# Application of Membrane Bioreactors for Water Reuse

**V. Jegatheesan[1*], L. Shu[1], C. Visvanathan[2]**

[1]School of Engineering, James Cook University, Townsville, QLD 4811, Australia

Tel: +61 7 4781 4871; Fax: +61 7 4781 6788; email: jega.jegatheesan@jcu.edu.au

[2]Environmental Engineering and Management Program, School of Environment, Resources and Development, Asian Institute of Technology, PO Box 4, Klong Luang, Pathumthani 12120, Thailand

## Abstract

Water reuse is becoming increasingly popular all over the world which requires advanced wastewater treatment processes to achieve the standards required for reuse water. This paper discusses the application of biotechnology in the state-of-the-art membrane bioreactor (MBR) that is used to treat domestic, aquaculture and industrial effluents for the purpose of reuse. The advantages of a MBR compared to the conventional activated sludge process that is used to treat wastewater effluents are (i) production of high quality treated effluent, (ii) low investment cost due to smaller foot-print, (iii) higher biomass concentration and therefore lower food to micro-organisms ratio and (iv) less cost on sludge handling due to lower sludge growth and higher sludge age. However, the disadvantages of a MBR are the disintegration of micro-organisms and excretion of soluble microbial products (SMP) that leads to frequent fouling of membranes. This paper evaluates the unique biological environment, in which a MBR is placed, the rate of fouling of membrane surfaces, level of extra-cellular polymeric substances produced and the quality of effluents obtained in treating the above mentioned wastewaters with the data obtained from laboratory and pilot scale studies.

**Keywords:** Aquaculture effluent, biological environment, domestic wastewater, membrane bioreactor, fouling, water reuse

[*] Corresponding author

## 1. Introduction

Water reuse is becoming increasingly popular all over the world due to diminishing resources of water supply and increasing demand. However, water reuse requires advanced wastewater treatment processes to achieve the standards required for reuse water. Membrane bioreactor (MBR) is one of the advanced wastewater treatment processes that is starting to replace the conventional activated sludge process (ASP) which is used to treat domestic, aquaculture, industrial and various other effluents. The conventional activated sludge process is comprised of an aeration tank where the biodegradable organic substances from the effluent are consumed by suspended microbial culture followed by a sedimentation tank to settle out the microbial culture from the suspension (Figure 1a). The MBR is constructed in one of the following two modes: (i) side stream MBR where the MBR is connected to the aeration tank externally (Figure 1b), (ii) submerged MBR where the MBR is submerged in the aeration tank (Figure 1c). In both modes the filtrate (or permeate) is obtained through the membrane either due to the available head or using suction pumps.

The advantages of a MBR compared to the conventional activated sludge process that is used to treat wastewater effluents are (i) production of high quality treated effluent, (ii) low investment cost due to smaller foot-print, (iii) higher biomass concentration and therefore lower food to micro-organisms ratio and (iv) less cost on sludge handling due to lower sludge growth and higher sludge age. However, the disadvantages of a MBR are the disintegration of micro-organisms and excretion of soluble microbial products (SMP) that leads to frequent fouling of membranes. In order to operate a MBR effectively, the factors such as of mixed liquor suspended solids (MLSS), sludge retention time (SRT), hydraulic retention time (HRT), the suction time of permeate, relaxation time of the membrane or the back flush time, aeration intensity etc. should be controlled at optimum values. This paper evaluates the unique biological environments, in which a MBR is placed, the rate of fouling of membrane surfaces, level of extra-cellular polymeric substances (EPS) produced and the quality of effluents obtained in treating the above mentioned wastewaters with the data obtained from laboratory and pilot scale studies.

## 2. Biological Environment of Membrane Bioreactors

### 2.1. Food to Micro-organisms (F/M) Ratio

The performance of a biological reactor depends on the ratio of food (F) to micro organisms (M) which can be computed by QS/VX where Q ($m^3$/d) is the flow rate of wastewater influent, S (mg/L) is the biological oxygen demand (BOD) of the influent, V ($m^3$) is the volume of the biological reactor and X (mg/L) is the concentration of MLSS. The lower the F/M ratio the higher the BOD removal efficiency by the micro-organisms that consume the BOD. For given Q and S, the two ways to achieve lower F/M ratio are (i) to increase V, which is not always economical and (ii) to increase X, which is possible if the MLSS could be concentrated in the biological reactor (Ben aim and Semmens, 2002). By extracting the treated effluent through a membrane will allow the MLSS concentration to be increased in the biological reactor which is what exactly happens in a MBR. Another difference between the conventional ASP and the MBR is that while the former would retain only the micro-organisms that would have better settlement in the sedimentation tank, the latter one would retain micro-organisms that would even have poor settling properties. Therefore, the microbial environment would be completely different in a MBR compared to that of a conventional ASP system.

## 2.2. Sludge retention Time (SRT)

Another term that affects the performance of a biological reactor is the SRT, which can be computed by $VX/qX_e$ where q ($m^3/d$) is the amount of MLSS (generally termed as sludge) wasted per day and $X_e$ (mg/L) is the microbial concentration of the sludge. In a conventional ASP system, the values of X and $X_e$ will be around 3,000 and 10,000 mg/L, respectively. However, in a MBR both X and $X_e$ will be equal and in the range from 15,000 to 20,000 mg/L. Thus, the SRT of MBR can be computed by V/q. Therefore, the SRT of a MBR could be three times more than the conventional ASP (the SRT of a conventional ASP is around 4 to 15 days). Due to longer SRT, the MBR will retain even slow growing micro-organisms such as nitrifiers, micro-organisms that grow on synthetic chemicals etc., which would usually be washed out in a conventional ASP system. Therefore a MBR is suitable for performing nitrification as well as treating industrial wastewater that contain synthetic chemicals in addition to BOD removal. Longer SRT and higher MLSS cause stress to the micro-organisms in a MBR which requires more energy for cell maintenance and therefore leave less energy for cell production. This leads to lower sludge production in a MBR compared to that of an ASP system.

