00	39.00
COD removal (%)	94.20	94.18	96.85	96.89	97.02	97.45	97.25
Effluent turbidity	0.10	0.09	0.08	0.04	0.09	0.08	0.03
Influent pH	5.88	5.67	5.99	5.84	5.79	5.40	5.84
Effluent pH	6.52	6.93	6.43	6.61	6.20	6.53	6.32
MLSS (mg/L)	9 245.00	9 390.00	8 680.00	8 705.00	9 920.00	10 037.50	9 812.00
SVI	88.70	85.20	92.20	107.70	85.70	77.70	76.50

Table B.2: Experiment 2: Effect of HRT in MBR System Performance

	HRT (hour)						
	4.00			2.58		1.30	
Run	1	2	3	1	2	1	2
Influent COD (mg/L)	787.20	788.50	810.20	784.00	769.00	784.00	753.00
Effluent COD (mg/L)	24.83	24.50	24.17	38.00	38.00	58.50	56.83
COD removal (%)	96.85	96.89	97.02	95.20	95.06	92.54	92.45
Effluent turbidity	0.08	0.04	0.09	0.07	0.08	0.05	0.10
Influent pH	5.99	5.84	5.79	5.69	5.51	5.56	5.63
Effluent pH	6.43	6.61	6.20	6.97	6.83	6.67	6.46
MLSS (mg/L)	8 680.00	8 705.00	9 920.00	7 125.00	7 863.00	7 883.00	8 175.00
SVI	92.20	107.70	85.70	105.30	96.70	101.60	100.30

Table B.3: Experiment 3: Effect of Mixed Liquor Suspended Solids (MLSS) in MBR System Performance

	MLSS (mg/L)						
	<4 000		MLSS 4 000-6 000		MLSS >7 000		
Run	1	2	1	2	1	2	3
COD influent (mg/L)	824.50	799.80	808.00	786.50	787.20	788.50	810.20
COD effluent (mg/L)	42.00	43.00	37.50	36.90	24.83	24.50	24.17
COD removal (%)	94.91	94.62	95.36	95.31	96.85	96.89	97.02
Effluent turbidity	0.04	0.10	0.10	0.08	0.08	0.04	0.09
Influent pH	5.55	5.87	5.59	5.70	5.99	5.84	5.79
Effluent pH	6.33	6.52	6.76	6.86	6.43	6.61	6.20
MLSS (mg/L)	2 443.00	3 085.00	5 928.00	5 778.00	8 680.00	8 705.00	9 920.00
SVI	118.70	87.50	97.70	96.90	92.20	107.70	85.70

Table B.4: DO Levels in Experiment 2: Effect of HRT on MBR System Performance

Time (min)	Dissolved Oxygen (DO)		
	HRT 1.30 h	HRT 2.58 h	HRT 4.00 h
0	6.87	7.59	7.88
15	3.13	4.68	6.52
30	2.41	3.56	6.51
45	1.96	3.83	5.92
60	2.06	3.21	6.02
75	1.85	3.21	6.08
90	2.09	2.76	6.01
105	1.79	2.83	5.59
120		2.55	5.58
135		3.04	5.46
150		3.21	5.35
165		3.27	5.41
180		2.92	5.52
195		3.52	5.44
210			5.59
225			5.54
240			5.58
255			5.57
270			5.36
285			5.68

Table B.5: Experiment 4 (a): Effect of Continuous Permeation on MBR Flux

Time (min)	Flux ($L/m^2 \cdot d$)
0	1 090.91
8	1 077.96
16	1 063.64
24	1 053.41
32	1 049.32
40	1 051.36
48	1 046.59
56	1 040.46
64	1 032.96
72	1 022.73
80	1 017.96
88	1 006.36
96	989.32
104	972.27
112	960.68
120	948.41

Table B.6: Experiment 4 (b): Effect of Intermittent Permeation on MBR Flux

Time (min)	Flux ($L/m^2 \cdot d$) 30 seconds off time	Time (min)	Flux ($L/m^2 \cdot d$) 1 minute off time	Time (min)	Flux ($L/m^2 \cdot d$) 2 minutes off time
0	1 090.91	0	1 090.91	0	1 090.91
8.00	1 076.59	8.00	1 085.46	8.00	1 090.91
16.50	1 071.82	17.00	1 088.86	18.00	1 092.27
25.00	1 069.77	26.00	1 086.82	28.00	1 092.27
33.50	1 062.96	35.00	1 082.73	38.00	1 086.82
42.00	1 061.59	44.00	1 075.91	48.00	1 084.09
50.50	1 056.82	53.00	1 073.18	58.00	1 078.64
59.00	1 054.77	62.00	1 071.14	68.00	1 071.82
67.50	1 050.68	71.00	1 067.05	78.00	1 072.50
76.00	1 046.59	80.00	1 062.96	88.00	1 065.00
84.50	1 044.55	89.00	1 054.77	98.00	1 058.86
93.00	1 039.09	98.00	1 050.68	108.00	1 056.14
101.50	1 030.91	107.00	1 044.55	118.00	1 052.73
110.00	1 027.50	116.00	1 036.36		
118.50	1 015.23				

