MEMBRANE FOULING STUDIES IN SUSPENDED AND ATTACHED GROWTH MEMBRANE BIOREACTOR SYSTEMS

by

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Abstract

The use of membranes in attached growth bioreactor has been growing interests for wastewater treatment plants. The membrane bioreactor (MBR) system can be regarded as an alternative way to achieve the design of compact wastewater treatment plants. Membrane fouling is known to be a serious problem in reductions of the membrane performance and the efficiency of the wastewater treatment. The objectives of this work were to examine the test conditions, to select the suitable media type, and to compare the effects of operating conditions, such as HRT and MLSS, on the membrane performance, fouling phenomena, extracellular polymeric substance (EPS) production and sludge properties in the suspended and the attached growth MBR systems.

To investigate the effect of hydraulic retention time (HRT) on membrane performance, EPS production and sludge properties, the MBRs were operated at different HRT values of 2, 4, 6 and 8 hrs. The MBRs consisted of three bioreactors which included (i) suspended growth without media, (ii) attached growth with moving media, and (iii) attached growth with fixed media. The cylindrical polypropylene (CP) with 24% reactor volume was used as the moving media, while the fixed media used polyvinylidine chloride fibers. The fixed media had the specific surface area of 7.33 m^2/m, and specific media volume of 0.3 L/m. The amount of the fixed media used in the reactor was 5% of the total reactor volume. The removal efficiency of COD was found to be greater than 90%, even with a short HRT. For nitrogen mass balance of MBRs, the nitrogen removal was accomplished by microorganism assimilation and nitrification reaction in the MBR at all HRT values. The attached growth MBR with the moving media obtained higher capillary suction time (CST) value, indicating a poor sludge dewatering property. The movement of the media in the attached growth MBR was thought to cause the floc breakage which led to the production of the small floc.

To examine the fouling mechanism in the attached and the suspended growth MBRs for three different biomass concentrations (6, 10, and 15 g/L of MLSS), two different sets of submerged MBRs: suspended (without media) and attached growth (with moving media) MBRs were used. The media used in the attached growth system was CP rings. Synthetic domestic wastewater was fed to the reactors at 2 h HRT and 500 mg/L COD. The biofouling phenomenon in the reactors was monitored by the changes in transmembrane pressure (TMP) as a function of operating time. It was found that the increase in fouling was associated with increasing MLSS concentration. The attached growth reactor was found to have lower fouling and prolong filtration as compared to the suspended growth reactor due to the difference in particle size distribution of biomass between these two reactors. The bound EPS contents in the suspended growth and attached growth reactors were very similar. The amount of soluble EPS at 15 g/L MLSS was higher than that at 6 and 10 g/L MLSS. In this work, the EPS was not the main factor to cause the fouling while the particle size of the biomass influenced by the movement of the media gave a significant effect on the formation of cake layers on the membrane.

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List of Abbreviations

AS	Activated Sludge
BAC	Biological Activated Carbon
BAF	Biological Aerated Filter
BOD	Biochemical Oxygen Demand
BSA	Bovine Serum Albumin
CAS	Conventional Activated Sludge
CFV	Cross flow velocity
COD	Chemical Oxygen Demand
CST	Capillary Suction Time
Da	Daltons
DNA	Deoxyribonucleic acid
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
EDTA	Ethylene diaminetetraacetic acid
EPS	Extracellular Polymeric Substance
F/M	Food/Microorganism ratio
GAC	Granular Activated Carbon
HRT	Hydraulic Retention Time
J	Permeate flux
kDa	Kilo Daltons
kg	Kilogram
kPa	Kilo Pascal
kWh	Kilowatt-hour
L	Liter
m	Meter
mg/L	Milligram per liter
MBR	Membrane Bioreactor
MF	Microfiltration
MFI	Membrane fouling index
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
MW	Molecular Weight
MWCO	Molecular Weight Cut Off
NTU	Nephelometry Turbidity Unit
OSBG	Optimum Support for Biological growth
P/C	Protein to Carbohydrate ratio
Pa	Pascal
PAC	Powder Activated Carbon
PB	Polyethylene Bead
PDCO	Pore Diameter Cut Off
PG	Polyethylene Granule
PS	Polyethylene Sheet
PVC	Polyvinyl Chloride
Q	Influent flow rate
Q_w	Wastage flow rate
R_c	Cake resistance
R_m	Intrinsic membrane resistance
R_f	Fouling resistance

R_t	Total resistance
RBC	Rotating Biological Contactor
RNA	Ribonucleic acid
rpm	Rotations per minute
s	Seconds
S	Polyethylene Sponge
SCOD	Soluble Chemical Oxygen Demand
SRT	Sludge Retention Time
SS	Suspended Solid
SVI	Sludge Volume Index
TDS	Total Dissolved Solid
TN	Total nitrogen
TOC	Total Organic Carbon
TKN	Total Kjedahl Nitrogen
TMP	Transmembrane Pressure
TS	Total Solids
UASB	Upflow Anaerobic Sludge Blanket
UF	Ultrafiltration
UV	Ultraviolet
V	Volume of reactor
VSS	Volatile Suspended Solid
ΔP	Transmembrane Pressure
μ	Viscosity
μm	Micrometer

Chapter 1

Introduction

1.1 Background

The conventional activated sludge (CAS) process is regarded as one of the most effective and economical processes for removal of organic pollutants using suspended biomass. The performance of the CAS process is dependent on two sub-processes; conversion of colloidal and dissolved organic matters into suspended biomass, and physical separation of resulting biomass from liquid by sedimentation. The overall efficiency of CAS is primarily dependent on the settelability and efficiency of the solid separation. There are many factors affecting the efficiency of CAS process such as sludge retention time and organic loading (Eriksson *et al.,* 1992; Lovett *et al.,* 1983), and the aeration which facilitates the production of biomass separated from liquid in clarifier (Chao and Keinath, 1980). At present, there has been growing interests in use of attached growth systems (biofilm processes) which are related to biomass growth on support media (Rusten *et al.,* 1999; Tavares *et al.,* 1994). The advantages of the attached growth systems over the CAS are better oxygen transfer, higher nitrification rate, higher biomass concentrations, more effective organic removal and relatively shorter hydraulic retention time (HRT) (Tavares *et al.*, 1994; Ødegaard *et al.,* 1994; Ødegaard, 2000).

Tavares *et al.* (1994) studied the effect of HRT on reactor performance with respect to soluble COD removal efficiency, and biofilm hold-up using different types of carrier materials at high organic loadings of 6.9-24.5 kg soluble COD/m^3.d, with varying HRT from 10 to 30 min. The results showed that the removal efficiency of soluble COD was in the range of 55 to 76% for all media used. The surface roughness of the optimum support for biological growth (OSBG) particles resulted in a more uniform microorganism attachment over the surface area of the particles, leading to thin and active biofilm. Rusten *et al.* (1999) applied a high-rate moving bed biofilm reactor (MBBR) for biological wastewater treatment. The results also suggested that at high organic loadings up to 16 kg BOD/m^3.d, the BOD removal ranged from 60 to 80%, and at organic loadings from 3-6 kg BOD/m^3.d, the BOD removal was greater than 95%. They also suggested that the MBBR process was simple to operate. This MBBR offered a compact process for complete biological treatment. The success of this system was mainly dependent on the performance of gravitational secondary clarifiers but, the sludge settleability cannot be easily controlled in real wastewater treatment plant.

The membrane bioreactor (MBR) for wastewater treatment has been currently one of the new technologies for both municipal and industrial wastewater treatments, especially when the effluent is intended for water reuse. The bioreactor which combines membrane system and biological treatment processes into a single unit, is designed to remove particulate, colloidal and dissolved substances from the solutions (Chang *et al.,* 2002). The membrane separation technique could be used to avoid a problem of non-settling sludge, to replace a secondary clarifier, and to obtain a high effluent quality and a compactness of treatment plants (Visvanathan *et al.,* 2000; Shim *et al.,* 2002). The use of the membrane in attached growth bioreactor could be an alternative way to achieve the above requirements. Leiknes and Ødegaard (2001) investigated potential of membrane separation unit combined with a high-rate MBBR for designing a compact wastewater treatment plant.

The loading rates used were in the range of 30 to 45 kgCOD/m^3.d with HRT of 20-30 min. They found that COD removal efficiency of 85-90% could be achieved if the biomass and particulate COD were completely removed in the moving bed reactor. The membrane separation of the biomass and particulate COD was maintained at a constant flux of 60 L/m^2.h and the results showed a high permeate quality in terms of suspended solid of less than 5 mg/L and turbidity of less than 1 NTU. Comparing with other membrane bioreactor, the MBBR could be operated at higher volumetric loading (about 10-15 times) and at shorter HRT (about 10-30 times). However, the use of membrane coupled with the biological process could cause a reduction in filtration capacity as a result of membrane fouling due to deposition of activated sludge constituents.

It is generally accepted that fouling reduces the performance of membrane. When the fouling occurs, a thick gel layer and cake layer are formed on and into the membrane, causing the permeate flux to decline and increasing the operating costs due to needs for cleaning or replacing the membrane. Fouling is usually attributed to a number of parameters, such as sludge particle deposition, adhesion of macromolecules such as extracellular polymeric substances (EPS) and pore clogging by small molecules (Bourgeous *et al.,* 2001; Bouhabila *et al.,* 2001; Nagaoka *et al.,* 1996). Soluble EPS (soluble macromolecule and colloid) can enter the membrane pores and then build up on the pore wall, leading to a reduction of total section area of membrane pore, causing pore plugging into membrane and eventually increasing the membrane resistance (Xing *et al*., 2002). The nature of fouling are strongly influenced by biomass characteristics, operating conditions and membrane characteristics. The membrane performance can be monitored through a number of factors such as membrane fouling, EPS production, treated effluent quality, biomass characteristic and microbial activity (Jefferson *et al.,* 2004; Kim *et al.,* 2001; Lee *et al.,* 2003). These factors are dependent on hydraulic retention time (HRT), sludge retention time (SRT), organic loading rate (OLR), process configuration, membrane material and biomass concentration (Jefferson *et al.,* 2004; Chang *et al.,* 2002; Judd, 2004).

A number of studies have been conducted on membrane fouling (Chang and Lee, 1998; Nagaoka *et al.,* 1998; Ognier *et al.,* 2002; Defrance *et al.,* 2000). Lee *et al.* (2001) experimentally investigated an attached growth bioreactor with fixed support media to minimize the fouling in submerged MBR. They observed that the rate of transmembrane pressure (TMP) increase in the attached growth MBR was 7 times greater than that in the suspended growth MBR. Better filtration performance with suspended growth was explained by formation of dynamic membrane with suspended solid. Bouhabila *et al.* (2001) characterized the fouling on membrane using hollow fiber membrane with 0.1μm pore size submerged in a bioreactor. The COD removal efficiency, sludge production, and fouling ability were monitored at different SRTs. The COD removal was greater than 95%, and sludge production decreased from 0.31 to 0.16 kgMLSS/ kgCOD with increasing SRT. A liquid fraction of the activated sludge (colloidal and solutes) also caused membrane fouling. This fraction resulted from the bacteria metabolites and the fouling could accumulate as SRT was increased. Hosseini and Borghei (2005) investigated the behavior of moving bed biofilm reactor (MBBR) units at different HRT (24, 20, 16, 12 and 8 h) and at different phenol concentrations (200, 400, 620 and 800 mg/L). The floating media was made of polyethylene which occupied about 70% of the reactor volume. The results showed that the MBBR reactor could be treated up to 220 mg/L phenol concentration without any inhibition.

Basu and Huck (2005) studied the effect of support media in integrated biofilter-submerged membrane system, and membrane fouling rate and water quality parameters were of interest. It was found that the membrane fouling rate doubled in the absence of support media. The authors also suggested that the support media enhanced the membrane surface scouring and the biofilm growth on the support media, which improved the removal efficiency.

The development of the attached growth system through a moving media which facilitates the organic removal rate and its impact on the biofouling formation mechanism in MBR is not investigated in detail. In this study, the fouling phenomenon was quantitatively evaluated and discussed in an attached growth system containing moving media. Relationship of TMP and operating time was established to monitor the fouling on the membrane. Then, the results were compared with those observed in the suspended growth MBR with respect to different, HRT and biomass concentrations. Particle size distribution, sludge characteristic, EPS compositions, and removal efficiency were also considered.

1.2 Objectives of the Study

1. To examine suitable test conditions and to select suitable media for attached growth reactor
2. To investigate effects of operating conditions, such as HRT and MLSS on membrane performance, fouling characteristics, EPS production and sludge properties
3. To compare membrane fouling behavior of attached and suspended growth MBRs

1.3 Scope of the Study

To accomplish the above objectives, the following tasks were undertaken.

1. Laboratory-scale experiments were carried out at ambient condition.
2. Synthetic wastewater with a constant COD value of 500 mg/L was used.
3. Batch reactor tests were conducted to select a suitable media for attached growth reactor. Five different types of media namely; polyethylene bead (PB), polyethylene granule (PG), polyethylene sheet (PS), cylindrical polypropylene (CP) and polyethylene sponge (S), were used.
4. Membrane bioreactor laboratory tests were conducted to investigate the effect of operating conditions (HRT and MLSS) on removal efficiency and biofouling mechanism in MBR system. HRT was varied at 2, 4, 6 and 8 h and the effect of MLSS was altered at 6, 10 and 15 g/L. The fouling behavior was monitored by measuring TMP as a function of operating time.
5. Sludge characteristics (fouling potential, viscosity, CST and particle size distribution), EPS production, fouling rate, cake resistance and microscope observation were determined.
6. The removal efficiencies of organic and nitrogen were evaluated.

Chapter 2

Literature Review

2.1 Domestic Wastewater

Domestic wastewater is wastewater from toilet, shower and kitchen which are created from human activities. It contains organic substances and nutrient compounds, that can promote the growth of aquatic plant and lead to water pollution. The compositions of domestic wastewater vary with time and rate of water used depending on life quality, living habits, climate, community size and density of development. As listed in Table 2.1, typical compositions of domestic wastewater can be classified as low, medium and high concentrations of the substances contained in the wastewater.

Table 2.1 Typical composition of untreated domestic wastewater (Metcaft & Eddy, 2003)

Contaminants	Unit	Concentration		
		Low	Medium	High
Total solid (TS)	mg/L	390	720	1,230
Total dissolved solid (TDS)	mg/L	270	500	860
Suspended solid (SS)	mg/L	120	210	400
BOD	mg/L	110	190	350
COD	mg/L	250	430	800
Total nitrogen	mg/L	20	40	70
Organic nitrogen	mg/L	8	15	25
Free ammonia	mg/L	12	25	45
Nitrite	mg/L	0	0	0
Nitrate	mg/L	0	0	0
Phosphorus	mg/L	4	7	12
Oil and grease	mg/L	50	90	100
Total coliform	No./100 mL	10^6-10^8	10^7-10^9	10^7-10^{10}
Fecal coliform	No./100 mL	10^3-10^5	10^4-10^6	10^5-10^8

2.2 Nitrogen Removal

Nitrogen in domestic wastewater occurs in many forms such as organic nitrogen (protein and urea) and ammonia nitrogen. The removal of nitrogen can be achieved by two principal processes that include assimilation and nitrification-denitrification. Microorganisms assimilate ammonia nitrogen, and can be converted into cell biomass. For nitrification-denitrification, the nitrogen removal is divided into two steps. In the first step, nitrification is a microbiological process that converts ammonium into nitrite and finally to nitrate, this occurring under aerobic condition. The nitrification process is performed by a group of autotrophic microorganisms. The principle mechanism for the nitrogen removal takes place by two reactions, one is ammonium oxidized to nitrite by *Nitrosomonas* and the other is nitrite to nitrate by *Nitrobacter*. In the second step, the nitrate is converted to nitrogen gas, this being called denitrification which occurs under anoxic condition. The nitrogen transformations in biological treatment process are illustrated in Figure 2.1.

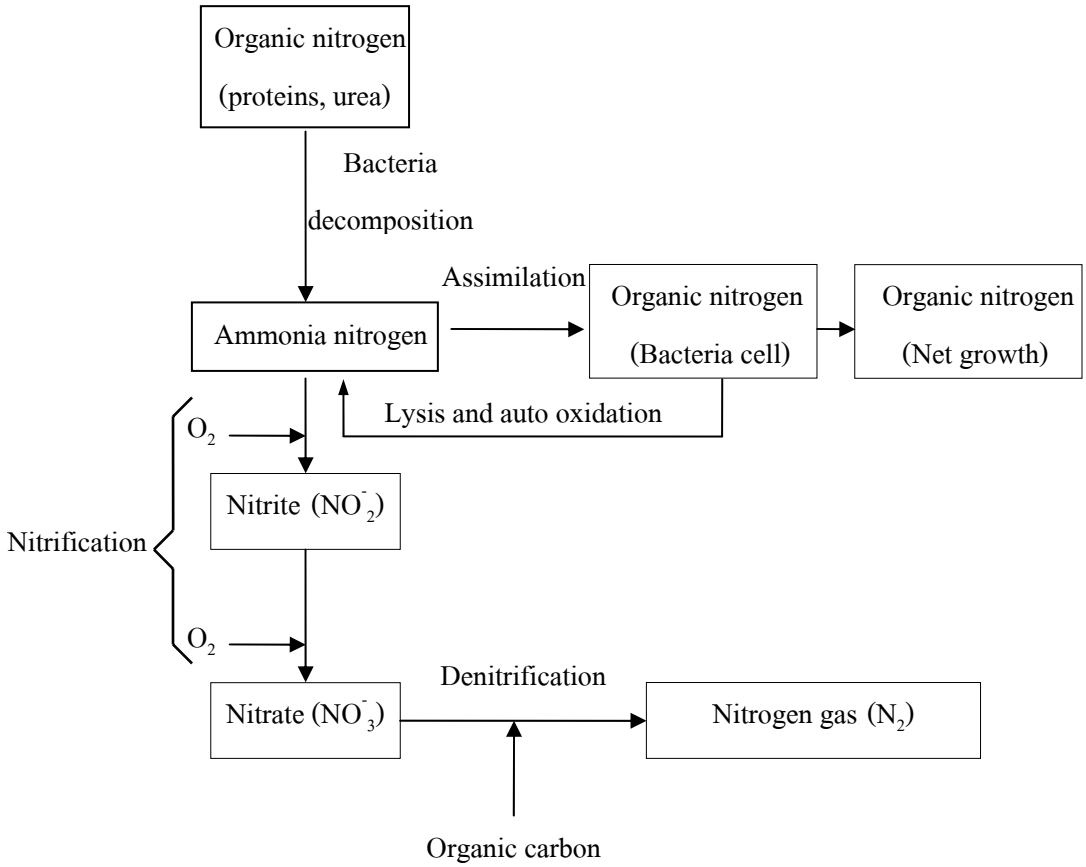


Figure 2.1 Nitrogen transformations in biological treatment process (Metcaft & Eddy, 2003)

Most domestic wastewaters treatment can be achieved by biological processes, which is one of the most effective and economical ways for removing organic pollutants.