A study carried out to compare the performance of a MBR and a completely mixed activated sludge system operated at shorter SRTs ranging from 0.25 to 5 days showed that the MBR was capable of achieving excellent quality effluent even at a SRT of 0.25 days (Ng et al. 2005). The non-flocculating micro-organisms that were present largely in the MBR increased significantly with decreasing SRT. While dispersed biomass and small flocs in the MBR increase the performance due to less mass transfer resistance, they contributed to the deterioration of sludge settling properties.

## 3. Fouling of Membranes

### 3.1. Membrane resistance

Even a clean membrane would exert a resistance on the permeate flow when it is in operation. This resistance is called intrinsic resistance of membrane ($R_m$) and could be estimated by the following equation, using the pure water flux ($J_w$) through the membrane at a given trans-membrane pressure (TMP): $R_m = TMP/(\mu J_w)$, where $\mu$ is the dynamic viscosity of the water. When wastewater is processed through a membrane, the membrane resistance would increase with due to (i) pore blocking (ii) adsorption (iii) gel-layer formation and (iv) concentration polarisation of the foulants in the wastewater (Figure 2). Thus, the total resistance of the membrane $R_t$ at a given time can be estimated by $R_t = R_m + R_c + R_f$, where $R_c$ is the resistance due to cake (gel layer, $R_g$ and concentration polarisation, $R_{cp}$) which could be removed by cleaning the membrane and $R_f$ is the resistance due to irreversible fouling (due to pore blocking, $R_p$ and adsorption, $R_a$), which is generally not removed by membrane cleaning.

The cake resistance is considered due to the deposition of different sizes of particles as well as EPS on the surface of the membrane and could be computed by $R_c = \alpha vX$, where $\alpha$ is the specific cake resistance (m/kg), v is the permeate volume per unit area of the membrane ($m^3/m^2$) and X is concentration of MLSS (mg/L); $\alpha = 180(1-\varepsilon)/(\rho d_p^2\varepsilon^3)$, where $\varepsilon$ is the porosity of the cake, $\rho$ is density of the particles and $d_p$ is the diameter of the particles that form the cake (Chang et al. 2002). Thus, smaller the particles, larger the specific cake resistance which would lead to higher cake resistance. This becomes significant in side stream MBRs where the particles are smaller (due to higher shear stresses caused by large cross-flow velocities) and result in large cake resistance compared to that in submerged MBRs. Meng et al. (2005) found that MLSS concentration should be maintained below

10,000 mg/L to make MBR system to operate effectively and smaller particles in the MLSS can deposit easily on the membrane surface and cause more fouling.

### 3.2. Extra-cellular Polymeric Substances (EPS)

Significant reduction in flux found to occur when the EPS of the MLSS increases as well. Generally, the origins of EPS are (i) secretion from microbial cells, (ii) un-metabolised wastewater components and (iii) lysis of microbial cells. For example, the EPS from higher molecular-weight mucous secretion of microbial cells generally consists of poly saccharides, proteins, lipids and nucleic acids. Previous studies carried out on activated sludge have found that the increase in the protein content of EPS ( = $EPS_P$) tends to increase the hydrophobicity of the sludge. This leads to better flocculation of sludge and better sludge dewatering. One study indicates that $EPS_P$:$EPS_C$ (subscript C denotes carbohydrate) to increase from 1.3 to 5 when the SRT was increased from 4 to 12 days and then decreased slightly to 4.2 when the SRT was further increased to 16 to 20 days (Liu and Fang, 2003). However, contradicting results have been reported, as described below, on the level of production of EPS when the SRT of activated sludge was increased: (i) in one study, EPS was found to increase from 20 to 67 mg (glucose equivalent)/ g suspended solids, when the SRT was increased from 1~2 to 11 days, (ii) in another study, EPS was decreased from 60 to 20 to 15 mg (glucose equivalent)/ g suspended solids, when the SRT was increased from 2 to 6 to 16 days. Endogenous respiration and cell lysis at higher HRT are reasoned for the increase in $EPS_P$.

The EPS can also be divided into two forms, (i) soluble EPS that will be present in the supernatant when the MLSS is centrifuged, (ii) bound EPS that will be attached to the flocs during centrifugation. The production of soluble EPS depended on the SRT. In a range from 10 to30 days of SRT, the greatest EPS production was found at 20 days of SRT (Hernandez

Rojas et al. 2005). Further, higher F/M ratio was found to make the foulant more proteinaceous (Kimura et al. 2005) and Hernandez Rojas et al. (2005) found that the specific resistance of membrane to increase with the concentration of proteins in the supernatant, whatever the operating conditions were and EPS in the flocs has no effect on the specific resistance. Meng et al. (2005) also found that the higher EPS concentration can cause poor cake permeability. While similar observations were made by Trussell et al. (2004), they also found that the total median EPS content did not change significantly with the decrease in SRT (or increase in F/M ratio) but the carbohydrate fraction did. They suggested that this increase could lead to the increasing importance of cake resistance at lower SRTs. Also in their study, they found that the carbohydrate content in the SMP to increase with the decrease in SRT and caused the increase in foulant resistance at lower SRTs.

### 3.3. Operation of MBR and Aeration through Bubbling

The rate of fouling of a MBR that is being operated under constant flux could be evaluated by measuring the TMP. The typical temporal variation of such MBR is shown in Figure 3 (Judd and Jefferson, 2003). The rate of fouling due to cake resistance would be significant and would require frequent cleaning in the form of relaxing the membrane by stopping the membrane filtration for a few minutes for every 10 to 12 minutes of operation or cleaning the membrane by back pulsing or by employing both relaxation and back pulsing. However, the irreversible fouling of membrane would increase with time and require recovery through chemical cleaning of membranes once in every 3 to 6 months depending on the quality of influent. Table 1 compares the properties and operating conditions of membranes manufactured by four different companies (Yang et al. 2006).