Table B.7: Experiment 4 (c): Effect of Backwash on MBR Flux

Time (min)	Flux (L/m²·d) 15 seconds backwash	Time (min)	Flux (L/m²·d) 30 seconds backwash	Time (min)	Flux (L/m²·d) 2 minutes off time
0	1 090.91	0	1 090.91	0	1 090.91
8.00	1 068.41	8.00	1 076.59	8.00	1 083.41
16.25	1 075.91	16.50	1 079.32	17.00	1 082.05
24.50	1 072.50	25.00	1 075.91	26.00	1 073.18
32.75	1 065.00	33.50	1 073.86	35.00	1 073.86
41.00	1 060.91	42.00	1 069.77	44.00	1 067.05
49.25	1 056.82	50.50	1 069.09	53.00	1065.00
57.50	1 054.77	59.00	1 066.36	62.00	1 058.18
65.75	1 048.64	67.50	1 060.91	71.00	1 062.96
74.00	1 045.91	76.00	1 062.27	80.00	1 059.55
82.25	1 042.50	84.50	1 059.55	89.00	1 054.77
90.50	1 040.46	93.00	1 058.86	98.00	1 052.05
98.75	1 037.73	101.50	1 052.73	107.00	1 045.91
107.00	1 033.64	110.00	1 053.41	116.00	1 044.55
115.25	1 029.55	118.50	1 052.73		

Table B.8: Experiment 4 (d): Effect of Combination Method (Backwash and Intermittent Permeation) on MBR Flux

Time (min)	Flux ($L/m^2 \cdot d$)
0	1 090.91
8.00	1 073.86
16.50	1 065.00
25.00	1 075.91
33.50	1 062.96
42.00	1 060.91
50.50	1 060.91
59.00	1 058.86
67.50	1 052.05
76.00	1 052.73
84.50	1 050.00
93.00	1 047.27
101.50	1 041.14
110.00	1 043.86
118.50	1 039.77

Table B.9: Experiment 4 (e): Effect of Continuous, Backwash, Intermittent Permeation and Combination Operation Mode (Backwash and Intermediate Permeation) on MBR Filtration Performance

	Continuous permeation	Intermittent permeation off time			Backwash duration			Combination
		30s	1 min	2 mins	15s	30s	1 min	
Total water production in 2hrs (mL)	11 244.50	10 884.50	10 471.50	9 456.50	10 831.00	10 359.00	9 225.50	10 790.00
Reduction in flux (%)	13.06	6.94	5.00	3.50	5.63	3.50	4.25	4.69
Efficiency in water production (%)	93.70	90.70	87.26	78.80	90.26	86.33	76.88	89.92