2.3 Introduction to Membrane

2.3.1 Fundamental of Membrane

Membrane is defined as a thin film separation of two or more components from a fluid flow. The advantage of membrane techniques include continuous separation, low energy consumption, easy combination with other existing technique, easy up-scaling, and no additives used. The membrane filtration is divided into four narrower ranges based on particle size as follows;

Microfiltration is the coarsest size of the membrane filtration classes. Its applications are to separate suspended particles from dissolved substances. Microfiltration membranes are classified by pore diameter cut-off (PDCO) which has the diameter of the particles in the range of 0.1 to 10 μm (Cheryan, 1998).

Ultrafiltration is used for separation of large macromolecules such as proteins and starches and all types of microorganism, such as bacteria and virus (Aptel and Buckley, 1996). Ultrafiltration membranes are classified by molecular weight cut-off (MWCO) which is defined as the molecular weight of the smallest molecules. Ultrafiltration covers particle and molecules that range from 1,000 to 500,000 daltons in molecular weight (Cheryan, 1998).

Nanofiltration membrane retains solute molecules ranging from 100 to 1,000 daltons in molecular weight. Nanofiltration membranes are classified by molecular weight cut-off like ultrafiltration membranes or by percentage sodium chloride rejection like reverse osmosis membranes. It can also reject contaminants as small as 0.001 μm (Taylor and Jacobs, 1996).

Reverse osmosis involves the tightest membranes which are capable of separating even the smallest solute molecules or particles with diameter of as small as 0.0001 μm (Taylor and Jacobs, 1996). Reverse osmosis membranes are classified by percentage rejection of sodium chloride in an aqueous solution under specified conditions and range from 95 to 99.5%.

Membranes can be manufactured by a wide variety of materials which include inorganic membranes (sintered metals and ceramics) and organic membranes (polymers). The inorganic membranes have better chemical, mechanical and thermal stabilities, but have disadvantages of being very fragile and more expensive than the organic membranes. The organic membranes are widely used in water and wastewater applications because they are more flexible and can be put into a compact module with very high surface area. The organic membranes can be made from cellulose, and all synthetic polymers which have relatively good chemical, mechanical and thermal stability tendencies, and also provide the membranes with better antifouling properties through the use of hydrophilic polymers (Cheryan, 1998; Aptel and Buckley, 1996).

Membranes can also be classified into two operation filtrations, such as dead-end filtration and cross-flow filtration (Figure 2.2). The filtration of coarse particles down to several micrometers is achieved by the conventional dead-end filtration. Particles retained by the filter in dead-end filtration build up with time as a cake layer resulting in an increased resistance to filtration. This requires frequent cleaning or replacement of filters. For cross-flow filtration, a fluid (feed) stream runs tangential to a membrane, establishing a pressure differential across the membrane. This causes some of the particles to pass through the membrane. Remaining particles continue to flow across the membrane. In contrast to the dead -end filtration, the use of a tangential flow prevents thicker particles from building up a "filter cake" by a high velocity gradient near the membrane surface, which assists in reducing the fouling and polarization effects.

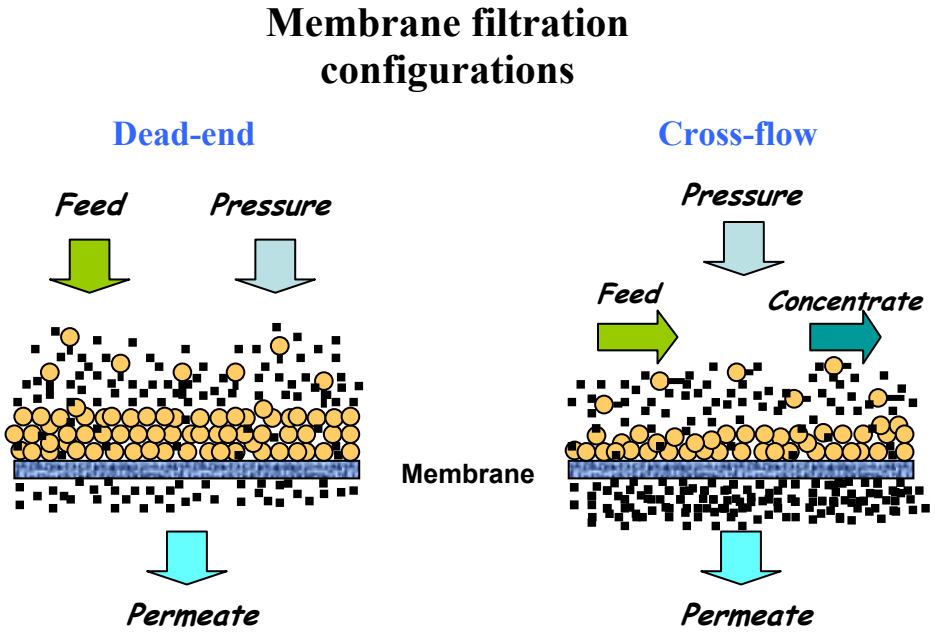


Figure 2.2 Dead-end and cross-flow filtration

2.3.2 Membrane Operation Parameters

Transmembrane pressure, flux and resistances

The transmembrane pressure is the driving force behind the filtration process. Equation 2.1 can be used to predict the permeate flux that remains proportional to hydraulic resistance for porous membrane system. The flux is the quantity of materials passing through a unit area of membrane per unit time and can be determined by both the driving force and the interfacial region adjacent to it. Under the simplest operating conditions, the resistance to flow is offered entirely by the membrane.

$$J = \frac{\Delta P}{\mu . R_t} \qquad \text{Equation 2.1}$$

Where J : permeate flux ($L/m^2.h$)

ΔP: transmembrane pressure (kPa)

μ: Viscosity of the permeate (Pa.s); (For example; Viscosity at 30°C = $0.798*10^{-3}$ $N.s/m^2$) when Pa = N/m^2

R_t: total resistance (1/m) : $R_t = R_m+R_c+R_f$

R_m : intrinsic membrane resistance

R_c: Cake resistance from by the cake layer (reversible fouling)

R_f: fouling resistance caused by solute adsorption into the membrane pore and gel formation (irreversible fouling).

All resistances shown in Equation 2.1 can be measured through a series of filtration experiments by comparing pure water filtration, sludge filtration, and pure water filtration after cake removal. However, the resistances are dependent on a number of experimental conditions, such as biomass characteristic, membrane material and temperature.

Figure 2.3 shows a relationship between transmembrane pressure and flux. It is observed that the higher the transmembrane pressure and the flux, the faster the particles deposit on the membrane surface and to form a cake, then the flux is independent of the transmembrane pressure and remains constant.

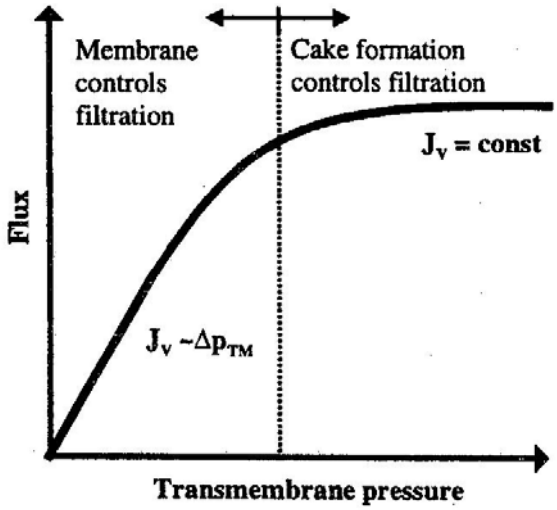


Figure 2.3 Relationship between transmembrane pressure and flux (Günder, 2001)

2.3.3 Membrane Bioreactor

The MBR system was first developed in the 1970s for treatment of sanitary wastewater, and consisted of a suspended-growth biological reactor combined with a membrane unit process into a single process. The first general operation of MBR can be either configured in side-stream operation (as external) or submerged in the bioreactor (as internal) (Figure 2.4). In the case of side-stream system, the membrane is independent of the bioreactor. Feed wastewater enters the bioreactor where it contacts with biomass. The mixture of feed wastewater and biomass is then pumped around a re-circulation loop containing a membrane unit where the permeate is discharged and the retentate is returned to the bioreactor. Excess sludge is pumped out to maintain a constant sludge age. Backwash and chemical washing are used for cleaning the membrane. The use of re-circulation loops leads to an increase energy costs from 2 to 10 kWh/m^3 of the water produced, depending on the internal diameter of the tubes used (Côté *et al.,* 1998). The submerged system is no re-circulation loop as the separation occurs within the bioreactor itself. This system reduces the operation costs. The energy consumption rates are 0.2 to 0.4 kWh/m^3, of which more than 80% are for aeration (Chua *et al.*, 2002). The pressure across the membrane in this system can be applied either by suction through the membrane or by pressurizing the bioreactor. The cost considerations of side-stream and submerged MBRs were discussed by Gender *et al*. (2000). Table 2.2 shows advantages and disadvantages of the submerged and side-stream MBRs.

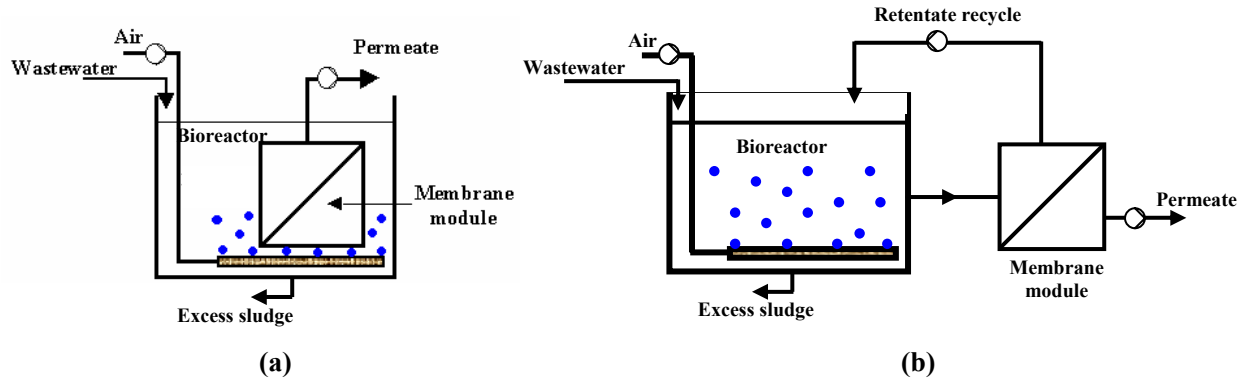


Figure 2.4 MBR configurations (a) Submerged MBR (b) Side-stream MBR

Table 2.2 Advantages and disadvantages of MBR configurations
(Modified Stephenson *et al.,* 2000)

Submerged MBR	Side-stream MBR
Advantages • Small footprint • Feed-forward control of O_2 demand • Less frequent cleaning required • Lower operating costs • Low liquid pumping costs (28% of total costs) (Gender *et al.,* 2000) • Low energy consumption (Côte *et al.,* 1998)	*Advantages* • Small footprint • Complete solids removal from effluent • Effluent disinfection • High loading rate capability • Combined COD, solids and nutrient removal in a single unit • Low/zero sludge production • Rapid start up • Sludge bulking not a problem
Disadvantages • Susceptible to membrane fouling • High aeration cost	*Disadvantages* • Aeration limitations • Membrane fouling • Membrane costs • High operating costs • High pumping cost (60-80% of total costs) (Gender *et al.,* 2000). • High cleaning requirement • Process complexity

Membrane biological processes can be applied to the treatment of municipal and industrial wastewaters. MBRs used for water de-pollution are based on the association of the bioreactor in which a culture of microorganisms degrades the polluting compounds, and a membrane filtration separator. Their main advantage is the ability to keep all biomasses in the bioreactor, thus removing all suspended solids from the treated water and disinfecting it according to the membrane cut-off threshold.

Separation of HRT and SRT means better control of biological activity. The MBR systems have been operated in long SRT (5-50 days) with high MLSS in the reactor and low F/M ratio (Visvanathan *et al.,* 2000). The MBRs have greater nitrification potential

than the conventional activated sludge process (CAS), owing to longer retention time of the nitrifying bacteria (long SRT, low F/M ratio) and smaller floc sizes. The smaller floc size allows for greater mass transport of nutrients and oxygen into the floc (Gender *et al.,* 2000). The presence of membrane in the MBR prevents the washout of nitrifiers at short SRT and HRT (Soriano *et al.,* 2003) and promotes the development of slow growth rate bacteria, such as nitrogen fixing bacteria, and produces little sludge (Muller *et al.* 1995; Trouve *et al.* 1994). Cicek *et al.* (2001) noted that the nitrification became slow down at 2 days SRT condition, indicating a partial loss of nitrifying bacteria. At nitrogen loading between 0.1 and 3.3 $kgNH_3/m^3.d$ with DO concentration of 1 mg/L, the ammonia removal was greater than 90% (Chiemchisri *et al.,* 1992). The organic removal in MBR was often greater than 95% even with relatively short HRT (Holler and Trösch, 2001; Soriano *et al*., 2003). Soriano *et al.* (2003) reported that the carbon and nitrogen removal performance in the MBR process was better than that in the CAS process, even short SRT (Table 2.3).

Table 2.3 Average influent and effluent characteristics and process removal performance under the different operating conditions (Soriano *et al.,* 2003)

Process	Parameters		Influent (mg/L)				Effluent (mg/L)				Performance % removal	
	SRT (d)	HRT (h)	NH_4-N	TKN	TN	COD	NH_4-N	TKN	TN	COD	TN	COD
CAS	7.0	11.0	57	66	66	365	9	20	25	54	62	85
	4.2	18.0	53	65	67	397	10	21	27	38	60	91
	2.0	11.0	62	77	77	420	51	57	58	109	25	74
	1.8	10.5	49	64	63	426	29	33	33	51	48	88
MBR	6.5	10.2	65	74	74	404	6	7	17	35	77	91
	3.2	11.5	56	71	71	425	14	15	19	19	73	96
	3.0	5.1	56	73	73	340	30	36	40	28	45	92
	2.2	3.9	63	74	76	410	43	47	49	43	36	90
	2.1	12.7	61	72	72	432	32	34	36	27	50	94
	2.0	8.5	49	62	62	370	24	28	31	30	50	92

Stephenson *et al.* (2000) noted that F/M ratio of MBR was in the range of 0.05 to 0.15 d^{-1}. In addition, MLSS concentration up to 20,000 mg/L can be easily maintained during municipal wastewater treatment (Rosenberger *et al.,* 2002), while, in some industrial situations, MLSS concentration can be increased to 80,000 mg/L (Fakhru'l-Razi, 1994). This is directly translated into a reduction in reactor volume and small footprint. The combinations of high biomass concentration and complete retention of solids allow the process to be operated at low F/M ratio. Table 2.4 shows the experimental results of Cicek *et al*., (1999) who compared the performance of an activated sludge plant with a sidestream MBR with the same synthetic sewage. The floc particle size in the MBR was shown to be significantly smaller than that in the activated sludge. It should also be noted that the sludge age in the activated system used by Cicek *et al.* (1999) was relatively long as compared with other works (Metcaft & Eddy, 2003) whose had sludge age was about 10 days of SRT.

Table 2.4 Performance comparison of activated sludge (AS) with MBR (Cicek *et al*., 1999)

Parameter	AS	MBR
Sludge age (d)	20	30
COD removal (%)	94.5	99
DOC removal (%)	92.7	96.9
TSS removal (%)	60.9	99.9
Ammonia N removal (%)	98.9	99.2
Total P removal (%)	88.5	96.6
Sludge production (kgVSS /COD.d)	0.22	0.27
Mean floc size (μm)	20-120	Less than 10

It is generally known that a perfect SRT control achieved in the MBR helps maintenance mechanisms which induced at high SRT values. The substrate could be used for other purposes than cell growth, thus minimizing the biomass production. Low F/M ratio is maintained in the MBR due to high biomass concentration which results in minimum sludge waste. Furthermore, most MBR plants operate at sludge age excess of 30 days. Long sludge ages could decrease sludge production, which reduces solids handling capital and operation costs. Table 2.5 shows sludge productions from different wastewater treatment processes published by various researchers (Gender *et al.,* 2000; Bouhabia *et al.,* 2001; Cicek *et al.,* 2001; Lee *et al.,* 2003; Xing *et al.,* 2003).

Therefore, coupling of the membrane with a bioreactor has increasingly gained interests both academically and commercially, because it has more advantages than conventional biological wastewater treatment systems, such as, small footprint, less sludge production, high effluent quality, and disinfection.

Table 2.5 sludge production for various wastewater treatment processes

Treatment process	Sludge production (mgVSS/mgCOD)	Reference
Submerged MBR	0.0-0.3	Gender *et al.* (2000)
Trickling filter	0.3-0.5	Gender *et al.* (2000)
Conventional activated sludge	0.6	Gender *et al.* (2000)
Granular media biological aerated filter (BAF)	0.63-1.06	Gender *et al.* (2000)
Submerged MBR	0.16-0.31	Bouhabia *et al.* (2001)
Submerged MBR	0.2-0.5	Cicek *et al.* (2001)
Submerged MBR	0.1-0.16	Lee *et al.* (2003)
Submerged MBR	0.26-0.32	Xing *et al.* (2003)

2.3.3.1 Aerobic and Anaerobic MBRs

Membrane bioreactor system can involve either aerobic or anaerobic of microorganism cultures. This system can remove organic pollutants over a wide range of conditions, producing a high quality permeate at high organic loading rate.