The air is supplied, for both the removal of BOD as well as the reduction in the rate of fouling, in the form of bubbles. It has been found that the smaller bubbles controlled the rate of fouling better compared to larger bubbles. However, the movement of the membrane fibres was insensitive to bubble size (Fane et al. 2005). Therefore, it can be concluded that the fouling control was provided by the larger number of shear stress events generated by the flow of smaller bubbles.

### 3.4. Literature Data on Fouling

Germain et al. (2005) conducted experiments on a pilot scale MBR to observe the effects of operating parameters on fouling. They used an anoxic tank (9.5 $m^3$) and an aerobic tank (12.7 $m^3$) with a retention time of 48 hours. Dissolved oxygen concentration was maintained above 2 mg/L with coarse bubble aeration. Two vertically mounted polyvinylidene fluoride (PVDF) microfiltration membrane cassettes with 0.04 µm nominal pore diameter were placed in the aerobic tank. The membrane surface area of each cassette was 21 $m^2$. The following are the conclusions from their study:

- No significant fouling occurred below a transitional flux (between 16.5 and 22 $L/m^2.h$) and the MBR could be operated at high solids concentration and low membrane aeration velocities. The mean fouling for all MLSS concentrations tested (4.3 to 13.5 g/L) and permeate flux ($L/m^2.h$) at three different airflow velocities are given below:
  - Fouling rate (mbar/min) = 0.014 exp(0.145×Permeate flux) ($R^2$=0.91 and airflow velocity = 0.07 m/s)
  - Fouling rate (mbar/min) = 0.008 exp(0.155×Permeate flux) ($R^2$=0.80 and airflow velocity = 0.10 m/s)

- Fouling rate (mbar/min) = 0.016 exp(0.111×Permeate flux) ($R^2$=0.84 and airflow velocity = 0.13 m/s)

- Permeate flux, MLSS, aeration velocity, $EPS_c$ affected the membrane fouling above the transitional flux. The mass median diameter (MMD), $EPS_P$, $SMP_C$ and $SMP_P$ had no influence.
- The greatest and least influence on fouling was from permeate flux and membrane aeration, respectively.

In another study by Lee et al. (2003), batch filtration experiments were conducted with hollow fibre membrane (hydrophilized polypropylene material with pore size of 0.4 μm; effective membrane filtration area of 0.1 $m^2$; permeate flux of 9 L/$m^2$.h; HRT of 7.8 h; air flow rate of 2 L/min.; SRT = 20, 40 and 60 days) to find the relative contribution of supernatant to overall membrane fouling at different SRTs. It was found that the relative contribution of supernatant to overall fouling was higher at a SRT of 20 days (37%) compared to its contribution of 28% and 29% at the SRTs of 40 and 60 days, respectively. Overall fouling resistance increased with the increase in SRT and hydrophobicity, surface charge and microbial activity that are related to the properties and composition of EPS were the key to fouling by microbial floc. Again the total EPS concentration was independent of the SRT, but the $EPS_C$ decreased with the SRT reflecting the decrease in available carbon at higher SRTs and $EPS_P$ increased with the SRT due to cell lysis.

Lee et al. (2003) also considered the particle size distribution of the sludge and found that the mean floc and colloidal sizes at the SRT of 20, 40 and 60 days were 5.2±0.3, 6.0±0.2 and 6.6±0.3 μm and 349±14, 420±23 and 458±26 nm, respectively. The proportion of the particles whose size is smaller than the membrane pore size (0.4 μm) were 68, 62 and 54% of the total colloids at the SRT of 20, 40 and 60 days. However, colloids did not affect the overall fouling resistance.

Meng et al. (2005) studied the effect of filamentous bacteria on membrane fouling. Polyethylene membrane with 0.1 µm pore size and 0.1 $m^2$ membrane area was used to conduct experiments. The air flow rate for the MBR was 0.2 $m^3/h$; the MLSS concentration was 6000±100 mg/L. The relative density of filamentous bacteria was evaluated by microscopic observation and the filamentous index, FI was scaled from 1 to 5, where FI = 1 being little or no filamentous organisms and FI = 5 being excess growth of filamentous organisms. When FI increased from 1 to 5, the following were observed:

- Membrane fouling increased
- EPS increased with protein appears to be the major component of EPS
- Zeta potential of the sludge floc decreased from -10 mV to -30 mV
- Relative hydrophobicity increased

Thus, when FI is small, the pin flocs can cause severe membrane pore blocking due to their small size; flocs with larger FI also could cause membrane fouling by forming non-porous cake layer due to the adhesion of filamentous bacteria to membrane surface.

EPS is also suggested to form foam in the MBRs (Nakajima and Mishima, 2005). This is not case for the formation of foam in an activated sludge process. In an activated sudge process, abundance of actinomycete such as *Nocardia* (*Gordona*) or *Microthrix* are known to form foam. However, large amount of foam have been found in MBR in the absence of actinomycete. The foaming power and foam stability was increased with the concentration of protein in the EPS and the foaming power was found to decrease with the addition of MLSS. Adsorption of EPS on to MLSS was found to be the reason for it.

## 4. Effluent Quality from Membrane Bioreactors

The authors' research groups have conducted laboratory-scale and pilot-scale MBR studies to treat the following waters and those results are compared with the literature data.

### 4.1. Aquaculture effluent

Some of the major problems with the rapid expansion of the aquaculture industry due to high seafood demand include water quantity and quality, cost of land, restrictions on water discharge, environmental impacts (i.e algal blooms and eutrophication) and diseases. These factors have driven the industry to undertake intensive practices as well as adopting environmentally friendly technologies due to increased regulatory pressure from environmental agencies to protect the environment. In order for the industry to be sustainable, this continued expansion will depend entirely on the high level of production per unit area (or volume) and the type of technology used that is considered to be environmentally sustainable. Currently, some of the main areas of research are focussed on genetics and stock improvement, improved feed formulations, disease control and farming of new species while intensive recirculating aquaculture systems (RAS) with linkages to hydroponics are considered as sound technologies that have minimal environmental impacts.