APPENDIX C: Setup of This Study

Figure C.1: Experiment Setup

Figure C.2: Hollow Fibre Membrane Module

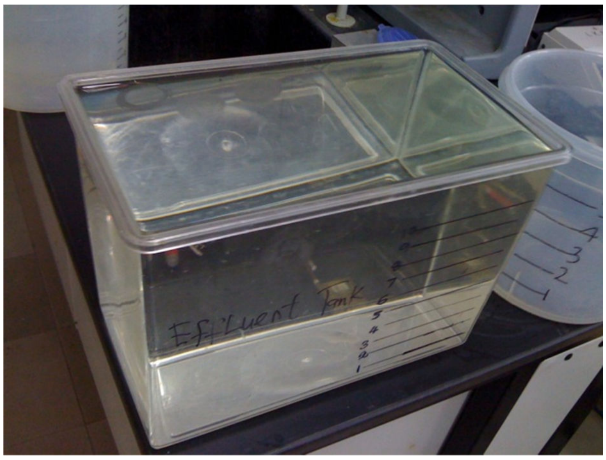


Figure C.3: MBR Effluent

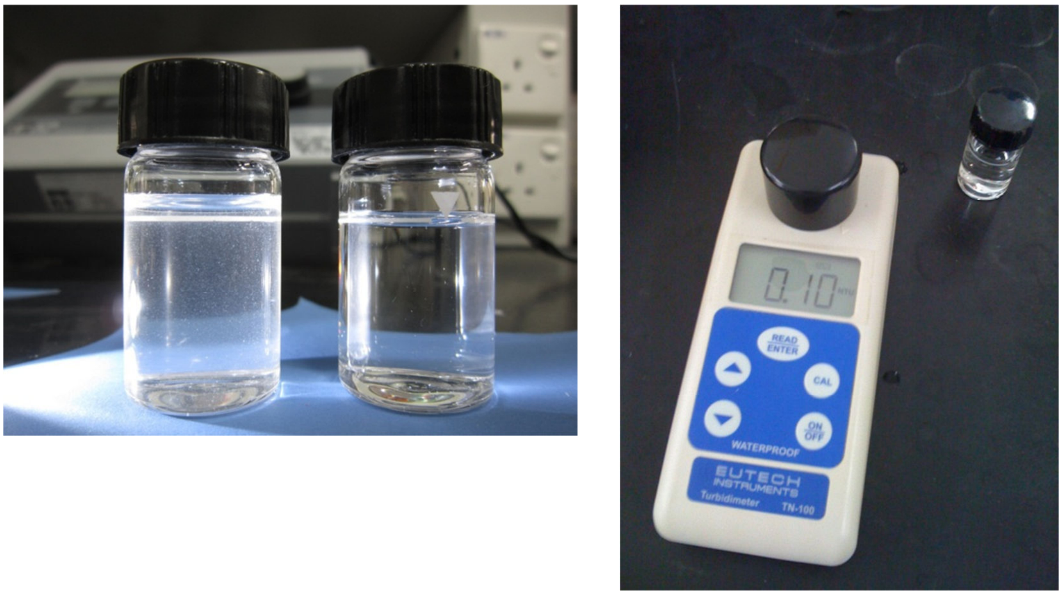
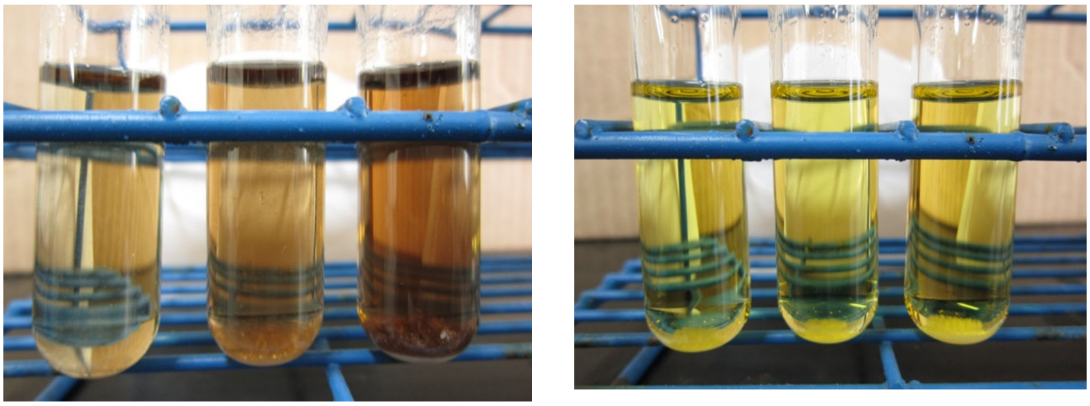


Figure C.4: Turbididty Test



(a) (b)

Figure C.5: COD Test (a) Influent (b) Effluent

Figure C.6: pH Test

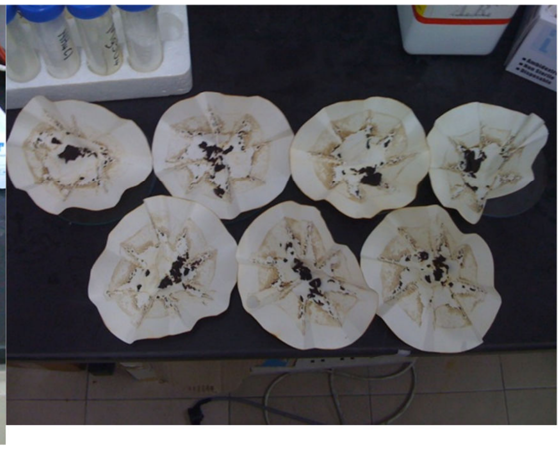


Figure C.7: MLSS Test