Recently, membrane separation in aerobic bioreactor has been studied, especially MBR with submerged-type membranes with respect to better effluent quality and lower sludge production, as compared to conventional activated sludge process. MBRs have the advantages of allowing HRT and SRT to be independent of each other. Organic loading rates in MBR are typically higher than those achieved in tricking filters, sequencing batch reactor and conventional activated sludge, owing to shorter HRT (Gender *et al.,* 2000). All the systems run at MLSS levels of up to 40 g/L and the organic loading rates range between 0.1 and 10 kgCOD/m^3.d with corresponding removal efficiency more than 85%. The performance appears to be relatively insensitive to HRT with values between 1 and 30 hours resulting in very high removal percentages. Sludge age also appears to have little influence on effluent quality, with sludge age (SRT) between 5 and 550 days. The operation conditions of membrane bioreactor processes are summarized in Table 2.6.

Wen *et al.* (2004) investigated the performance of a submerged membrane bioreactor for treatment of a hospital wastewater. The bioreactor was operated at the conditions of 7.2 h HRT, NH_4^+-N with average 17.7 mg/L and COD range from 49 to 278 mg/L. They found that the removal efficiency for COD, NH_4^+-N and turbidity was 80, 93 and 83%, respectively. The bacteria removal was greater than 98% and the effluent had no color and odor.

Chaize and Huyard (1991) studied membrane bioreactor on domestic wastewater treatment sludge production and modeling approach. The effect of SRT at 50 and 100 days and HRT at 2, 4 and 8 days on sludge production and removal efficiency was examined. The results showed that MBRs were found to be very attractive process. High SRT and very low excess sludge production were obtained because of the membrane efficiency. At SRT of 100 days and HRT of 2 days, a good effluent quality could be obtained.

Yamamoto and Win (1991) evaluated a sequencing batch membrane reactor for treating tannery wastewater, which included high strength organic matter of COD 1,500-2,200 mg/L and heavy metal of Cr 19-32 mg/L. The reactor was investigated at different SRTs namely 10, 20 and 550 days, and volumetric loading rates of 3, 5 and 10 kgCOD/m^3.d. The COD and Cr removal efficiency were greater than 93% and 95%, respectively. Nitrogen removal increased with increasing the organic loadings. The SRT of 20 days gave the best, result, in the light of the removal of organic matter, nitrogen and chromium and the flux. It was recommended at SRT of 20 days that the volumetric organic loading be kept less than 8 kgCOD/m^3.d. Higher SRT gave better settling of sludge because higher SRT yielded higher Cr content. However, sludge at high MLSS concentration above 10,000 mg/L would not be maintained without membrane separation. Higher SRT gave higher MLSS and suction pressure, which resulted in membrane clogging.

Trouve *et al*. (1994) determined municipal wastewater treatment on a semi-industrial aerobic pilot-scale MBR at 24 h and 25 days of HRT and SRT, respectively. In their work, a complete nitrification was obtained and the process was effective from 93 to 99% removals of COD, N-NH_3 and suspended solid. The sludge production in the MBR was lower than that in the conventional process. In addition, an improvement of MBR was obtained by optimizing filtration performance.

Shimizu *et al*. (1996) investigated the effect of membrane configuration on the filtration flux in domestic wastewater with a BOD of 0.2 kg/m^3 and total nitrogen of

0.05 kg/m^3. Four types of hollow fiber membrane modules and a tubular alumina ceramic membrane module were used for filtration experiment. The flexibility of hollow fiber membrane elements caused a rapid crowding of elements, and reduced the effective membrane surface area at high rate filtration operation or under low fluidity conditions. The improvement of flux by the movement or vibration of hollow fiber membrane was small. A highly packed membrane surface of hollow fiber module can be effectively used for filtration. The filtration flux of the hollow fiber membrane module could be applied to an earlier filtration model that had been constructed for a ceramic tubular membrane packed in low density.

Seo *et al*. (1997) studied an ultrafiltration coupled with activated sludge treated the residual organic matter in oil wastewater. This experiment varied HRT and SRT at 5, 10, 20 and 30 days. The removal efficiency of SCOD was more than 90% at HRT greater than 10 days, showing the possibility of a biological treatment. However, the combined membrane activated sludge process could maintain high removal efficiency more than 95% for the residual organic in the oil wastewater. The enhancement of organic removal was contributed to an increased biomass in the system, resulting in a reduction of the organic loading.

The application of membrane coupled anaerobic bioreactor has proven to be an alternative process for industrial and municipal wastewater treatments. In particular, the anaerobic culture in the biological system has slower growth rates than the aerobic culture. It takes a relatively long HRT to prevent biomass washout in the completely mixed anaerobic digester (Fakhru'l-Razi and Noor, 1999). Anaerobic biomass also exhibits poor settleability due to their diffusible and somewhat filamentous nature (Elmaleh and Abdelmoummi, 1998). The emission of residual gas and the resulting rise of biomass make the incomplete separation in the final clarifier. Therefore, membrane coupled anaerobic bioreactor incorporating UF or MF as the separation step after the anaerobic bioreactor has been applied to complete retain biomass in the reactor, and to obtain the final effluent of better quality. However, some problems related to cake formation and biofouling offer limitations to the acceptance of membrane units for biological wastewater treatment. Choo and Lee (1996) reported that the soluble inorganic precipitate, resulting in several membranes fouling, was identified as struvite, $MgNH_4PO_4.6H_2O$. This was generated during anaerobic digestion which played a significant role in the consolidation of biomass cake on membrane surface. Several studies on membrane anaerobic processes for the treatment of various wastewaters have been carried out (Fakhru'l-Razi, 1994; Harada *et al.,* 1994; Choo and Lee, 1996a; Choo and Lee, 1996; Elmaleh and Abdelmoumni, 1998; Fakhru'l-Razi and Noor, 1999). A summary of various studies with anaerobic MBR is presented in Table 2.7.

Table 2.6 Summary of operation conditions of aerobic membrane bioreactor processes

Wastewater type	Synthetic	Municipal	Synthetic	Domestic	Domestic	Organic compounds	Oil wastewater	Tannery
Reactor volume (L)	7	3900	2.5	4.5	66	30	-	2.25
Membrane area (m^2)	0.1	13.9	0.03	4	0.24	0.04	0.087	0.27
HRT (h.)	7.8	10.4-15.6	3.3	5	30	7.5	5, 10, 20, 30	1
SRT (d.)	20, 40, 60	-	10, 20, 30	5,10,20,40	-	60	5, 10, 20, 30	10, 20, 550
MLSS (g/L)	2.4-5.5	18-20	17.2-27	-	-	0.8	0.2	10-40
Initial COD (mg/L)	280	786	800-880	95-400	74-102	8,200	146,000-36,000	1,500-2,200
COD loading ($kg/m^3.d$)	-	1.2-1.8	5.7	-	0.14-0.18	-	0.49-0.11	3, 5, 10
COD removal (%)	>95	90-95	97	>90	>85	-	>90	93
Flux ($L/m^2.d$)	9	432-648	-	-	28	300	-	6.7-3.5
TMP (kPa)	-	18-26	-	-	-	-	101	27
Reference	Lee *et al.* (2003)	Rosenberger *et al.*(2002)	Bouhabia *et al.* (2001)	Huang *et al.* (2001)	Jefferson *et al.* (2001)	Tardieu *et al.* (1998)	Seo *et al.* (1997)	Yamamoto *et al.* (1991)

Table 2.7 Summary of operation conditions of anaerobic membrane bioreactor processes

Wastewater type	Palm Oil Mill	Synthetic	Alcohol distillery	Synthetic	Synthetic	Brewery
Reactor volume (L)	50	10	4	-	10	120
Membrane module	UF	UF, MF	UF	UF	UF	UF
Membrane area (m^2)	-	-	0.36	0.3	0.2	-
HRT (h.)	67	-	360	-	120, 80, 48	87-96
SRT (d.)	161	-	-	26	-	83-59
MLSS (kg/L)	50	-	-	-	15	31.5-38.3
Initial COD (mg/L)	39,910	-	22,600	-	5,000	46,200-84,010
COD loading ($kg/m^3.d$)	14.2	-	1.5	1.5	1, 1.5, 2.5	12-20
COD removal (%)	93.2%	-	97%	-	> 98%	>96%
Flux ($L/m^2.d$)	-	120	5	-	-	-
TMP (bar)	1.5	0.5	2	-	0.5	1-2
Reference	Fakhru'l-Razi and Noor(1999)	Elmaleh and Abdelmoumni (1998)	Choo and Lee (1996a)	Choo and Lee (1996)	Harada *et. al.* (1994)	Fakhru'l-Razi (1994)

2.3.3.2 Attached Growth Bioreactor

Over the last decade, there has been growing interests in attached growth systems (biofilm process) for both municipal and industrial wastewater treatments as compared to conventional biological process due to several reasons as follows; (Ødegaard *et al.,* 1994; Ødegaard, 2000)

- Being more compact and requiring less space
- Being independent of final sludge separation
- Being utilized due to the lack of sludge return

There are many types of attached growth systems for wastewater treatment, which can be summarized in Table 2.8.

Table 2.8 Different types of attached growth systems (Modified from Ødegaard, 2000)

Type of attached growth systems	Comments
Tricking filter	❖ High surface area for biofilm attachment ❖ Not volume effective
Rotating biological contactor (RBC)	❖ High surface area for biofilm attachment ❖ Mechanical failure
Fixed media submerged biofilter	❖ High surface area for biofilm attachment ❖ Simultaneous biological treatment and suspended solid removal ❖ Poor distribution of the load on the hole carrier
Granular media biofilter	❖ Simultaneous biological treatment and suspended solid removal ❖ Need backwashing
Fluidized bed reactor	❖ Highest volumetric rate for carbon and nitrogen removal ❖ Stability for shock loading ❖ Hydraulic instability
Air lift	❖ Good mixing capacities and enhanced mass transfer
Moving bed biofilm	❖ Good oxygen transfer, ❖ Auto-regulation of biofilm thickness ❖ Simple distribution of liquid flow that enables raw unsettled wastewater to be treated directly

In addition, the above attached growth processes can be classified into two groups with regard to the carrier, these being fixed bed and moving bed reactors.

The fixed bed reactors with granular media were developed in France, and are characterized by higher surface area for biofilm attachment, better oxygen transfer and higher nitrification rate. Three typical fixed beds, such as Ringlace® and BioMatrix®, Bio-2-Sludge® and the RBC were widely used in various wastewater treatment processes (Lee *et al.,* 2001; Lessel, 1994).

The moving bed reactors are defined as the biomass growth on small carrier materials that move along with water in the reactor. The movement is typically produced by coarse bubble aeration in the aerobic zones, and by mechanical mixing in the anoxic or anaerobic zones as shown in Figure 2.5. The biofilm carrier is selected to have low density

close to water (sponge or plastic carriers), high specific surface area, good holding capacity, and it must avoid the clogging by increased biomass. The permeations of food and oxygen into the deeper layers of the culture in the biofilm must be assured (Lessel, 1991). Two types of the moving bed have been developed to full scale. The first type is the sponge Captor® and Linpor® making from polyurethane material. The other type is the moving bed with large floating plastic carriers, this being referred to as Kaldnes®. The moving bed biofilm reactor can obtain COD removal of 65-70% at very high volumetric loadings at 10-50 kgCOD/m^3.d (Broch-Due *et al.,* 1994). The specifications of media for attached growth bioreactors are shown in Table 2.9.

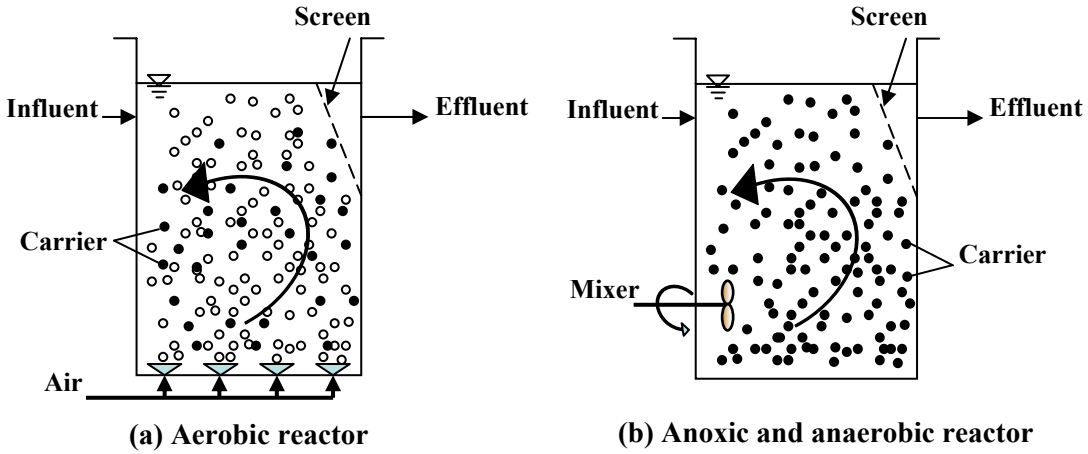


Figure 2.5 Principle of the moving bed biofilm reactor (Metcaft & Eddy, 2003)

Activated carbon carriers have also been applied for treatment of different wastewater types (Pirbazari *et al.,* 1996; Kim *et al.,* 1998). The efficiency of the activated carbon carriers in the purification of toxic wastewater is attributed to its excellent microbial attachment properties and high adsorption capacity for toxic organic compounds.

In wastewater treatment processes, development of attached growth bioreactor with high biomass concentrations has been of interests to be achieved in short hydraulic retention time (HRT) in comparison to suspended growth system with equivalent solid retention time (SRT). This results from the use of high specific surface area of carriers. Short HRT could lead to a compact system of the reactor, which can be beneficial when the plant area is limited.

Comett *et al.* (2004) studied a treatment of leachate wastewater from the anaerobic fermentation of solid wastes using two biofilm support media. Biofilm growing on different carrier media had different responses to the nutrient contaminated in wastewater. The sequencing batch system consisted of two reactors containing Kaldnes and Linpor carrier materials with specific areas of 490 and 270 m^2/m^3, respectively. The total COD removals for Linpor and Kaldnes reactors were 47% and 39%, respectively and the average ammonia removals for Linpor and Kaldnes were 72% and 42%, respectively. The surface of Linpor had higher concentrations of microorganisms than that of Kaldnes. The average dry solids in Linpor and Kaldnes were 170 g/m^2 and 63 g/m^2, respectively.

Table 2.9 Media specification for attached growth bioreactor (Modified from Leslie Grady *et al.* (1999) and Metcalf &Eddy (2003))

Media	Media dimensions	Specific density (g/cm^3) and specific surface area (m^2/m^3)	Volume % of aeration basin	Comments
Reticular polyurethane • Captor® • Linpor®	3 cm x 2.5cm x 2.5 cm 1.0-1.3 cm cubes	0.95 g/cm^3	10-30	High biomass concentrations lead to anaerobic condition
Looped media • Ringlace® • BioMatrix®	Looped PVC about 5 mm in diameter, placed 4 to 10 cm apart. Polyvinylidene chloride loop	120-150 m^2/m^3	25-35	Low organic loading lead to worm growth. Worms controlled by anoxia
Kaldnes®	cylindrical shaped polyethylene elements 10 mm in diameter and 7 mm in height	0.96 g/cm^3 200-400 m^2/m^3	25-50	No need for sludge recycling. High volumetric loading rate corresponding to area of media
Trickling filter media • Bio-2-Sludge®	PVC vertical trickling filter media	90-165 m^2/m^3	25-75	Able to use with or without suspended growth produced by return sludge recycle form secondary clarifier

Mann *et al.* (1999) investigated the performance of floating and sunken media biological aerated filters under an unsteady state condition. The floating media was made of polypropylene with a relative density of 0.92, and sunken media contained a mixture of polypropylene and calcium carbonate (the mixture having a relative density of 1.05). From an initial start-up at loadings of 0.486 kg/m^3.d (SS) and 0.568 kg/m^3.d (soluble COD), the suspended solid and soluble COD removal rates dropped below 50% at loadings of 1.397 kg/m^3.d (SS) and 1.403 kg/m^3.d (soluble COD). The floating media performed better at higher flow rates under shock loading condition than the sunken media.

Tavares *et al.* (1994) studied the effect of hydraulic retention time on the reactor performance, expressed as the soluble COD removal efficiency, and also compared the reactor efficiency and biofilm hold up for two different types of carrier materials, namely; polystyrene beads and particles of a trade material known as Optimum Support for Biological Growth (OSBG). High organic loadings of 6.9-24.5 kg Soluble COD/m^3.d were used and the reactor was operated at HRT of 10, 20 and 30 min. The results showed that the removal efficiency of soluble COD was in the range of 55 to 76% with both media. The surface roughness of the OSBG particles resulted in a more uniform microorganism attachment over the surface area of the particle, leading to thin and active biofilm. Several researchers have studied the attached growth bioreactors for wastewater treatment using different types of media, their findings are detailed in Table 2.10.

The need for compact wastewater treatment plants increasingly becomes a global concern where the environmental impact by the population also sets high demands to treatment of waste produced by the community. The attached growth bioreactor coupled with membrane separation as attached growth membrane bioreactor (attached growth MBR) is an alternative way to achieve high effluent quality, compactness treatment plants and economical management (Ødegaard, 2000).

Lee *et al*. (2001) reported filtration performance between attached and suspended growth systems in a submerged membrane bioreactor (MBR) under comparable operating conditions. Hollow fiber membrane with pore size 0.1μm was immerged in the bioreactor and the reactors were fed with synthetic wastewater at a constant flux of 25 L/m^2.d. For the attached growth MBR, looped core media (BioMatrix®) of the total surface area 4.37 m^2 was immerged into the reactor. Suspended growth MBR was set up and operated at the same conditions with attached growth, except for the elimination of the looped media from the bioreactor. The performance of MBRs was determined in terms of filtration characteristics and quality of treated water. The treatment efficiencies of both reactors were greater than 98% of COD and 95% of NH_4-N removals under 8 h HRT. The rate of fouling was evaluated by an increasing in transmembrane pressure (TMP). The increasing rate of TMP for the attached growth MBR was 7 times higher than that for the suspended growth MBR. Better filtration performance with the suspended growth was explained by the formation of dynamic membranes with the suspended solids. The suspended growth had smaller specific cake resistance due to the rougher cake layer than that with the attached growth.