RAS is defined as "aquaculture systems that incorporates the treatment and reuse of water with less than 10% of total water volume replaced per day". RAS are also known as "closed systems" (i.e denitrification included) due to minimal connection with ambient environment and water sources. They consists of mechanical and biological filtration components, pumps and holding tanks and may include a number of additional water treatment elements that improve water quality and provide disease control within the system. Recently research and development in recirculating aquaculture area have focused on reducing this waste output to a level of zero emissions. As defined by Suzuki et al. (2003), the characteristics of a zero emission system are: (1) Water use is minimized; (2) Drainage water is purified to the same level as raw water, and (3) Sludge is further utilised as fertilizer.

RAS is considered to offer a number of potential advantages for aquacultural practices which includes the following:

- Full control of all parameters that influence growth so that the fish farmer can better manage economic and production performance,
- Production in locations where limited water is available,
- An ability to manage waste production to provide greater environmental sustainability than traditional aquaculture systems,
- Bio-security,
- Ability to locate the operation close to markets to reduce product transport time and costs,
- Reduction in land area required when compared to pond-based systems, and
- Ability to integrate with agricultural activities (e.g. use of water effluent for hydroponics, horticulture or pre-use of irrigation water).

However, despite these advantages, there are also impediments involved such as high capital and running costs (eg. mechanical filtration, pumping, and maintenance), rigorous monitoring of water quality thus requires high level of management and pathogen outbreak (Lucas and Southgate, and 2003;  Hutchinson et al., 2004).

### 4.1.1. Laboratory-scale RAS

RAS require efficient treatment to remove suspended solids, ammonia, nitrite and nitrate from aquaculture effluent in order to reuse the treated effluent (Pulefou et al. 2008). A laboratory scale biological reactor consisting of a denitrifying compartment followed by a submerged MBR was used to treat 40 L/d of aquaculture effluent with an average nitrate concentration of 74 mg/L. A hollow fiber membrane with a pore size of 0.4 μm and a filtration area of 0.20 $m^2$ was used in the MBR and was operated at an average flux of 0.20 $m^3/m^2$.d. An intermittent suction time of 12 minutes followed by a relaxation period of 3 minute was maintained in the MBR.

Long term experiments were conducted at a C:N mass ratio of 4:1 in order to reduce the nitrate present in the influent. The average temperature at which the experiments were conducted was $25^0$C. The pH level in the influent ranged between 6 and 9 with an average value of 7.3 while the effluent pH averaged 7.8. In fact the pH of the effluent was always higher than the pH of the influent due to the denitrification process that took place in the treatment system (van Rijn et al., 2006). The membrane was operated at a constant flux of 0.2 $m^3m^{-2}d^{-1}$ while the TMP increased gradually to 14 kPa as a working suction pressure in order to determine the rate of fouling for each aeration rate. Figure 3a illustrates the temporal variation of TMP at different air flow rates. Throughout the experiments the effluent from the MBR had turbidity less than 0.5 NTU (Figure 3b) which is important if the effluent is to be recirculated back to an aquaculture system.

#### 4.1.1.1. Rate of increase of TMP at different rates of aeration

The average rate of increase of TMP was calculated using the number of days needed for the TMP to reach 14 kPa from the initial TMP at the start-up of an experiment. Table 10 shows the average rate of increase of TMP at different rates of aeration. When the experiments were conducted at 1, 3, 5 and 10 Lpm of aeration, the rates of fouling were 1.17, 0.70, 0.48 and 0.52 kPa/d, respectively. The rate of increase of TMP decreased when the rate of aeration was increased from 1 to 5 Lpm. Thus, in order to operate the membrane at a lower rate of fouling, a minimum of 5 Lpm of aeration is required. Further increase in the rate of aeration to 10 Lpm did not decrease the rate of fouling. In fact, it increased the rate of increase of TMP slightly which is probably due to the breakage of suspended particles into finer particles that could have increased the rate of fouling of membranes.

#### 4.1.1.2. Cake formation on the membrane and the membrane resistance

Table 11 shows the amount of suspended solids accumulated on the membrane surface during each experimental run. Around 2.4 to 3.2 g of suspended solids could be accumulated per square meter of membrane surface before physical cleaning of membrane is required (at a transmembrane pressure of 20 kPa and C:N mass ratio of 4:1). Table 11 also shows the membrane resistance at the end of each experimental run and corresponding resistance due to cake as well as irreversible internal fouling. The intrinsic resistance ($R_m$) of the membrane module used was $4.04 \times 10^{11}$ $m^{-1}$. It can be seen from the Table that the total membrane resistance at a TMP of 20 kPa was between $9.52 \times 10^{12}$ $m^{-1}$ to $10.2 \times 10^{12}$ $m^{-1}$ and the corresponding resistance due to cake and irreversible fouling were between $7.27 \times 10^{12}$ $m^{-1}$ to $8.44 \times 10^{12}$ $m^{-1}$ and $0.67 \times 10^{12}$ $m^{-1}$ to $2.32 \times 10^{12}$ $m^{-1}$, respectively. A power correlation could be obtained between the cake density and the cake resistance as follows:

$$[\text{Cake resistance } (m^{-1})] = 4.6795 \times 10^{12} \, [\text{Cake density } (g\ m^{-2})]^{0.423} \qquad (r^2 = 0.89)$$

These information are useful when designing a full scale MBR for the purpose of RAS.

### 4.1.2. Fouling reduction of membrane through the application of powdered activated carbon

In another study, a RAS consisted of an anoxic reactor, a MBR and a UV-disinfection unit was used to process 10,000 L/day of aquaculture effluent (Jegatheesan et al. 2008). The schematic of RAS and the membrane used in the MBR are shown in Figure (a) and (b) respectively. The specifications of the membrane are given in Table 2. The system provided high quality treated water for recirculation to a Barramundi fish culture. The permeate from the membrane that was recirculated to the fish tank contained <21 mg/L of nitrate, <2 mg/L of nitrite and 0 mg/L of ammonia. This allowed maintaining the water quality in the fish tank and the nitrogen species levels in the fish tank were: <20 mg/L of nitrate, <3 mg/L of nitrite and <0.6 mg/L of ammonia. However, the rate of fouling in the MBR was around 1.47 kPa/day. Thus, cleaning of membrane required every 16 days. In order to reduce the rate of fouling, 500 mg of powdered activated carbon (PAC) per litre of MBR volume was introduced which decreased the rate of fouling to 0.90 kPa/day, while maintaining the treated effluent quality. The turbidity of membrane effluent was 0.34 and 0.13 NTU for non-PAC and PAC runs, respectively.