Table 2.10 Attached growth bioreactors for wastewater treatment using different types of media

Wastewater type	Synthetic	Sewage	Synthetic	Municipal	Synthetic	Synthetic
Type of media	Bionet Linpor Ring-Lace	Polyethylene glycol, ∅5 mm.	Spherical shape polymer plastic (OSBG)* ∅2.7mm.	Cylindrical shape polypropylene	Polyurethane foam pads 1.5*1.5*1.5 cm^3 Surface area $3.5*10^4$ m^2/m^3	High density polyethylene Particle size 1 mm
Density (g/cm^3)	-	1.02	1.18	1.01	0.2	0.73
No of media (% of the reactor volume)	20 (Bionet) 25 (Linpor) 25 (Ring-Lace)	20	42	40	15	23
HRT (h)	-	9	30 min	2-3	-	0.8, 5
DO (mg/L)	6-7	2-6	-	3	-	6
BOD loading ($kg/m^3.d$)	0.52-1.12	1.1-2.8	-	1.2-1.9	-	-
COD loading ($kg/m^3.d$)	-	-	8.1	-	-	-
COD removal (%)	85	-	>80	80	> 90%	72-90
Nitrogen removal	95(NH_3-N removal)	73	-	60	-	69-100 (NH_3-N removal)
Reference	Lessel (1991)	Mishima *et al.* (1996)	Tavares *et al.* (1995)	Tsubone *et. al.* (1994)	Shin and Park (1991)	Nogueira *et al.* (2002)

*(OSBG: Optimum support for biological growth)

Leiknes and Ødegaard (2001) investigated a potential of membrane separation unit combined with a high-rate moving-bed-biofilm reactor for the design of compact wastewater treatment plants as shown in Figure 2.6. The loading rates used was in the range of 30 to 45 kgCOD/m^3.d with HRT of 20-30 min. The results showed 85-90% of COD removal efficiency if the biomass and particulate COD were completely removed in the moving bed reactor. Membrane separation of the biomass and particulate COD was maintained with a constant flux of 60 L/m^2.h and showed a high permeate quality in terms of suspended solid of less than 5 mg/L and turbidity of less than 1 NTU. Compared to other membrane bioreactors, the moving bed biofilm reactor could operate at higher volumetric loading (10-15 times) and at shorter HRT (10-30 times).

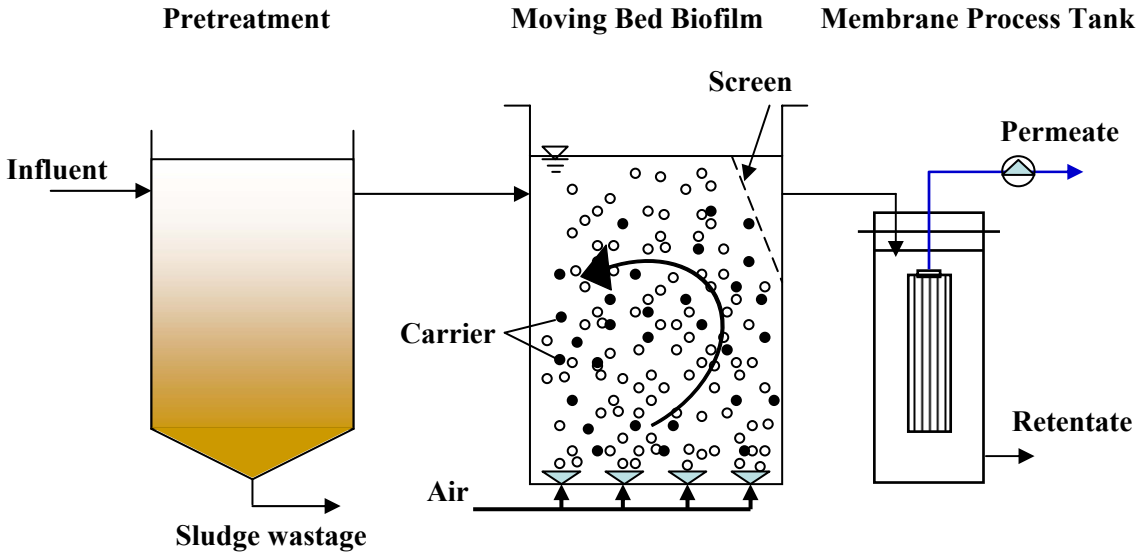


Figure 2.6 Moving-Bed-Biofilm reactor configuration
(Leiknes and Ødegaard, 2001)

2.4 Membrane Fouling

2.4.1 Fouling

Membrane fouling is characterized as reduction of permeate flux through the membrane, which results from an increased flow resistance due to pore blocking, concentration polarization and cake formation. Fouling is attributed to many factors such as sludge particle deposition, adhesion of macromolecules to the membrane surface and pore clogging by small molecules, among which the cake layer formation by sludge particle deposition is the most common reason for the flux decline. Fouling will not be observed when the flux is maintained below “critical flux”, but beyond this critical value, the particles start to deposit on membrane surface as a cake layer. The cake layer is readily removable from the membrane by physical washing protocol, this being classified as reversible fouling. On the other hand, internal fouling caused by adsorption of dissolved matter into the membrane pore, and pore blocking is considered irreversible, and is generally removed by chemical cleaning. In addition, formation of the gel layer on a membrane surface is often irreversible, although it is theoretically reversible. This is because it forms a cake layer and reduces membrane lifetime.

The mechanisms of membrane fouling are shown in Figure 2.7. Three accepted mechanisms are gel/cake formation caused by concentration polarization, pore plugging, and pore narrowing.

- Gel or cake layer formation is an extreme case of concentration polarization where a large amount of matter has accumulated on the membrane surface due to size exclusion from pores.
- Pore plugging is caused by insertion of organic macromolecules (EPS) into membrane pores and some metal ions might function as a fastener. Smaller bacteria can also be a contributor to pore plugging.
- Some foulants, particularly small bacteria and soluble EPS enter the membrane pores and further build up on the pore wall, leading to a reduction of total section area of membrane pore and eventually an increase of filtration resistance. This mechanism is called pore narrowing. It has been hypothesized that once the pore size is reduced the concentration polarization is amplified further, this causing an increase in fouling (Bourgeous *et al*., 2001).

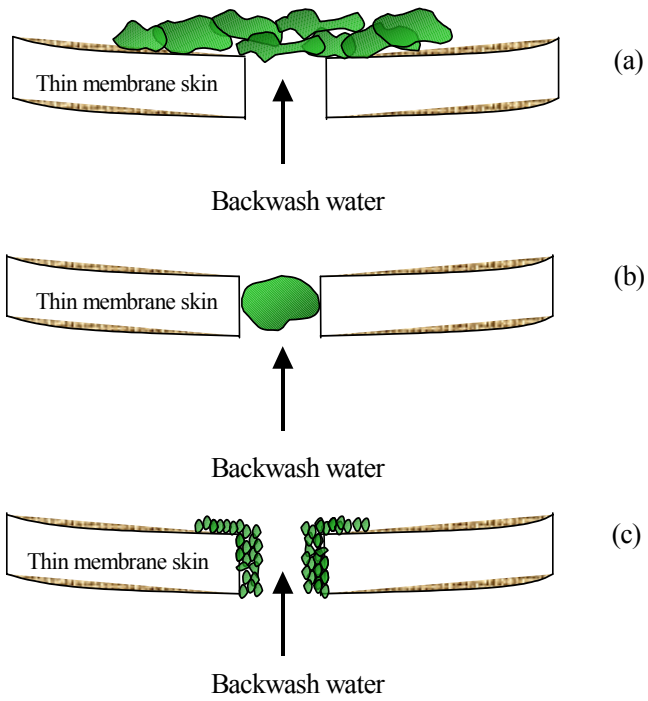


Figure 2.7 Mechanisms of membrane fouling; (a) gel/cake formation; (b) pore plugging; and (c) pore narrowing (Bourgeous *et al*., 2001)

In membrane bioreactor, the clogging of the membrane is proportional to a reduction of permeate flux, especially by accumulation of bacterial cell producing extracellular polymeric substances (EPS) on membrane surface. Nagaoka *et al.* (1996) carried out the influence of bacterial EPS on the membrane separation process, using a loop-type hollow fiber membrane module with pore size of 0.1 μm. The experiments were intermittently operated with a cycle of 10-minute-on and 5-minute-off. The feed wastewater was a mixture of acetic acid (as carbon source) and necessary nutrients. The results indicated that EPS accumulated in the aeration tank and on the membrane surface caused increases in viscosity of the mixed liquor and in filtration resistance. A linear

relationship between the filtration resistance and the viscosity of the mixed liquor was found, which was caused by rapid attachment of the suspended EPS.

Nagaoka *et al*. (1998) proposed a mechanism for biofouling in the membrane separation activated sludge system. The EPS accumulation on the membrane surface was analyzed in terms of pressure, flux and filtration resistance. The synthetic wastewater having acetic acid as carbon source, and NH_4Cl as N source were used. The reactor was operated at different organic loading rates of 1.5 gTOC/L.d and 0.5 gTOC/L.d. They found that increasing the loading in the reactor increased the transmembrane pressure, but decreased the flux. The measure of the flux, the pressure and the resistance could be explained by the model behavior of the permeate flow rate, which was reduced by membrane fouling especially by accumulation of the bacteria cell and EPS.

Mukai *et al*. (2000) estimated the flux decline of ultrafiltration membrane at different cultural growth phases (i.e. different EPS and metabolic products concentrations in activated sludge process). The flux decline was affected by protein to sugar ratio of EPS and metabolic products. Low permeate flux was found at high retention of protein during filtration.

Hodgson *et al*. (1993) investigated the role of bacteria extracellular matrix as a major factor on cake resistance and solute rejection in the microfiltration of bacteria. The EPS was associated with the bacteria which effectively filled the void spaces between the particles in the cake.

Three main types of foulants can be differentiated (Mulder, 1996) as follows:

- *Organic precipitates* (biological substances, macromolecules, etc.): Macromolecules can be protein molecules in wastewater, and EPS or long chain organic by-products generated from biodegradation process.
- *Inorganic precipitates* (metal hydroxides, calcium salts, etc.): Changes in the environmental conditions (pH, solute/ion strength) are due to microorganism actions in MBR which can form precipitates. Gelatinous precipitates (such as hydrated complex of calcium phosphate and citrate, etc.) can easily foul membranes.
- *Particulates* (cells, debris, microbial flocs, etc.): Particulates in the mixed liquor build-up the solid cake on the surface of membrane which results in a decrease of the flux.

2.4.2 Extracellular Polymeric Substances (EPS)

2.4.2.1 Definition and Composition

Extracellular polymeric substances (EPS) as biopolymers are products of natural microorganisms excretion, cell lysis, hydrolysis products and adsorbed matter. EPS production seems to be an important element for microbial aggregation, such as floc and biofilm formations. EPS are mainly related to the structure and function of biofilms and are considered as the key components determining the physicochemical and biological properties of the biofilm. It forms a gel matrix for keeping the biofilm bacteria together, and protection of bacteria against the toxic influences from the environment. In general, the proportion of EPS in the biofilm ranges from 70 to 98% of the total organic carbon (Jahn and Nielsen, 1998), according to the environment and the conditions, to which the biofilm

is exposed. EPS can be presented in two forms: 1) bound EPS: sheaths, capsular polymers, condensed gel, loosely bound polymers, attached organic material, and 2) soluble EPS: soluble macromolecules, colloids and slimes (Nielsen and Jahn, 1999). These two forms of EPS are shown in Figure 2.8.

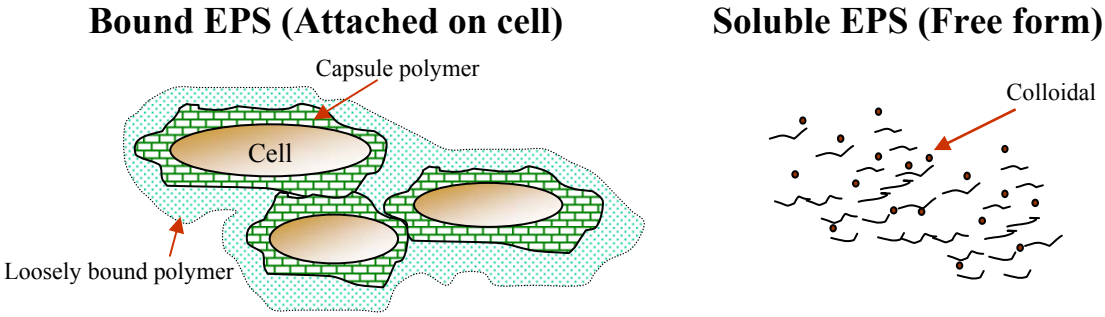


Figure 2.8 Two forms of EPS

EPS are composed of various organic substances. The main compositions of EPS are protein, carbohydrate, humic substances (Jin *et al.,* 2003), DNA and RNA (Jorand *et al.,* 1994; Plamgren *et al.,* 1996). Flemming and Wingender (2001) suggested that carbohydrate was the predominant composition in pure culture while Dinac *et al.* (1998) found that the amount of EPS content in the activated sludge was protein. However, the compositions of EPS are mostly dependent upon extraction method, which is discussed in section 2.4.2.3. Flemming and Wingender (2001) suggested that the EPS of *Pseudomonas aeruginosa* may be served as an individual example, as this is a model organism with which many biofilm investigations have been carried out. Alginate is known as the main EPS component. The data are summarized in Table 2.11.

Table 2.11 Composition of EPS from agar-grown biofilm
(Flemming and Wingender, 2001)

Component	Biofilm ($\mu g/10^9$ cells)	EPS ($\mu g/10^9$ cells)	Proportion found in EPS
Total carbohydrates	1,005.8	766.6	76.2
Uronic acid (alginate)	473.8	402.8	85.0
Proteins	585.0	266.4	45.5

EPS in the anaerobic sludges are different from those in the activated sludge. Morgan *et al.* (1990) noted that EPS in UASB granule contained 10-20 mg/gSS while that in activated sludge was 70-90 mg/gSS. Under anaerobic conditions, bacteria may quickly degrade, forming CO_2 and CH_4 as by-products. Lower concentration of EPS was observed in these anaerobic systems.

Jia *et al.* (1996) studied EPS yields in anaerobic digestion process with three carbon sources such as propionate, butyrate and glucose. The results showed that the EPS production was dependent on the growth phase of the microorganism. An increase of EPS in the initial stage could be attributed to the prolific growth of bacteria due to high substrate concentration and high F/M ratio. However, the EPS concentrations decreased to their initial levels as substrate became depleted, this occurring in the declined growth phase.

Horn *et al.* (2001) suggested that the EPS can be used as carbon or energy sources during the substrate limited phase. The anaerobic microorganisms hydrolyze organic polymer (EPS) and lipids to monosaccharides, amino acid and related compound, then the acidogenic bacteria broke down the products from the hydrolysis to organic acid. The methanogenic bacteria then converted hydrogen and organic acid to methane and carbondioxide. In the activated sludge, the dominant component of EPS was carbohydrate, while the anaerobic sludge tended to have higher concentration of protein in their extracted polymers.

2.4.2.2 Function and Characteristics of EPS

The functions and characteristics of EPS are reported to be related to microbial aggregation, flocculation (Li and Ganczarczyk, 1990), physicochemical properties of sludge floc (Wilén *et al.,* 2003), and sorption properties (Liu *et al.,* 2001). These properties can be reviewed in detail as follows;

Microbial aggregation and flocculation

Microbial aggregates, such as biofilms, flocs and sludge, can be kept together by EPS. The aggregation and flocculation are responsible for cohesive force as physico-chemical interaction. The EPS fill the space between cells, and form the matrix in which the cells live. The formation of EPS matrix is dependent on their structures, properties and compositions, which vary dynamically due to changes in environmental conditions.

Li and Ganczarczyk (1990) studied the structure of activated flocs, and found that activated sludge flocs had large amount of EPS of microbial origin. These biopolymers were seen within the flocs which formed a matrix and bound the microorganism cells together. The large amount of EPS was excreted by cell autolysis at low growth stages. Higher loading stimulated higher microorganism growth rates, resulting in the presence of small amount of EPS.

Figure 2.9 shows the formation and structure of flocs by many components as follows;

- **Slime polymeric compounds are produced by bacteria like glue for sticking cells together.**
- **Bacteria are negative charge, and they bind with positively charged ions such as Ca^{2+}, Mg^{2+} to form flocs.**
- **Some bacteria form a network of extremely thin filaments (fibrils) around their cells. This network contributes to the bonding of the cells and to the entrapment of other bacteria and particles.**

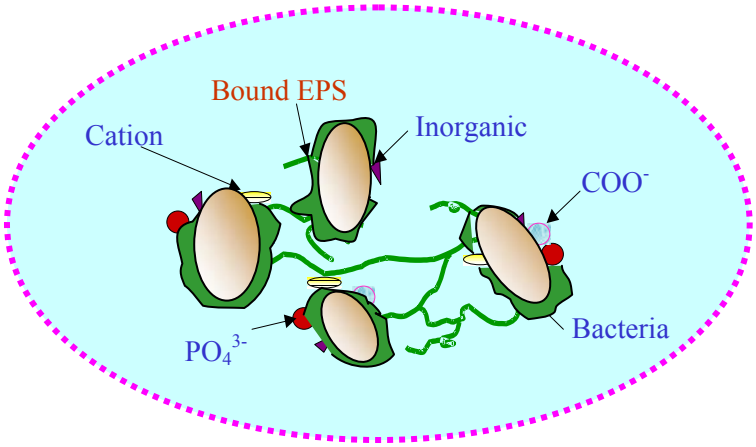


Figure 2.9 Floc structure

Physicochemical properties of sludge floc

The principle of the activated sludge floc is dependent on physical characteristic of the flocs. EPS are mainly responsible for the structure and functional integrity of the aggregates, and are considered as a key to the physicochemical and biological properties (Flemming and Wingender, 2001). Wilén *et al.* (2003) suggested that EPS compositions, such as EPS/protein and EPS/carbohydrate, strongly influence the surface properties such as hydrophobicity and surface charge of sludge. The hydrophobic interactions play an important role in flocculation formation and settlement of sludge. The adhesion to the flocs is dependent on the overall hydrophobicity. Hydrophobic bacteria are preferred to adhere to the flocs. Jorand *et al.* (1998) suggested that hydrophobic fraction of EPS was made up only of proteins, not carbohydrates. The amino groups in proteins carry positive charge from carboxyl and phosphate groups and therefore, decrease the net negative surface charge of sludge floc (Jorand *et al.,* 1994). The composition and properties (e.g. hydrophobicity and surface charge) of EPS are more important with respect to the settleability than the amount of EPS (Bura *et al.,* 1998; Liao *et al.,* 2001).

Sorption properties

Dissolved substance can be sorbed by biofilm, and in particular, by the EPS matrix. Liu *et al.* (2001) investigated the adsorption capacity of EPS on various heavy metals. The six most common heavy metals polluting in Hong Kong, namely; cadmium, cobalt, copper, nickel, zinc and chromium were selected. It was found that more metals were removed by the EPS, in spite of the metal concentration ranging from 10 to 100 mg/L. Zn^{2+} Cu^{2+} and Cr^{3+} removal efficiencies were achieved by EPS of greater than 97-99% while CrO_4^{2-} was the lest effective due to its negative charge.

Jang *et al*. (2001) determined the effect of heavy metals (Cu, Pb, and Ni) on the compositions of EPS in biofilm. It was reported that metal uptake by biofilm gradually increased with time. The affinity of heavy metal to the biofilm increased in order of Cu>Pb>Ni over a given time period.

2.4.2.3 Extraction and Analysis

As stated, EPS can be classified into soluble and bound EPS. The bound EPS are closely associated with the cells while the soluble do not have any direct contact with the cells. The way to separate two forms of EPS is usually by centrifugation. The soluble EPS can be extracted by centrifugation alone while the bound EPS are required additional treatment methods. The extraction procedures include sampling and pretreatment, extraction, purification and analysis. Many methods for EPS extraction are regular centrifugation, EDTA, ultracentrifugation, steaming extraction, regular centrifugation with formaldehyde (Zhang *et al*., 1999; Jang *et al*., 2001), sonication, sonication with cation exchange resin (Dignac *et al*., 1998; Wuertz *et al*., 2001), crown ether (Wuertz *et al*., 2001), glutaraldehyde (Azeredo *et al*., 1998) and heat treatment (Liu *et al.,* 2001; Lee *et al.,* 2003). The suitable methods should have less cell lysis, no interruption of biopolymer and releasing all the EPS biopolymer. It is hardly possible to obtain these requirements with the extraction methods as no standard extraction method has existed. However, it is important to minimize the effect within extraction procedure such as time, shear and temperature. Frølund *et al.* (1996) recommended 0.5-1 h for EPS extraction time with minimum risk of induced cell lysis. Figure 2.10 shows a summary of EPS extraction and analytical procedure.

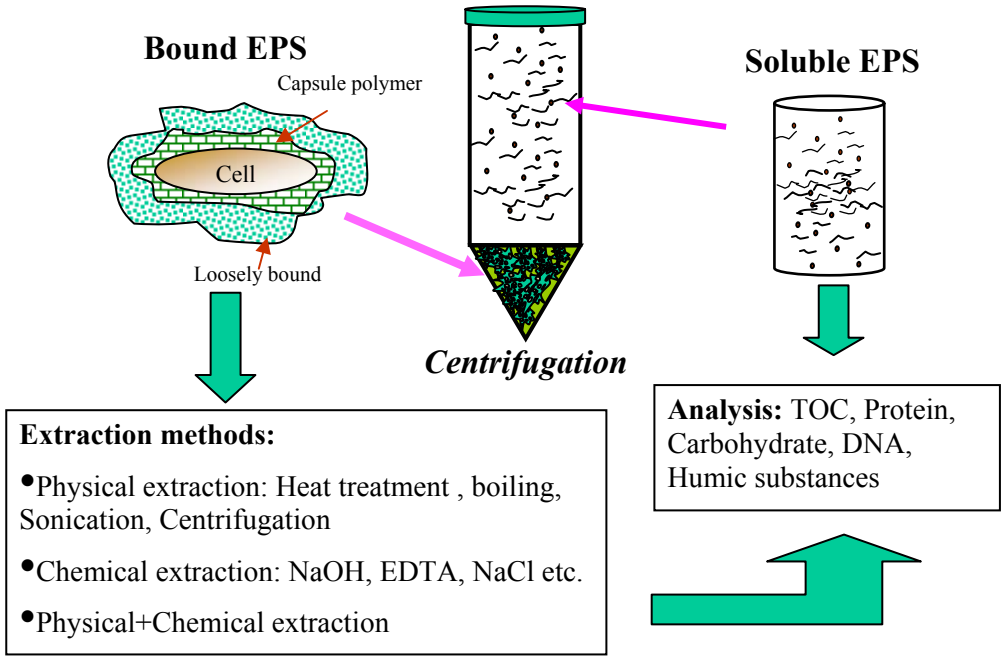


Figure 2.10 EPS extraction and analytical procedure

Zhang *et al*. (1999) compared the quantities of EPS in many different extraction methods. The best-investigated component of EPS was the polysaccharide content. The EPS matrix was composed of many more components such as proteins and nucleic acids (Plamgren *et al*., 1996) and lipids. Nielsen *et al.* (1996) investigated the activated sludge EPS which was extracted by cation exchange. The results showed that the protein was the major EPS component.

Azeredo *et al*. (1998) reported a comparison between three extraction methods (such as vapor, sonication and combined sonication with Dowex resin) and a new method using glutaraldehyde. The extraction methods were effectively estimated by measuring the total protein, TOC and monosaccharide constituents. It was found that the sonication promoted the excretion of large quantities of proteins, indicating cellular lysis or breakage of the cell membrane. Glutaraldehyde was found to be the most suitable method for biopolymer extraction because it produced a high TOC/protein ratio and had no disruptive effect on the biomass. Finally, the yield of EPS extracted increased with the volume of glutaraldehyde added to the sludge.

Zhang *et al.* (1999) compared five extraction methods, namely; regular centrifugation, EDTA extraction, ultracentrifugation, steaming extraction and regular centrifugation with formaldehyde (RCF) by examining the effectiveness and repeatability. This was to determine the amount of cell lysis during the extractions indicated by DNA concentration. The results showed that the RCF extraction gave the greatest carbohydrate yield. The steaming extraction resulted in the greatest protein yield. DNA in the EPS was 27 times smaller than that in the pellets, indicating no obvious cell lysis occurring during the five different extractions.

Jang and co-workers (2001) evaluated the change of EPS compositions when the biofilm was exposed to heavy metal. The composition of EPS was represented by the ratio of carbohydrate to protein(C/P). The EPS were composed of slime loosely bound to the cell, and capsular material was extracted by four extraction methods, such as centrifugation, centrifugation with formaldehyde, EDTA extraction and steam extraction. As a result, EDTA extraction was found to be the most effective method for the biofilm, since it released a significant quantity of carbohydrate from biofilm and caused less cellular disruption. In contrast, the steaming extraction and centrifugation methods released low concentrations of carbohydrate from biofilm without significant cell disruption.

Liu and Fang (2002) studied the efficiency of extracting EPS from aerobic, acidogenic and methanogenic sludge using EDTA, cation exchange resin, and formaldehyde. It was noted that formaldehyde plus NaOH was most effective in extracting EPS for all sludges without being contaminated by the intracellular cell. EDTA extraction method caused cell lysis and released intracellular DNA. The EPS in the aerobic and acidogenic sludges were greater than those in granule sludge from methanogenic sludge.

Table 2.12 shows EPS constituents in the literature using a variety of extraction methods, including heat treatment (Liu *et al.,* 2001; Alavi Moghaddam *et al.,* 2003), ion exchange (Dinac *et al.,* 1998; Liao *et al.,* 2001; Wilén *et al.,* 2003), sonication (Dinac *et al.,*1998), Formaldehyde, NaOH and EDTA (Liu and Fang 2002). It can be seen that there were large differences in reported data, mainly due to the variations in the sample sources and extraction methods used. The extraction methods and their advantages are summarized in Table 2.13.

Table 2.12 Summary of constituent of EPS and their extraction methods

Extraction methods	Quantity of EPS constituents (mg/gVSS)				Source of EPS	Reference
	Protein	Carbohydrate	Other	P/C ratio		
Heating at 105°C	195	77	-	2.5	Activated sludge	Alavi Moghaddam *et al.* (2003)
Heating at 80°C with NaCl	44.9	13.0	-	3.5	Activated sludge	Liu *et al*. (2001)
Cation exchange	78 17.6	15 12.7	71 48	5.2 1.4	Activated sludge Activated sludge	Wilén *et al.* (2003) Liao *et al.* (2001)
Centrifugation	13.3	8.1	2.0	1.6	Biofilm	Zhang and Bishop (2003)
Formaldehyde-NaOH	42.1 54.6	19.1 40.5	25.6 55.0	2.2 1.4	Methanogenic sludge Activated sludge	Liu and Fang (2002)
EDTA	22.9	12.4	61.8	1.8	Activated sludge	Liu and Fang (2002)
Centrifugation with glutaraldehyde	71	17	6.6	4.2	Activated sludge	Sponza (2002)
Centrifugation and steaming	1.1-2.8	69-135	0.05-0.13	0.02	Biofilm	Choi *et al.* (2001)
Sonication/Ion-exchange	242	11.4	-	21.2	Activated sludge	Dinac *et al.* (1998)

Table 2.13 Extraction methods and their advantages

Method	Extraction product	Advantage	Reference
Heat extraction	Protein Carbohydrate	High protein	Chang and Lee (1998) Lee *et al.* (2003)
Centrifuge with formaldehyde	Carbohydrate, protein, DNA	Greatest carbohydrate yield	Zhang *et al*. (1999) Flemming and Wingender (2001)
Steaming extraction	Carbohydrate, protein, DNA	Greatest protein yield Cellular disruption less	Zhang *et al*. (1999) Jang *et al*. (2001) Bura *et al*. (1998)
Sonication	Protein, DNA TOC, Monosacharide, Uronic acids	Large protein Minimum amount of cell lysis	Azeredo *et al*. (1998) Dinac *et al*. (1998) Bura *et al*. (1998)
EDTA extraction	Carbohydrate, protein, DNA	Less cell disruption Effective for biofilm High carbohydrate yield	Jang *et al.* (2001)
Cation exchange resin	Protein, Carbohydrate DNA , Uronic acids Humic compounds	Greatest protein	Nielsen *et al*. (1996)
Formaldehyde with NaOH	Protein, Carbohydrate, DNA, Humic substance, Uronic acid	Effective and no cell lysis for aerobic, acidogenic and methanogenic sludges	Liu *et al.* (2001)

2.5 Sludge Properties and There Technique

2.5.1 Rheology and Viscosity Properties of Sludge

Rheology is the science of flow and deformation of a matter. In wastewater industry, it is referred to as the viscous characteristic of sludge, in terms of a relationship between shear stress and shear rate. This can be measured using a viscometer. The sludge rheological characteristics are related to two specific parameters, such as solid concentration and sludge nature (particle size, surface charge, degree of hydration, and cohesion of flocs of agglomerated particles in suspension) (Lotito *et al.,* 1997; Monteiro, 1997). Günder (2001) and Nagaoga *et al.* (1996) suggested that the existence of extracellular polymer and filamentous microorganisms increased sludge viscosity.

The viscous characteristic of sewage sludge is non-Newtonian and has usually been modeled in the literature using the pseudoplastic rheological model (Lotito *et al.,* 1997). Non-Newtonian viscosity can be explained using Equation 2.2 and Figure 2.11.

$$\eta = \frac{\tau}{D}[Pa.s] \qquad \text{Equation 2.2}$$

Where η: Viscosity (Pa.s), τ : Shear stress (Pa) and D: Shear rate (s^{-1})

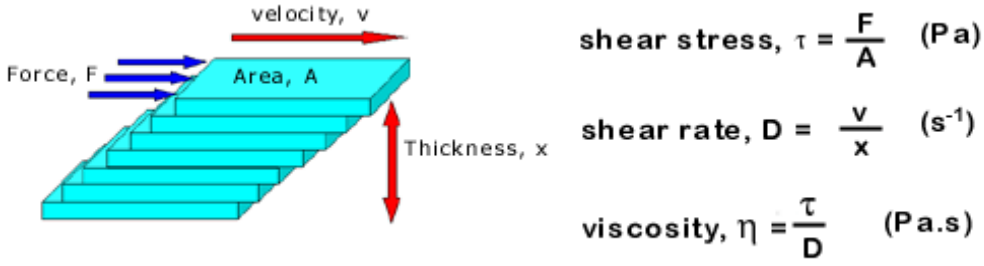


Figure 2.11 Laminar shear field due to applied shear stress

A rotational viscometer (Bookfield DV-II) can also be used to measure the rheological properties of suspended biomass in the reactor. The working principle of the viscometer is to drive a spindle which is immerged in the tested fluid through a calibrated spring. The viscous drag of the fluid against the spindle is measured by the spring deflection measured using a rotary transducer. The measurement range is dependent on the rotational speed of the spindle, the size and shape of the spindle, the container the spindle is rotating in, and the full scale torque of the calibrated spring. Figure 2.12 shows the sludge viscosity in MBR with varying rotational speeds (shear rates). This rheological behavior of sludge in bioreactor exhibited pseudoplastic non-Newtonian in nature, suggesting that the sludge viscosity decreased with shear rate (rotational speed).

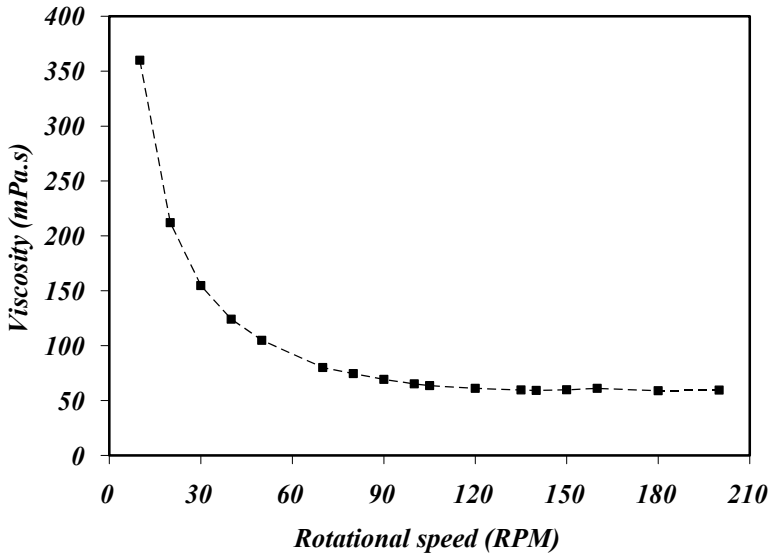


Figure 2.12 sludge viscosity in MBR with vary rotational speed (shear rate)

Furthermore, rheology and viscosity properties of sludge were influenced by the sludge concentration as shows in Figure 2.13 (Rosenberger *et al.*, 2002). It can be observed that the values of apparent viscosity vary up to 10 or even 100 between low and high shear rates. The biomass particles tend to flocculate resulting in a large-scale network. With increasing shear rate, this network is disrupted and results in a decrease in viscosity. Rheology measurements of highly concentrated activated sludge show a strongly pseudoplastic behavior indicating that MBR activated sludge can be regarded as a non-Newtonian fluid. Itonaga *et al.* (2003) studied the influence of suspension viscosity and colloidal particles on permeability of membrane used in membrane bioreactor. They reported that high MLSS concentration caused high suspension viscosity in MBR. MLSS concentration might be expected to have a profound influence on MBR performance owing to its effect on both the dynamic cake layer thickness and the viscosity.

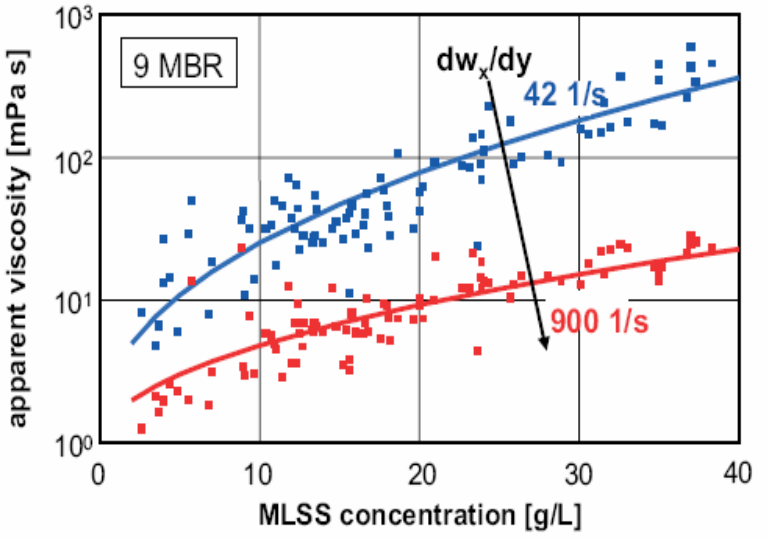


Figure 2.13 Relationship between viscosity and MLSS concentration at different shear rate

2.5.2 Dewatering Property

The dewatering of sludge can be characterized by capillary suction time (CST). The CST test determines the rate of water released from sludge. It provides a quantitative measure, of how readily sludge releases its water. The CST test has been used as a relative indicator to characterize the performance of most sludge dewatering processes. The CST test is fast, simple and cheap to measure dewatering characteristic of the sludge. The procedure can be obtained in detailed as in APHA method 2710G (APHA, 1998). A large CST value usually implies poor sludge filterability. Table 2.14 shows the variation of filterability (CST) of different sludge samples.

Table 2.14 Variation in filterability of sludge in 18mm reservoir
(Carberry and Englane, 1983)

Type of Sludge	Total solids concentration (%)	Filterability CST (sec.)
Mixed primary sludge	3.3	283
Humus (low rate)	4.9	1,023
Humus (high rate)	3.3	580
Activated (very low rate extended-aeration) sludge	1.1	7
Activated (slow rate) sludge	2.0	14
Activated (high rate) sludge	2.0	223
Anaerobically digested sludge	2.5	278

2.5.3 Settling Property

Sludge flocculation and settling are very important for an effective operation of activated sludge process. The effectiveness of bioflocculation and settling of sludge are often characterized by sludge volume index (SVI), which is defined as the volume in milliliters occupied by 1 g of a suspension after 30 min of settling in a 1 L cylinder. The lower the SVI, the denser the settled sludge, and thus the better the settleability of the sludge. An activated sludge with a SVI below 120 mL/g is considered satisfactory, and that over 150 mL/g is considered bulking (Jenken *et al.,* 1993). Cicek *et al.* (1999) reported that the activated sludge had a SVI of 80 mL/g whereas the MBR sludge did not settle at all.