When alum was used in an MBR, it improved the performance of the membrane by reducing the organic fouling material and improving the activated sludge floc strength and structure (Holbrook et al. 2004). When alum addition was suspended, the TMP increased from around 12 to 20 kPa over a period of 11 days. During the same period, the $UV_{254}$ absorption of the MLSS supernatant increased from 0.28 to 0.37. Particle counts, of three different sizes of particles 3.5, 7.5 and 15 μm, also increased and the largest effect was observed for 15 and 7.5 μm particles. The capillary suction time increased by 25% showing the decrease in floc strength. Reintroduction of alum improved the performance of the membrane again by returning the concentration of mixed liquor non settleable organic material, permeate quality and floc strength to initial levels, but the TMP only partially recovered showing some irreversible fouling. Selective binding of polysaccharide to alum was found to occur which could have prevented the rapid increase of TMP when alum was added. Thus, the colloidal polysaccharide material may have substantial effect on irreversible fouling of membrane.

### 4.2. Landfill leachate treatment

A study was conducted to evaluate the performance of an aerobic thermophilic MBR in treating landfill leachate (Visvanathan et al. 2007). A laboratory scale MBR was used to treat 6 L/d of leachate at 45$^{o}$C with a COD, $NH_3$-N and Total Kjeldhal Nitrogen (TKN) concentrations of 12,000, 1,000 and 1,300 mg/L, respectively. A ceramic membrane with 22 open fibers was used (internal diameter of 2 mm). The membrane module had a surface area of 0.04 $m^2$ and a permeability of 411 L/$m^2$.h.bar (when filtered with pure water). More than 70% COD removal was observed when the ratio of BOD to COD was maintained at 0.65. Removal of TKN and $NH_3$-N were both around 60%. The concentrations soluble and bound EPS were 287.6 and 146.4 mg/ g VSS, respectively; the ratio of $EPS_P$ to $EPS_C$ in both soluble and bound forms were 0.81. The amount of EPS produced under thermophilic conditions were 2.5 times higher than that observed under mesophilic conditions and the thermophilic sludge generally contained higher number of smaller particles (16 % thermophilic sludge volume contained particles with less than 5 μm diameter as opposed to 4% mesophilic sludge volume). The average d[TMP]/dt was around 2.0 kPa/day.

### 4.3. Oily wastewater treatment

Car wash in gas stations of Thailand could generate around 20 $m^3$ wastewater per day per gas station (Tri et al. 2006). A submerged MBR with U-shaped hollow fiber micro-filtration module with a pore size of 0.1 μm and a surface area of 0.42 $m^2$ was used to treat synthetic oily wastewater with 150 - 600 mg/L of oil and 13.6 – 54.4 mg/L of non-ionic emulsifier. The corresponding COD of the wastewater increased from 555 to 1813 mg/L. The hydraulic retention time was increased from 2 to 4 hours when the COD was increased from the lower value to higher value and the permeate flux decreased accordingly from 7.14 to 3.57 L/$m^2$.h. The COD and oil and grease removal ranged from 90 to 99% and 97.6 to 99.9 %, respectively. The values of $R_t$, $R_c$ and $R_f$ when operated at 3.57 L/m$^2$.h were 27.35 × $10^{11}$ / m, 10.69 × $10^{11}$ /m and 7.68 × $10^{11}$ /m, respectively. Further, the average d[TMP]/dt was around 2.6 kPa/day at 7.14 L/m$^2$.h of flux, while it was nearly zero for 16 days at 3.57 L/m$^2$.h of flux.

### 4.4. Biodegradation of pentachlorophenol (PCP)

PCP is a synthetic chlorinated organic compound released to the environment as herbicides, fungicide etc. (Visvanathan et al. 2005). A MBR consisted of a hollow fiber membrane with a pore size of 0.4 μm and a filtration area of 0.20 m$^2$ was used to treat 240 mg/day of PCP at a HRT of 12 hours (at a flow rate of 12 L/d). The PCP removal was 99.9% at an average d[TMP]/dt of 0.27 kPa/day.

## 5. Conclusions

MBR as an advanced wastewater treatment option provides several benefits. Higher removal of BOD, COD, suspended solids (turbidity) and nutrients could be achieved through appropriate operation of a MBR. High MLSS (more than 10,000 mg/L), low F/M values and longer SRT that prevail in a MBR help to achieve better effluent quality so that the effluent could be reused or safely disposed of. Laboratory scale studies indicate an average rate of change of TMP to vary from very small values to around 2.6 kPa/day. Providing an appropriate operational cycle of MBR would extend the period of operation between two consecutive chemical cleaning that required to restore the permeate flux back (closer) to the original value.

## References

Ben Aim, R. and Semmens, M.J. (2002), *Water Science and Technology* **47** (1), 1-5.

Chang, I., Le Clech, P., Jefferson, B., and Judd, S. (2002), *Journal of Environmental Engineering*, November, 1018-1029.

Fane AG, Yeo A, Law A, Parameshwaran K, Wicaksana F, Chen V, 2005, Low pressure membrane processes ~ doing more with less energy, *Desalination*, 185, 1585-1591.

Germain E, Stephenson T, Pearce P, 2005, Biomass characteristics and membrane aeration: Towards a better understanding of membrane fouling in submerged membrane bioreactors (MBRs), Biotechnology and bioengineering, 90(3), 316-322.

Hernandez Rojas M.E., Van Kaam R., Schetrite S. and Albasi C. (2005), *Desalination* **179**, 95-107.