2.5.4 Membrane Fouling Index (MFI)

The accumulation of substance on membrane surface or within the membrane pore results in a deterioration of membrane performance. It is not evitable and generally a rapid decrease in membrane permeability occurs at the very beginning of the filtration operation. Membrane fouling index (MFI) is used to predict the potential of fouling in membrane system based on the cake filtration mechanism (Roorda and van der Graaf, 2001; Boerlage *et al.,* 2003). This index is based on the cake filtration mechanism, which follows the relationship between filtration time and volume in dead-end flow and at a constant TMP. MFI is found to increase significantly with increasing applied pressure due to cake compression (Boerlage *et al.,* 2003). The compression of the cake does not occur during the experiment, as is found to be reasonable within a short time interval. The MFI can be

determined from the gradient of the general cake filtration as shown in Equation 2.3 for constant pressure in a plot of t/V versus V (Boerlage *et al*., 2003).

$$\frac{t}{V} = \frac{\mu R_m}{\Delta P A} + \frac{\mu \alpha C_b}{2 \Delta P A^2} V \qquad \text{Equation 2.3}$$

Where V is the filtrate volume, t the filtration time, ΔP the transmembrane pressure, μ the solution viscosity, α the specific resistance of the cake deposited and C_b is the concentration of particles in feed water.

The t/V versus V plot typically shows three regions, which corresponds to blocking filtration, cake filtration and cake clogging or cake compression (Figure 2.14). The first sharp increase in slope is attributed to membrane pore blocking followed by cake filtration, which is a liner region of minimum slope. The MFI is defined as the gradient of the linear region of a relationship between ratio of filtration time and filtrate volume (t/V) and filtrate volume (V). The MFI value was dependent on a number of factors, such as sample source, membrane characteristic and applied pressure that are shown in Table 2.15.

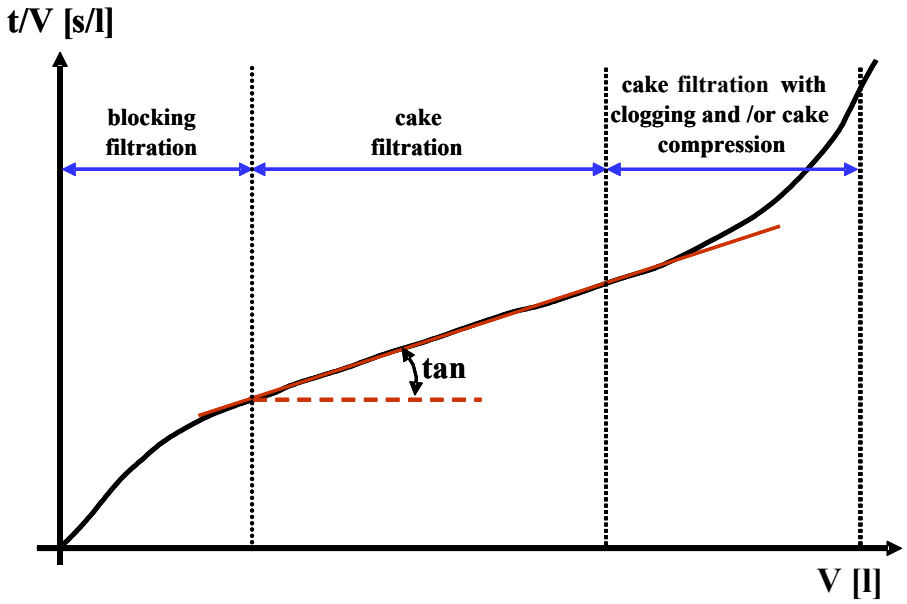


Figure 2.14 Ratio of filtration time and filtrate volume (t/V) versus filtrate volume (V). MFI determined from the gradient (tan) of the liner portion of the relationship. (Boerlage *et al.*, 2003)

Table 2.15 Summary of MFI with different sources

Sample	Membrane type	Pore size (μm)	Pressure applied (bar)	MFI (s/L^2)	References
Effluent of WWTP	PVDF*	0.03	1	0.08	Roorda and van der Graaf (2001)
Effluent of WWTP	PES/PVP**	0.02	1	0.15	
MBR Suspension after centrifugation	Nitrocellulose	0.05	0.5	$2.76*10^6$	Ognier *et al.* (2002)
Protein solution (1g/L)	Nitrocellulose	0.05	0.5	$2.40*10^6$	
Canal water	Polyacrylonitrile	UF13kDa	1	$1.64*10^4$	Boerlage *et al.* (2003)
Tap water	Polyacrylonitrile	UF13kDa	0.5	$1.80*10^3$	
Tap water	Polyacrylonitrile	UF13kDa	1.0	$3.86*10^3$	
Tap water	Polyacrylonitrile	UF13kDa	1.5	$5.00*10^3$	
Tap water	Polyacrylonitrile	UF13kDa	2.0	$6.26*10^3$	

*PVDF: Hydrophilic Poly Vinyl ldene Fluoride

**PES/PVP: Hydrophilic Poly Ether Sulfone/Poly Vinyl pyrolidone

2.5.5 Particle Size and Size Distribution

Particle size and size distribution are defined as the relative percentage by weight or number of each of the different size fractions of particulate matter. Particle sizing is carried out using a Malvern Mastersizer/S (Malvern, UK.) which is based on static laser light scattering. The Mastersizer software generates a volume weighed floc size distribution. In order to describe the mean particle size, the volume weighed average diameter which is also known as the mass mean diameter. Fresh activated sludge sample is collected directly from bioreactor system. For analysis, fixing the obscuration level at 10-30% in the Masterzer software controlls the sludge concentration. Particle size and size distribution can differ substantially as a result of differences in the environment in the treatment plant. A number of particle size or floc size could be expected to exert some direct or indirect influence on the sludge properties. Zhang *et al*. (1997) suggested that the particle size distribution of the MBR flocs was narrower than that observed with conventional activated sludge (CAS) systems, with significantly smaller mean size values. In the MBR process, the median diameter of the flocs ranged from 4 to 40 μm, while ranging from 50 to 400 μm for the CAS system. The smaller floc size in the MBR resulted from the high aeration and turbulent which can be broke cell particle. However, the shear force arising from pumping during crossflow filtration also led to the breakup of biological flocs and generating fine colloidal (Wisniewski and Grasmick 1998).

2.5.6 Microscope Observation

The microscopic image can provide information concerning several visually observable properties of activated sludge. This information is related to the qualitative assessment of the sludge. In addition, it can assist in making a diagnosis if the treatment plant is not a function of expectation. The microscope observation does not provide any direct information on the activity of the biomass. However, the frequency, by which sludge investigation is carried out is linked to the sludge age. The microscopic investigation

should be carried out with sludge that is as fresh as possible. Sample that cannot analyze directly must be kept cool (4-7°C). The sample must not be frozen as it could affect the structure of the floc. It should be noted that the properties of the sludge change gradually during storage. The observation variables are related to form, structure, dimensions and composition of the flocs, filamentous microorganism, bacteria, which are bound to the flocs or free cell between the flocs and other organisms.

2.6 Factor Affecting Membrane Fouling

Membrane fouling can be classified as reversible and irreversible. The nature and extent of membrane fouling in MBR are strongly influenced by operating conditions, and biomass characteristics. There are explained below;

2.6.1 Operating Conditions

2.6.1.1 Organic Loading Rate (OLR) and Hydraulic Retention Time (HRT)

Increasing flux rate increases the probability of particles contacting (fouling) the membrane surface. Several studies have investigated the effects of organic loading rate and hydraulic retention time on membrane fouling (Yamamoto *et al.,* 1991; Harada *et al.,* 1994; Seo *et al.,* 1997; Rosenberger *et al.,* 2002). The decrease of HRT corresponds to the increases of organic loading rate and MLSS concentration. This directly affects the membrane fouling. Visvanathan *et al.* (1997) suggested that a decrease in HRT could lead to a rapid formation of compact cake layer on the membrane surface, thus increasing the transmembrane pressure due to increased in MLSS concentration in the bioreactor.

Nagaoka *et al*. (2000) investigated the influence of organic loading rate on biofouling in membrane separation for activated sludge system. A flat-sheet membrane module was used. The changes in pressure, filtration resistance, and consolidation characteristics of sludge accumulated on membrane were measured. The TOC loading rates were in the range of 0.3 g/L.d to 1.5 g/L.d. The results showed that high loading rate gave an unexpected increase of trans-membrane pressure, while low loading rate exhibited a slight increase of the pressure.

Nagaoka and Kudo (2002) studied the performance of submerged membrane separation for activated sludge process with intermittent aeration by changing organic loading rates and intermittent aeration cycles. A flat-sheet microfiltration membrane made of poly-olefin and having a pore size of 0.2 μm was submerged in an aeration tank. Aeration cycle was changed from 10 min-10 min (aeration- stop) to 120 min-120 min in different organic loading conditions. The organic loading rates to the reactor were carried out at 0.3 and 0.8 gTOC/L.d. It was found that the membrane fouling rapidly occurred at the organic loading rate of 0.8 gTOC/L.d. However, when organic loading rate was 0.3 gTOC/L.d, bacterial metabolic substances were rapidly degraded, resulting in a decreased viscosity in mixed liquor.

2.6.1.2 Sludge Retention Time (SRT)

Sludge retention time (SRT) or sludge age is directly linked to the sludge production of excess sludge, and significantly affects biological performance by changing sludge compositions (Bouhabia *et al*., 2001). A long SRT and a short HRT would

predictably increase the biomass concentration that may facilitate the biodegradation of refractory pollutants. On the other hands, this may have some negative effects, such as high sludge viscosity which leads to excessive fouling (Ueda *et al.,* 1996; Mamen *et al*., 1996) and low oxygen transfer, which reduce the performance of MBR.

Alari Moghaddam *et al*.(2003) studied the effect of SRT on performance of coarse pore filtration for activated sludge process. SRT of 10, 30 and 75 days were used. The results of the reactors with SRT 10 and 30 days gave relatively good effluent quality without any filter clogging for more than 4 months operation. For long SRT (75 days), the filter clogging due to maximum EPS content occurred after 80 days of operation, which caused the increase the operation pressure. The existence of high amounts of suspended solid in the effluent due to increase in the negative pressure inside the membrane module which reached 40 kPa (normal 8 kPa) deteriorated in the effluent quality for a few days.

Bouhabia *et al*. (2001) characterized the fouling in membrane bioreactor using hollow fiber membrane with pore size 0.1μm, immerged in the bioreactor for treating synthetic wastewater. The COD removal efficiency, sludge production and fouling ability were compared in the three reactors which were operated at different SRT (10, 20 and 30 days). The COD removal was greater than 95% and the sludge production decreased from 0.31 to 0.16 kgMLSS/ kgCOD with increasing SRT. The liquid fraction of activated sludge (colloidal and solutes) plays an important role in membrane fouling. This fraction resulted from the bacteria metabolism that was more concentrated when the SRT was increased. The specific resistance of this fraction was about 10 times greater than that of the total sludge (suspended solid, colloidal and solutes).

Nuengjamnong *et al.* (2004) investigated the effects of extractable extracellular polymeric substances (EPS) and the supernatant of sludge flocs on the membrane fouling in submerged membrane bioreactors (SMBRs). Three laboratory-scale SMBRs were operated at a constant permeate flux (12.5 L/m^2 h) with a flat sheet microfiltration membrane at different SRT (8, 20 and 80 days). The results showed that as SRT was increased the organic carbon content in extractable EPS decreased whereas DOC in the supernatant was independent of SRT. The protein concentrations of extractable EPS and supernatant of sludge flocs declined with increasing SRTs.

2.6.1.3 Cross Flow Velocity (CFV)

Cross flow velocity in a submerged membrane bioreactor is a major influence on membrane fouling. Sufficient cross flow velocity should be induced to hinder membrane fouling and maintain a long operating period (Liu *et al.,* 2000). The CFV is mainly influenced by a number of factors, such as aeration rate, reactor structure and fluid viscosity (Liu *et al.,* 2003). The CFV, which was created by aeration, not only provided oxygen to the biomass, but also maintained the solids in suspension, scoured the membrane surface and removed fouling. The CFV affected the mass transport of particles away from the membrane surface, and thus the resultant cake layer thickness, by increasing the shear and shear-induced diffusion. In order to reduce deposition of suspended solids at the membrane surface, a high cross flow velocity should be supplied by a circulation pump.

Tardieu *et al*. (1998) studied a hydrodynamic control of bioparticle deposition in a MBR for wastewater treatment. It was noted that at low recirculation velocity (0.5m/s), the floc particles were rapidly accumulated onto the membrane, and formed a cake which was

probably compressible, leading to a rapid increase in the TMP, This was required to maintain the flux. On the other hand, the particle deposition was very limited under turbulent flow condition (CFV 4 m/s). More fouling was predicted at lower CFV.

The impact of hydrodynamic conditions on membrane fouling rate was studied by cross-flow velocity, membrane flux and sludge concentration (Liu *et al.,* 2003). The hydrodynamic conditions can be generated by cross-flow across the membrane surface. A lift-velocity was produced, and some particles depositing on the membrane surface were removed.

Lui *et al.* (2000) suggested that the cross flow velocity was a function of aeration intensity, dimensional parameter of bioreactor. The critical cross flow velocity was found to be 0.3 m/s. Transmembrane pressure sharply increased due to rapid deposition of suspended solids on the membrane surface and a corresponding increase of membrane resistance at CFV lower than 0.3 m/s.

2.6.1.4 Aeration

Increases in aeration rate and cross flow velocity (CFV) suppress fouling and increase permeate flux although most studies on permeate flux are based on side-stream operation. Studies carried out with submerged MBR or with ideal feed solution suggest that an increase in air flow rate at the membrane surface can limit the fouling. Ueda *et al.* (1997) observed an optimum aeration rate beyond which a further increase has no effect on fouling suppression. Hwang *et al.* (2002) suggested that adjusting aeration rates from 2 to 4 L/min at 5.6 g/L of sludge, and 50 kPa of pressure increased flux from 10 to 13 L/m^2.h. It was obvious that the strong aeration improved the filtration efficiency.

2.6.2 Biomass Characteristics

Activated sludge is a heterogeneous suspension. It contains compounds from feed water components and metabolites produced during the biological reactions. It forms flocs which are a complex biological matrix structure. The biomass contains both solids and dissolved polymers (eg. EPS) contribute to fouling.

2.6.2.1 Extracellular Polymeric Substances (EPS :Protein and Carbohydrate)

EPS is high molecular weight mucous secretion from microorganism cell. It plays an important role in bacteria attachment and biofilm formation. It provides gel matrix which barrier to permeate flow in the MBR. EPS is composed of many organic compounds such as polysaccharide, protein and humic substances. It was considered to enhance microbial attachment to membrane surface. Microorganism produces EPS during both suspended and attached growths. The attached cell produced more EPS than the suspended cell during slow growth rates (Wolfaardt *et al.,*1999). The EPS in the suspended growth have been studied by many researchers (Campos *et al.,* 2002; Kim *et al.,*1998; and Thuy 2003). A summary of EPS production is shown in Table 2.16.

Kim *et al.* (1998) reported that addition of powder activated carbon (PAC) to the MBR could increase flux permeability by reducing dissolved EPS levels from 121-196 to 91-127 mg/gVSS. Thuy (2003) investigated the performance of biological activated carbon (BAC) by adding granular activated carbon into MBR (BAC-MBR) and AS-MBR

(activated sludge MBR) to treat inhibitory phenolic compounds. The comparison of the two systems in terms of membrane fouling was carried out. It was found that the TMP suddenly increased in the AS-MBR while the BAC-MBR was linearly increased. TMP in the BAC-MBR after 90 days were slightly higher than that in the AS-MBR, and the bound EPS of the BAC-MBR was higher than that of the AS-MBR. The protein/carbohydrate (P/C) ratio in soluble EPS was high in BAC-MBR (0.86-2.13), but soluble EPS production (0.49-2.03 mgC/gVSS) was low. The P/C ratio and soluble EPS were the two important factors in biofouling.

Table 2.16 Summary EPS production in both suspended and attached growth systems

System	Sample	Attached material	EPS (mg/gVSS)	Reference
SBR	Attached growth	Cube type (Polyurethane) moving media	71.26-134.26	Choi *et al*. (2001)
SBR	Attached growth	Expanded polystyrene: Pack media	86.53-163.72	Choi *et a*l. (2001)
RBC	Attached growth	Acrylic RBC	70.12-137.89	Choi *et al.* (2001)
Air lift reactor	Attached growth	Polystyrene particle	19 (mg/L)	Campos *et al*. (2002)
Air lift reactor	Suspended growth	-	67 (mg/L)	Campos *et al*. (2002)
MBR	Attached growth	Powder activated carbon	90-127*	Kim *et. al,* (1998)
MBR	Suspended growth	-	121-196*	Kim *et. al.* (1998)
MBR	Attached growth	Granular activated carbon	59.07 - 83.06	Thuy (2003)
MBR	Suspended growth	-	37.6 - 47.08	Thuy (2003)

* Soluble EPS

Likewise, Nagaoka *et al.* (1996) reported that EPS could accumulate in the aeration tank of the membrane separation for activated sludge process, which caused an increase in mixed liquor viscosity and thus in the filtration resistance. Change and Lee (1998) noted that the EPS contents of activated sludge could be an indicator for estimating the membrane fouling.

Mukai *et al*. (2000) estimated flux decline of ultrafiltration membrane at different cultural growth phases i.e. different EPS and metabolic concentrations in AS process. The authors reported that the flux decline was affected by protein to sugar ratio of EPS and metabolic products. Lower permeate flux occurred at higher retention of protein and greater amounts of retained protein during the filtration.

2.6.2.2 Biomass Concentration (MLSS)

Biomass concentration is expected to have a profound influence on membrane fouling and performance of MBR (dynamic layer thickness and the viscosity). These affected the sludge circulation, because of change on hydrodynamic and the shear stress at the filtration cake surface (Stephenson *et al.,* 2000).

Chang and Kim (2004) investigated the effect of biosolid concentration (3,700, 2,900, 250 and 90 mg/L) on filtration characteristics in wastewater treatment system. It was found that the cake resistance (R_c) decreased with MLSS concentration. This was expected for the dead-end type membrane filtration. The specific cake resistance (α) also increased as the MLSS concentration was decreased. R_c and α behaved oppositely even though the particle size distributions of activated sludge suspensions are different but the MLSS concentration was similar. This suggested that the cake resistance could not be used as criteria for the estimation of cake fouling, especially at low MLSS concentrations.

Itonaga *et al.* (2003) studied the influence of suspension viscosity and colloidal particles on permeability of membrane used in membrane bioreactor. It was reported that high MLSS concentration caused high suspension viscosity in MBR. The optimum MLSS concentration for an efficient operation of MBR was found to be around 10g/L. In addition, membrane fouling occurring in membrane bioreactors was attributed to three aspects of biomass, these being such as sludge particle deposition, adhesion of macromolecule, and pore clogging. The sludge particle deposition has been commonly recognized as greatly contributing to membrane fouling (Gui *et al.,* 2002). The fouling was characterized by a rapid and continuous reduction of permeation flux with time, which has commonly been attributed to the high concentration of suspended solid in wastewater (Bai and Leow, 2002).

Gui *et al.* (2002) determined the effect of operational parameters on sludge accumulation on membrane surfaces in a submerged MBR at high SS concentration of 10g/L and low SS concentration of 1 g/L. The membrane fouling status at different operation conditions was directly observed by monitoring the TMP and the average increased rate of TMP. It was noted that aeration intensity, membrane flux, suction time and non-suction time were identified as significant factors for sludge accumulation on membrane surface at high SS concentration. At low sludge concentration of 1 g/L, the deposition of sludge was not observed. Therefore, membrane fouling was presumed to be mainly concerned with adhesion of macromolecule soluble organic matter on the membrane surface.

2.6.2.3 Particle/Floc Size

Kwon and Vigneswaran (1998) studied the influences of particle size and surface charge on critical flux of cross flow microfiltration. It was found that the fouling and the increase of resistance were relatively sensitive to the deposition of particles when particles of similar size as that of the membrane pores were filtrated through the membranes. Larger particles depositing on the membrane surface did not increase the TMP. Bai and Leow (2002) suggested that finer particles caused more severe membrane fouling. This was important to consider in microfiltration modeling and system design. Table 2.17 shows a summary of particle/floc size in MBR affecting membrane fouling which was reported by several researchers.

Table 2.17 Summary particle /floc size in MBR affecting membrane fouling

System	Particle /Floc size (μm)	Results	Reference
Hollow fiber MF (polyethylene) (0.2 μm)	Suspended solid Colloidal matter Soluble matter	Colloidal fraction in biomass suspension played an important role in membrane fouling. The colloidal fraction causing membrane fouling was originally retained in the EPS matrix and then released into the bulk solution.	Itonaga *et al.* (2003)
PVDF MF (0.1 μm)	0.1-500 (Suspension) 0.1-50 (Removing the settable fraction) 0.1-0.3 (Filtering suspension fraction)	The reduction of particle size in the feed suspension would result in greater resistance and therefore lower permeate flux.	Bai and Leow (2002)
Ceramic membrane (0.1 μm)	Suspended biomass Colloidal Dissolved matter	The suspended biomass (65%) and colloidal particles (30%) were predominant contribution to membrane fouling	Defrance *et al.* (2000)
Tubular MF (0.05 μm)	Suspension (200-1,000) Small particle (1-2) Soluble fraction (0-0.05)	The soluble fraction is mainly composed of compounds that have the same size or are smaller than the membrane pore size. These cause very strong physical and physico-chemical interactions with the membrane material which induce the build-up of a deposit.	Wisniewski *et. al.* (2000)
PVDF MF (0.2 μm)	Polystryrene latex particles (0.46, 3.2 and 11.9 μm in diameter)	The fouling was relatively sensitive to the deposition of particles when particles of nearly same size as that of the membrane pore were filtered through the membranes. Larger particles depositing on the membrane surface did not increase the TMP up to a significant permeate flux value.	Kwon and Vigneswaran (1998)
MF (0.05 μm)	Settleable Supracolloidal-colloidal Soluble fraction	The amount of soluble elements can play a significant role in the membrane fouling.	Wisniewski and Grasmick (1998)

Chapter 3

Methodology

The objective of this research was to investigate effects of operating conditions on removal efficiency and biofouling phenomena as a result of biological floc formation, and extracellular polymeric substances (EPS) in two different membrane systems, suspended and attached growth membrane bioreactors. The studies were divided into two parts; 1) Preliminary study, 2) Laboratory-scale membrane bioreactor study.

3.1 Preliminary Study

The preliminary study was carried out into two sections which were batch reactor and EPS extraction analysis as shown in Figure 3.1.

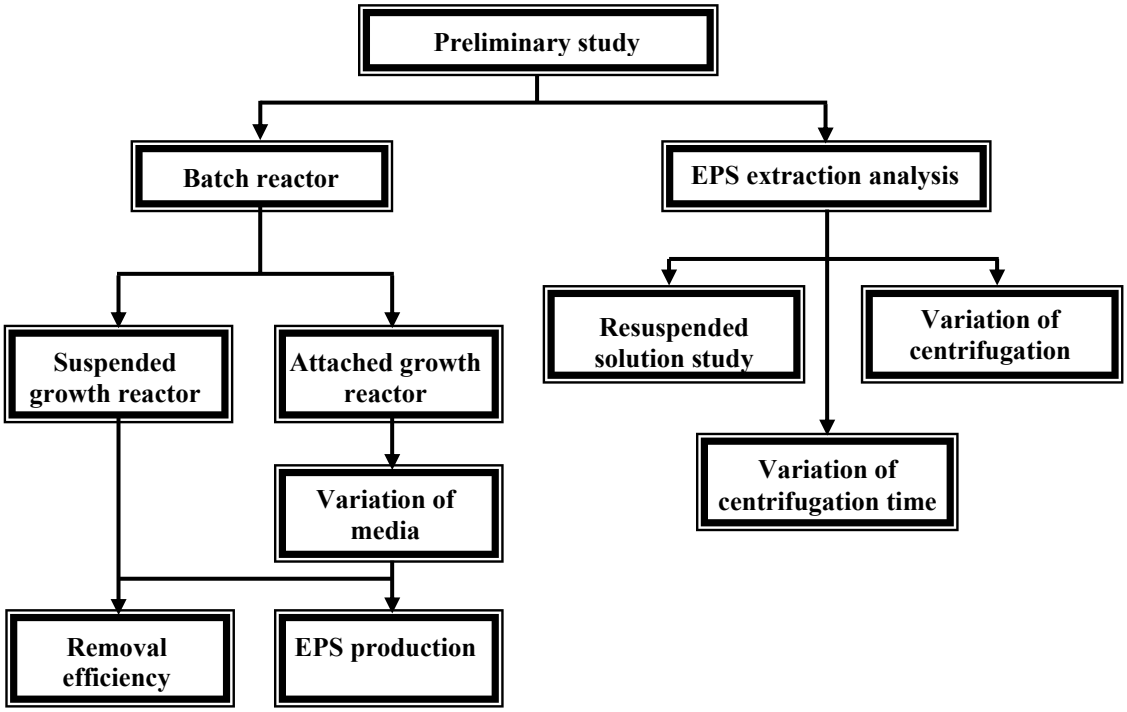


Figure 3.1 Preliminary study

3.1.1 Selection of Media Type for an Attached Growth Reactor

It was intended to select the suitable media for an attached growth reactor. The batch reactors having 2 L of working volume were divided into suspended and attached growth reactors. The attached growth reactor was added with five different media which included polyethylene bead (PB), polyethylene granule (PG), polyethylene sheet (PS), cylindrical polypropylene (CP), and polyethylene sponge (S). The physical characteristics of all media are shown in Table 3.1 and Figure 3.2. The experimental set-up and the operating conditions for suspended growth (as control reactor) were exactly same as used

for attached growth but without the media. A timer was used to monitor the mixing time and air-aeration. Figure 3.3 shows the schematic diagram of the batch reactors.

Table 3.1 Characteristics of media used in the attached growth system

Media	PB	PG	CP	PS	S
Shape	Beads	Granule	Cylindrical	Sheet	Cubic
Size	∅ 0.9 mm	∅ 3 mm	Internal∅ 3 mm External ∅ 4 mm Length 5 mm	∅ 11 cm	15*15*15 mm.
Surface area (m^2/g)	$2.54*10^{-3}$	$1.22*10^{-3}$	$5.81*10^{-3}$	$1.94*10^{-3}$	0.91
Weight (g)	44.70	68.50	49.52	10.38	1.34
Volume (mL)	125	125	250	3 sheets	20 pieces
Total surface area/ 2 L of reactor (m^2)	0.114	0.084	0.288	0.020	1.220

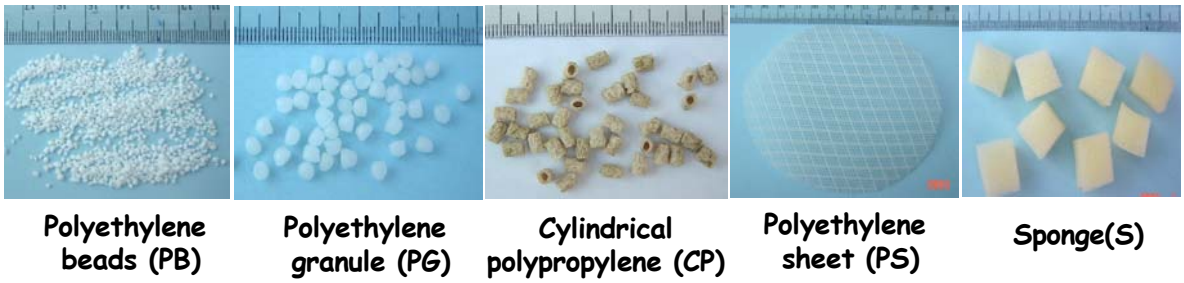


Figure 3.2 Physical characteristics of the media used

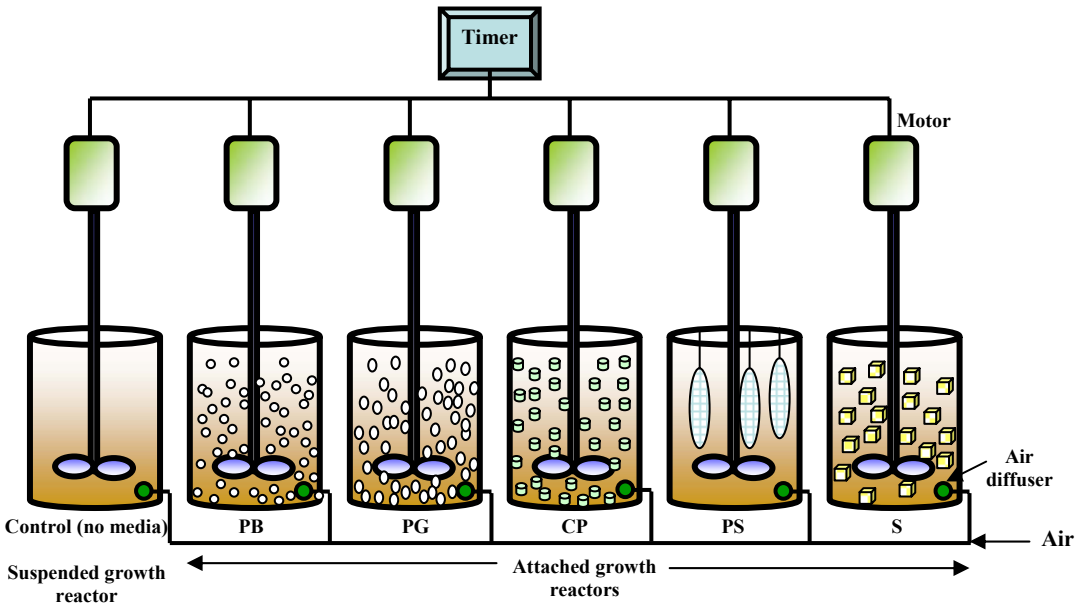


Figure 3.3 Schematic diagram of the batch reactors

The batch reactors were operated in four sequential steps (filling, reacting, settling and drawing) and the operating conditions in the batch reactors are listed in Table 3.2. The removal efficiency and EPS production in the batch reactors were evaluated in terms of COD, TKN and MLSS in accordance with the Standard methods (APHA, 1998). The values of pH and DO were measured using a pH meter and a DO meter, respectively.

Table 3.2 Operating conditions for the batch reactors

Parameters	Units	Values
HRT	hour	6
SRT	day	10
pH	-	7.0-8.0
MLSS	mg/L	4,000
Temperature	ºC	28± 2
DO	mg O_2/L	2-4
F/M ratio	kgCOD/kgMLSS.d	0.1

Synthetic wastewater

The synthetic wastewater was prepared as stock solution which was diluted to the required concentration by adding with tap water. The synthetic wastewater had a constant COD value of 500 mg/L, and used glucose as carbon source which is easily degradable and necessary nutrients for microorganism growth. The compositions of the synthetic wastewater are given in Table 3.3.

Table 3.3 Compositions of the synthetic wastewater used (COD 500 mg/L)
(Adapted from Nagaoka *et. al*., 1998)

Components	Concentration (mg/L)
Glucose	469
NH_4Cl	128
KH_2PO_4	19.3
$FeCl_36H_2O$	1.5
$CaCl_2$	3.0
$MgSO_4.7H_2O$	3.0
KCl	3.0
NaCl	3.0
$NaHCO_3$	739

Activated sludge

The seed microorganism from activated sludge system of domestic wastewater treatment plant was conducted in this experiment. The sludge having a MLSS of 4,000 mg/L was used during start-up of the experiment. The diffused aeration system was used for mixing the sludge and supplying the air. The sludge was acclimatized in the batch reactors.

EPS analysis

The compositions of EPS in the suspended biomass were analyzed using thermal extraction/solvent precipitation technique as suggested by Morgan *et al*. (1990). The supernatant was collected for two purposes, one for examining carbohydrate and protein contents, and the other for evaluating total EPS. The extracellular polymer in the supernatant was precipitated using a mixed solvent of ethanol and acetone. A total carbohydrate assay protocol was used to quantify the EPS as described by Dubois *et al.,* (1956). The protein was analyzed through the Biuret protein method (Rodney, 1993).

3.1.2 Extraction Conditions of EPS

The main purpose of this study was to investigate the optimum test condition of an extraction method for obtaining reliable and reproducible EPS value. The effects of resuspended solution, centrifugation speed and centrifugation time were of interest in this work. The resuspended solutions and centrifugation speed used four samples from the batch reactors and MBR reactors. First two samples were selected from the suspended growth reactor (without media) and the attached growth system (with cylindrical polypropylene media). The other two samples were collected from the phenolic MBR reactors (suspended growth, and biological activated carbon (BAC) MBR reactors) (Thuy, 2003). Three resuspended solutions including distill water, Ringer's solution (8.6 g sodium chloride, 0.3 g potassium chloride, and 0.33 g calcium chloride per liter) and 0.9% NaCl were used to select the one which gave reproducible results. The centrifugation speeds were varied from 2,000 to 4,000 rpm within 30 min. In the case of centrifugation time, two sludge samples from the suspended growth reactor (without media) and the attached growth system (with cylindrical polypropylene media) were used. The centrifugation time was varied from 10 to 30 minutes at a constant centrifugation speed of 4,000 rpm.

The soluble and bound EPS were measured in terms of TOC, protein and carbohydrate. A total carbohydrate assay protocol was used to quantify the EPS as described by Dubois *et al.,* (1956). The protein was analyzed through Lowry assay method (Lowry *et al.,* 1951).

3.2 Laboratory-Scale MBR Study

The main aim of this part was to investigate the effect of operating conditions (HRT and MLSS) on removal efficiency and biofouling phenomena in membrane bioreactor system. Three submerged membrane bioreactors (MBRs) having 5 L of working volume were used under a laboratory-scale. The reactor had a rectangular cross section and was separated into two compartments by a vertical holed baffle plate to prevent the moving media from contacting the membrane module and protecting it from breakage. The MBR system consisted of three bioreactors, which included (i) suspended growth (without media), (ii) attached growth (with moving media), and (iii) attached growth (with fixed media). It should be noted that the moving media used was cylindrical polypropylene (CP) while the fixed media was poly(vinylidine chloride). These three reactors were operated in parallel as shown in Figure 3.4 which illustrates the experimental arrangement of the MBRs. Three-hollow fiber membrane modules were submerged in all bioreactors shown in Figure 3.4. The characteristics of the membrane used in this work are listed in Table 3.4.

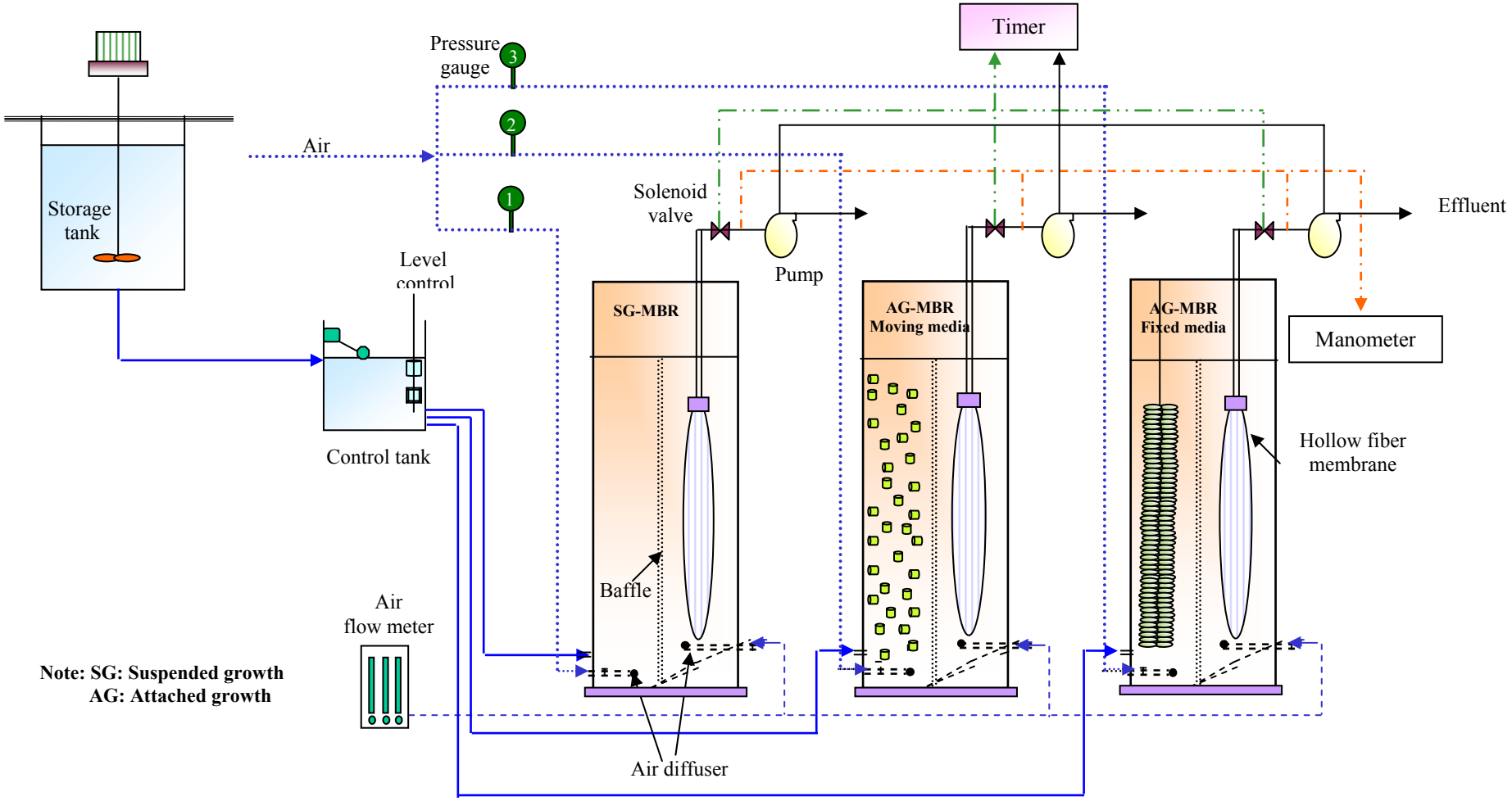


Figure 3.4 An experimental arrangement of the MBRs

The membrane filtrated effluent was continuously removed with a suction pump (MasterFlex pump, Cole-Parmer) under intermittent operation mode in a cycle of 10 minute on, and 2 minute off by using a timer (Omron, model H3CR). The membrane cleaning process was temporarily required when the membrane was clogged, which was indicated by an increase in the transmembrane pressure (TMP) up to ~60 kPa. The TMP value was measured using a U-shaped Hg manometer.