Holbrook RD, Higgins MJ, Murthy SN, Fonseca AD, Fleischer EJ, Daigger GT, Grizzard TJ, Love NG, Novak JT, 2004, Effect of alum addition on the performance of submerged membranes for wastewater treatment, Water Environment Research, 76(7), 2699-2702.

Hutchinson, W., M. Jeffrey, et al. (2004). Recirculating Aquaculture Systems: Minimum Standards for Design, Construction and Management. South Australia, Inland Aquaculture Institution.

Jegatheesan V, Senaratne N, Steicke C, Kim SH and Rajasekaran P, 2008, Application of powderd activated carbon to reduce fouling of membrane in a pilot-scale recirculating aquaculture system, Proceedings of the 8th Specialized Conference on Small Water and Wastewater Systems organized by International Water Association, Coimbatore, 06-09 February.

Judd, S. and Jefferson, B. (2003) Membranes for Industrial Wastewater Recovery and Reuse, Elsevier Science Publishers Ltd.

Kimura K., Yamato N., Yamamura H. and Watanabe Y. (2005), *Environmental Science and Technology*, **39**(16), 6293-6299.

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

Liu, Y. and Fang, H.H. P. (2003), Critical Reviews in Environmental Science and Technology **33**(3), 237-273.

Lucas, J., S. and Southgate, P, S. (2003). Aquaculture: Farming Aquatic Animals and Plants, Blackwell Publishing Ltd.

Meng, F., Zhang, H., Li, Y., Zhang, X. and Yang, F. (2005), *Journal of Membrane Science* **262**, 107-116.

Meng F, Zhang H, Yang F, Li Y, Xiao J, Zhang X, 2005, Effect of filamentous bacteria on membrane fouling in submerged membrane, *Journal of Membrane Science*,

Nakajima J, Mishima I, 2005, Measurement of foam quality of activated sludge in MBR process, Acta Hydrochim. Hydrobiol., 33(3), 232-239.

Ng HY, Hermanowicz SW, 2005, Membrane bioreactor operation at short solid retention times: performance and biomass characteristics, *Water Research*, 39, 981-992.

Pulefou, T., Jegatheesan, V., Steicke, C. and Kim, S.H. (2008), *Desalination* **221**, 534-542.

Suzuki, Y., Maruyama, T., Numata, H., Sato, H.and Asakawa, M., 2003. Perfomance of a closed recirculating system with foam seperation, nitrification and denitrification units for intensive culture of eel: towards zero emission. Aquacultural Engineering 29, 165-182.

Tri, P.T., Visvanathan, C. and Jegatheesan, V. (2006), *J. Environ. Eng. Sci*. **5**, 309-316.

Trussell RS, Merlo RP, Hermanowicz SW, Jenkins D, 2004, The effect of organic loading of membrane fouling in a submerged membrane bioreactor treating municipal wastewater, *WEFTEC*,

Visvanathan, C., Choudhary, M. K., Montalbo, M. T. and Jegatheesan, V. (2007), *Desalination* **204**, 8-16.

Visvanathan, C., Thu, L.N., Jegatheesan, V. and Anotai, J. (2005), *Desalination* **183**, 455-464.

Yang, W., Cicek, N. and Ilg, J. (2006), *Journal of Membrane Science* **207**, 201-211.

Table 1 Properties and operating conditions of membranes from four different manufacturers [8]

| | Zenon | USFilter | Kubota | Mitsubishi-Rayon |
|---|---|---|---|---|
| Membrane type | Hollow fiber | Hollow fiber | Flat sheet | Hollow fiber |
| Configuration | Vertical immersion | Vertical immersion | Vertical immersion | Horizontal Immersion |
| Pore size (μm) | 0.04 | 0.1 | 0.4 | 0.1/0.4 |
| Material | Proprietary | PVDF | Polyethylene | Polyethylene |
| Module size ($m^2$) | 31.6 | 9.3 | 0.8 | 105 |
| Cleaning method | Back pulse and relax | Back pulse or relax | relax | Relax |
| Cleaning frequency (min/min) | 0.5 (cleaning)/15 (operation) | 1/15 | 1/60 | 2/12 |
| Recovery method | Chemical soak | Chemical soak | Chlorine backwash | Chlorine backwash |
| Recovery frequency | ≥3 months | ≥2 months | ≥6 months | ≥3 months |
| Recovery location | Drained cell or in situ (updated) | Drained cell | In situ | In situ |

Table 2 Average transmembrane pressure gradient for each aeration rate at 14 kPa

| Experiment No. | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Rate of aeration (Lpm) | 1 | 3 | 5 | 10 |
| Time taken for TMP to reach 14 kPa (d) | 12 | 20 | 29 | 27 |
| Average $\frac{d(TMP)}{dt}$ (kPa $d^{-1}$) | 1.17 | 0.7 | 0.48 | 0.52 |

Table 3 Cake density and membrane resistance at the end of each experiment

| Experiment No. | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Rate of aeration (Lpm) | 1 | 3 | 5 | 10 |
| TMP at cleaning( kPa) | 20 | 14 | 20 | 15.2 |
| Cake density (g $m^{-2}$) | 3.2 | 0.8 | 2.4 | 1.2 |
| Total membrane resistance, $R_t$ ($\times 10^{12}$ $m^{-1}$) | 9.52 | 6.74 | 10.2 | 7.14 |
| Cake resistance, $R_c$ ($\times 10^{12}$ $m^{-1}$) | 7.27 | 4.49 | 7.51 | 4.55 |
| Resistance due to irreversible fouling, $R_f$ ($\times 10^{12}$ $m^{-1}$) | 1.84 | 1.84 | 2.32 | 2.19 |
| Contribution of cake to the total resistance (%) | 76.4 | 66.7 | 73.4 | 63.7 |

Table 4 Specifications of the micro-filtration membrane used in the RAS

| Parameters | Description |
|---|---|
| Module type | Cleanfil-S20 |
| Type of membrane | Braid-Reinforced Hollow Fiber |
| Material of coating layer | Polysulfone, Polyethersulfone, PVDF |
| Coating thickness | 0.05~0.1 mm |
| Outer diameter | 2 mm |
| Inner diameter | 0.8 mm |
| Pore size | 0.3 μm |
| Dimensions of the module (L×W×D) | 1184×105×628 (mm) |
| Area of membrane | 20 $m^2$ |
| Flux | 20~25 LMH |
| Manufacturer | Kolon Industry Inc., Yongin City, Kyunggi-Do, South Korea |

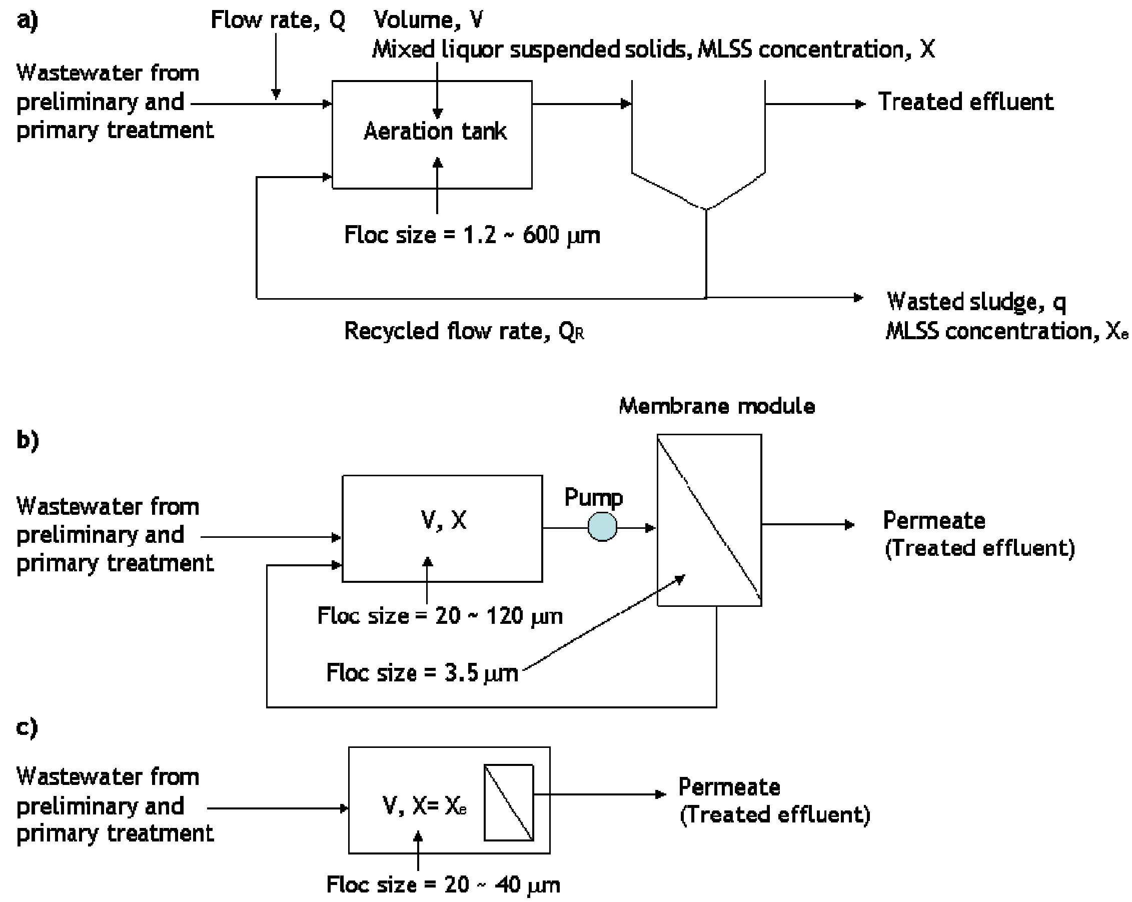


Figure 1 Configurations of secondary biological wastewater treatment systems

a) Activated sludge process b) Side stream MBR c) Submerged MBR

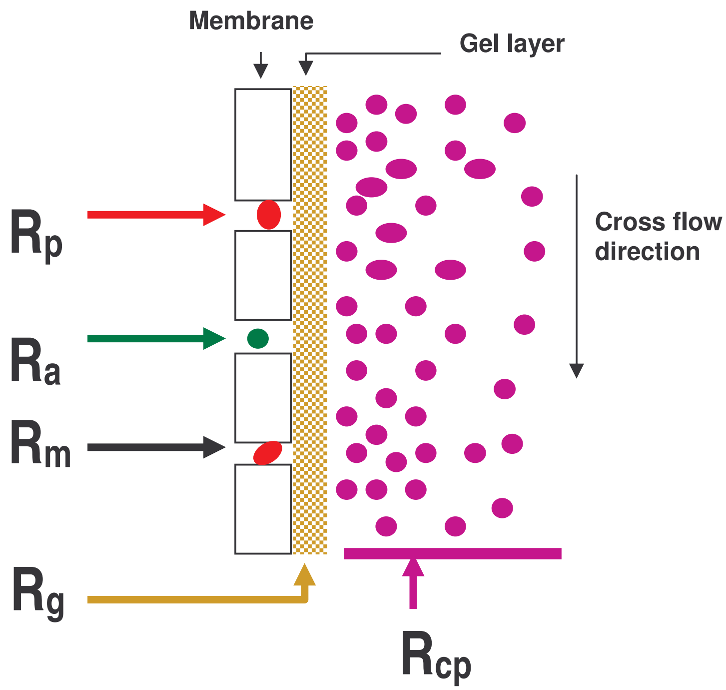


Figure 2 Components of total membrane resistance, $R_t$

($R_m$ – Intrinsic membrane resistance, $R_g$ – resistance due to gel layer, $R_{cp}$ – resistance due to concentration polarisation, $R_p$ – resistance due to pore blocking, $R_a$ – resistance due to adsorption)

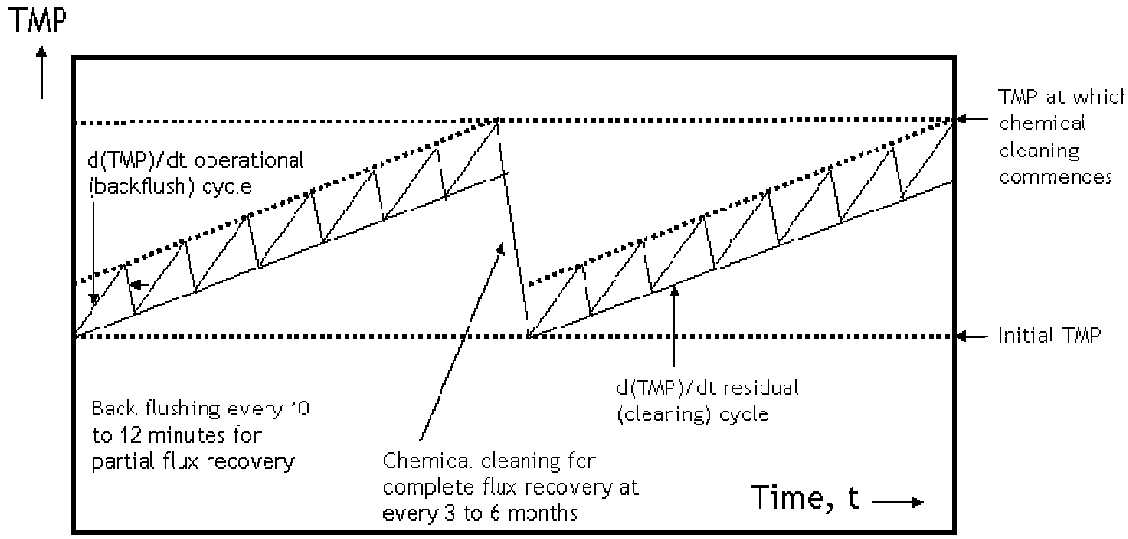


Figure 3 Typical temporal variation of TMP due to both operational cycle and chemical cleaning cycle (Yang et al. 2006)

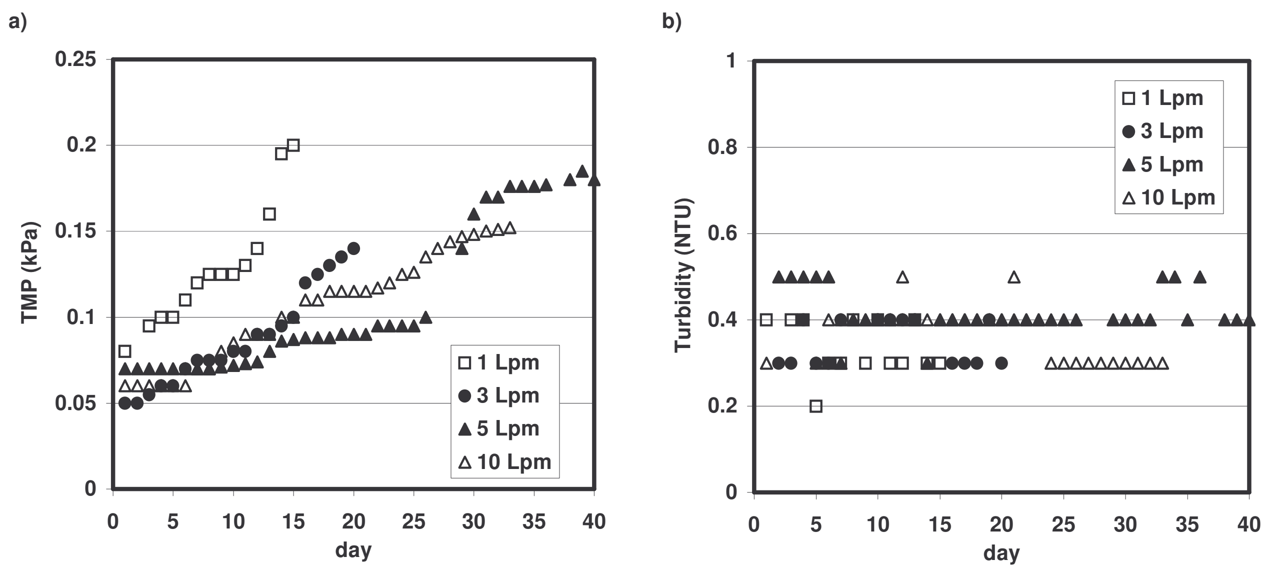


Figure 4 TMP and turbidity at different air flow rate

a) TMP of the membrane b) Turbidity of the effluent

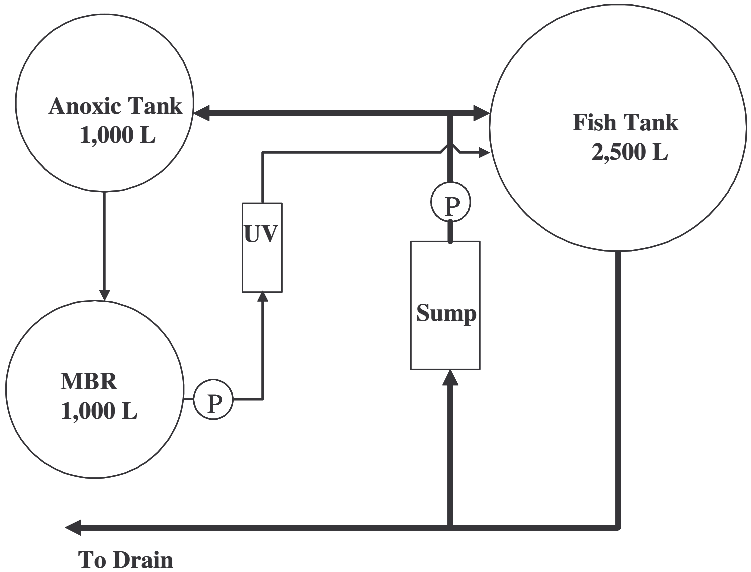


Figure 5 (a) Schematic of the RAS

Figure 5 (b) Micro-filtration membrane used in the MBR of the RAS