Table 3.4 Membrane characteristics used in this work

Item	Membrane characteristics
Model	STNM424
Membrane material	Polyethylene (coating with hydrophilic)
Membrane configuration	Hollow fiber
Pore size	0.1μm
Surface area	0.42 m^2
Manufacturer	Mitsubishi Rayon Co., Ltd (Japan)

Support media

Two different types of the support media were used in the attached growth MBRs. The ring lace was used as the fixed media, which consisted of fiber string of polyvinylidine chloride. The fixed media had 0.09 mm in string diameter, 2 cm in rope woven diameter, and had the specific surface area and specific media volume of 7.33 m^2/m and 0.3 L/m, respectively. The amount of the fixed media used in the reactor was 5% of the total reactor volume. The cylindrical polypropylene hollow rings having outer and inner diameters of 4 mm and 3 mm, respectively, and a nominal density of 1.001 kg/m^3, was utilized as the moving media. The amount of moving media occupied 24% of reactor volume. Figure 3.5 shows the physical characters of the fixed and moving media used.

a) Fixed media (Polyvinylidine chloride)

b) Moving media (Polypropylene)

Figure 3.5 Physical characters of polyvinylidine chloride media and cylindrical polypropylene media

Activated sludge

The seed microorganism from the activated sludge system of domestic wastewater treatment plant was acclimatized with the synthetic wastewater which had COD concentration of 500 mg/L and was used for the MBR systems.

Synthetic wastewater for MBR study

General, domestic wastewater contains both soluble and colloidal material. Synthetic wastewater used in this study was comprised mainly of glucose, ammonium chloride and sodium bicarbonate which are soluble material. Soy protein used for organic carbon and nitrogen source is in the form of soluble as well as colloidal material which simulates domestic wastewater. The wastewater used contained glucose, nitrogen, and necessary nutrients for microorganism growth. The composition of domestic wastewater had both organic and ammonia nitrogen. The commercial soy protein (Food Equipment Co., Ltd., Thailand) was utilized to obtain the feed wastewater that imitated a domestic wastewater having organic nitrogen content. The ratio of COD:N:P in the wastewater was maintained at 100:10: 2 with an influent COD concentration of 500 mg/L. The compositions of the synthetic wastewater are listed in Table 3.5.

Table 3.5 Compositions of the synthetic wastewater used in the MBRs

Component	Concentration (mg/L)
Glucose	235
Soy protein	250
NH_4Cl	115
KH_2PO_4	43
$CaCl_2$	10
$MgSO_4.7H_2O$	10
$FeCl_3$	3
$NaHCO_3$	600

In the laboratory-scale MBR, the suspended and attached growth MBRs were operated in parallel. The effects of varying hydraulic retention times (HRTs) and mixed liquor suspended solid (MLSS) concentration on the removal efficiency, fouling mechanism, EPS production, sludge characteristics and microscope observation were carried out. The overall laboratory-scale MBR study is systematically shown in Figure 3.6.

3.2.1 Effect of Hydraulic Retention Time (HRT)

The objective of this section was to investigate the effect of hydraulic retention time (HRT) on membrane performance, EPS production and sludge properties. The three membrane bioreactors (MBRs) were operated at different HRT values of 2, 4, 6 and 8 h. The membrane performances were evaluated in terms of removal efficiency of COD and nitrogen compounds, EPS production, sludge characteristics and microscopic observation.

3.2.2 Effect of Mixed Liquor Suspended Solid (MLSS)

This part was to monitor fouling mechanism of the attached and suspended growth MBRs at different mixed liquor suspended solid (MLSS) concentrations. The effect of MLSS was carried out in two membrane bioreactors, the suspended growth and the attached growth with moving media reactors. The MLSS concentration was varied at 6, 10 and 15 g/L. The fouling behaviors were followed by measuring TMP as a function of operating time, sludge characteristics (viscosity, CST and particle size distribution), EPS production, fouling rate and ratio of cake resistance to total resistance.

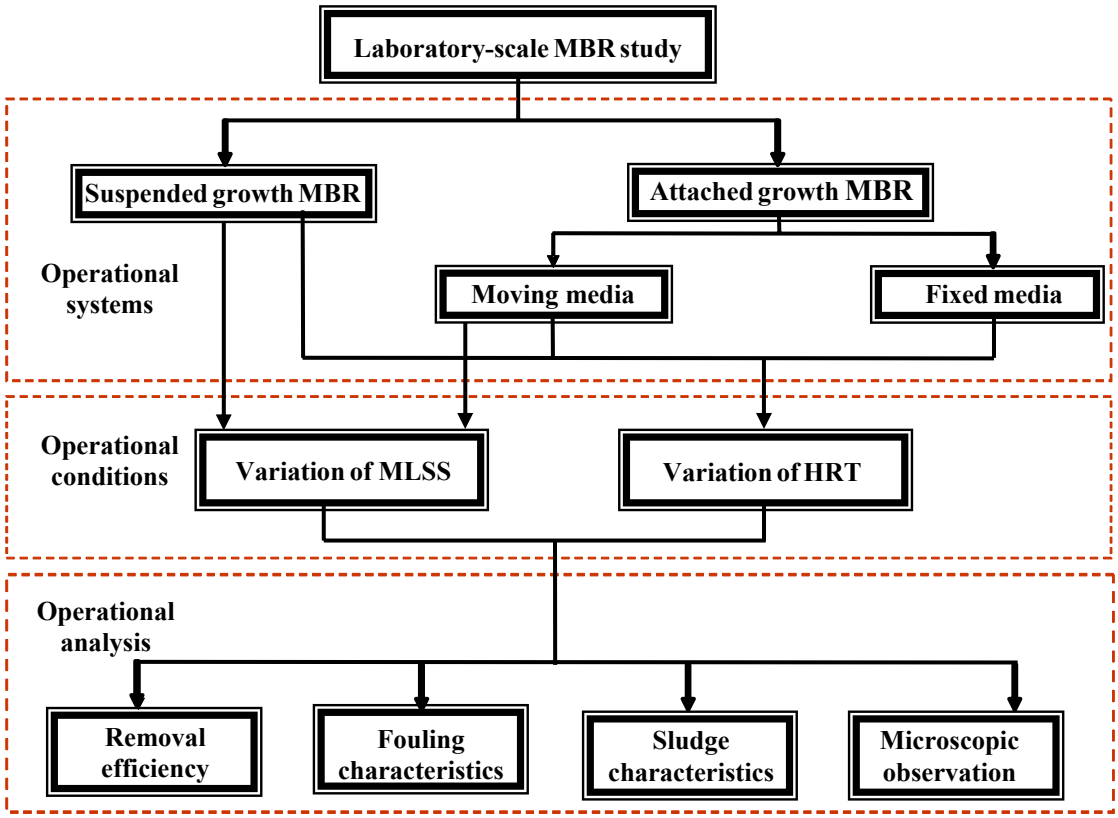


Figure 3.6 Overall laboratory-scale MBR study

3.3 Analytical Methods

It should be noted that most analytical techniques used in this study followed the Standard methods described by APHA *et al.* (1998). The MLSS measurement for the attached growth system was referred to as suspended biomass fraction. Since the attached portion of the biomass was relatively small, the measurement was negligible. Table 3.6 lists all the parameters and their analytical methods used.

Filtration test and specific cake resistance (α)

The sludge samples from each reactor were filtrated using a filtration set (Satorius module, Germany) at a constant pressure of 0.2 Bar. The filtration set consisted of a pressurized filtration cell having a working volume of 200 mL. Cellulose acetate (Cat.11107-047N, Satorius membrane) having 0.2 µm of pore size, 47 mm of diameter and 11.3 cm^2 of filtration area was used. The membrane fouling index (MFI) was calculated from the ratio of filtration time to filtrate volume (t/V) as a function of the total filtrate volume. The filtration time of 20 min was used for the MFI analysis. The schematic diagram of the experiment set-up for MFI test is shown in Figure 3.7. The specific cake resistance (α) was calculated from the slope of the t/V curve as shown by Equation 3.1 (Boerlage *et al.,* 2003).

$$\frac{t}{V} = \frac{\mu R_m}{\Delta P A} + \frac{\mu \alpha C_b}{2 \Delta P A^2} V \qquad \text{Equation. 3.1}$$

Where V is the filtrate volume, t is the filtration time, ΔP is the transmembrane pressure, A is the surface area of membrane, μ is the viscosity of water, α is the specific resistance of the cake deposited, and C_b is the concentration of particles.

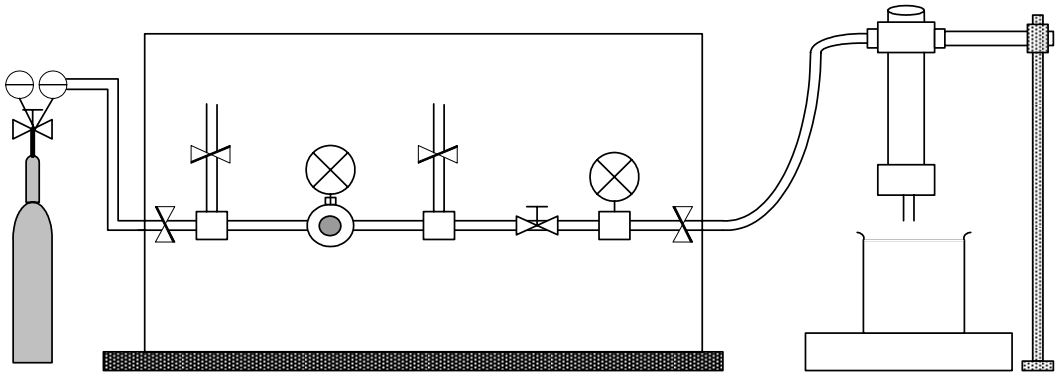


Figure 3.7 Schematic diagram of the filtration test set-up

Sludge morphology

The sludge morphology was viewed using an optical microscope (Olympus, Japan) equipped with a digital camera Nikon Coolpix995 (Nikon, Japan) for visual. A drop of mixed liquor (0.05 mL) was carefully deposited on a glass slide and covered with a cover slip before being observed through the microscope. The quantity of filamentous bacteria was evaluated by microscope observation according to Jenkins *et al.* (1993).

Particle size distribution

The particle size distribution was determined using a Malvern Mastersizer/S (Malvern, UK.), based on static laser light scattering. Fresh activated sludge samples were directly collected from the reactors. For analysis, the sludge concentration was fixed at an obscuration level in the range from 10% to 30% in the Mastersizer software.

Capillary suction time (CST)

A CST determination provides a quantitative measure, reported in seconds, of how readily sludge releases its water. The CST was in this work performed using a Triton CST apparatus (Type 165, UK), with a CST paper being purchased from Triton Electronics. The CST test has been used as a relative indicator to characterize the dewatering ability of the sludge. The detailed procedure can be obtained in the APHA method 2710G (APHA, 1998).

Sludge viscosity (SV)

The sludge viscosity was measured by Brookfield DV II+ (version 3.2) viscometer (speed of 5 rpm with spindle No.1).

Extracellular polymeric substances (EPS)

The analysis of EPS in biomass was made through a thermal extraction method. The mixed liquor of activated sludge was centrifuged at 4,000 rpm for 20 min in order to remove the soluble EPS from bound EPS. After collecting the soluble EPS, the remaining pellet was washed and re-suspended in saline water (0.9% NaCl solution). The extracted solution was obtained from a heat treatment at $80^{O}C$ for 1 h. The extracted solution was then separated from the sludge solids by centrifuging under similar conditions (4,000 rpm for 20 min), the supernatant obtained at this stage being referred to as bound EPS solution. The EPS is composed of many components such as protein, carbohydrate, nucleic acid, and lipids. In this study, the main component of EPS to be considered were protein and carbohydrate, which were measured by Lowry method (a), and by phenol/sulphuric acid method (b), respectively. The sum of the protein and carbohydrate content could represent the total amount of EPS content (Lee *et.al.,* 2003).

(a) Protein: Protein content was measured using Lowry Assay method (Lowry *et al.,* 1951). The sensitive range was 5-100 μg/mL. The absorbance of the color after 30 min was read against a blank at 750 nm. The standard curve was constructed using Bovine Serum Albumin (BSA).

(b) Carbohydrate: Carbohydrate content was measured using phenol/sulphuric acid method of Dubois et al. (1956). The absorbance of the color was allowed to develop for 30 min, after the sample was read against a blank at 490 nm. The standard curve was then constructed using glucose.

3.4 Membrane Cleaning

A membrane cleaning was required when transmembrane pressure (TMP) was increased up to 60 kPa. The procedure of membrane cleaning was commenced by disconnecting the suction lines from the membrane modules, and then the membranes were taken out from the reactors in order to remove the cake layers on the membrane by shaking in a 2L plastic cylinder which contains tap water. After that the membranes were immersed in a chemical cleaning tank (base solution) for 12h. The cleaning base solution was prepared by mixing 10% sodium hypochlorite (NaOCl having effective chlorine concentration of 3,000 mg/L) with 4% NaOH. The cleaning base solution was removed by rinsing with tab water, and filtered with 1% HNO_3 (acid solution) for 2 h. The effectiveness of the membrane cleaning was evaluated by measuring the membrane resistance (R_m), which should be about 80% membrane resistance recovery as compared with the initial membrane resistance of a new membrane. If not, the above chemical cleaning process was repeated.

Table 3.6 Parameters and their analytical methods

Parameters	Analytical methods	Analytical Equipment	Source
pH	pH meter	pH meter (310i WTW)	-
DO	DO meter	DO meter	-
TOC	Combustion method	TOC analyzer (Shimadzu TOC-V_{CSN})	APHA *et al.* (1998)
COD	Closed reflux	Titration	APHA *et al.* (1998)
BOD	OxiTop	OxiTop® (WTW, Germany)	-
TKN	Macro-Kjedahl	Titration	APHA *et al.* (1998)
NH_4-N	Distillation	Titration	APHA *et al.* (1998)
NO_2-N	Colorimetric	Hach spectrophotometer (DR/2000) at 507 nm	APHA *et al.* (1998)
NO_3-N	Colorimetric	Hach spectrophotometer (DR/2000) at 500 nm	APHA *et al.* (1998)
MLSS	Dry at 103-105^{0}C	Filter/Oven	APHA *et al.* (1998)
MLVSS	Dry at 550^{0}C	Furnace	APHA *et al.* (1998)
EPS	Thermal extraction	Centrifuge	Morgan *et al.* (1990)
EPS	Thermal extraction	Centrifuge	Present study
Carbohydrate	Phenolic-sulfuric acid	Spectrophotometer (Hitachi U-2001)	Dubois *et al.* (1956)
Protein	Lowry	Spectrophotometer (Hitachi U-2001)	Lowry *et al.* (1951)
CST	Capillary time	CST apparatus (Triton electronic limited)	APHA *et al.* (1998)
Viscosity	Rotating torque cylinder at 5 rpm	Brookfield, UK. (model: DV-II+ version 3.2)	-
Specific cake resistance	Dead-end filtration	Filter holder (Sartorious; SM16249)	Boerlage *et al.* (2003)
Particle size distribution	Laser light scattering	Malvern Mastersizer/S	-
Sludge morphology	Microscopic observation	Microscope	Jenkins *et al.* (1993)

3.5 Membrane Resistance Measurement

The resistances-in-series model was applied to evaluate the filtration resistances using Equation 3.2 and 3.3.

$$J = \frac{\Delta P}{\mu . R_t} \qquad \text{Equation 3.2}$$

$$R_t = R_m + R_c + R_f \qquad \text{Equation 3.3}$$

Where J is permeate flux, ΔP is trans-membrane pressure, μ is viscosity of the permeate, R_t is total resistance, R_t is total resistance, R_m is intrinsic membrane resistance, R_c is cake resistance formed by the cake layer (which could be removed by physical membrane cleaning mechanism) and R_f is fouling resistance caused by solute adsorption into the membrane pore (which can be cleaned mainly by chemical cleaning operation).

At the start of the experiment run, the R_m is calculated using Equation 3.2 by filtering pure water. Later, the same membrane module was used for the MBR operation, and when the membrane was fully clogged, filtration operation was conducted using pure water. At this stage, the total resistance R_t can be calculated using Equation 3.3. Then the membrane modu1e was carefully washed with running tap water to remove all visible cake layers from the surface. During this physical water cleaning operation, the fibers must not undergo any air or water backwashing arrangement. Then, the term *"R_m+ R_f"* was measured by filtration of pure water. Following this, the membrane was chemically cleaned by immersing the membrane for a minimum period of 12 h in a solution containing 10% NaOCl and 4% NaOH. The membrane was then washed with tap water, and filtered with 1% HNO_3 for 2 h. This chemical cleaning process was required to estimate the R_f. The protocol for membrane resistance measurement is shown in Figure 3.8

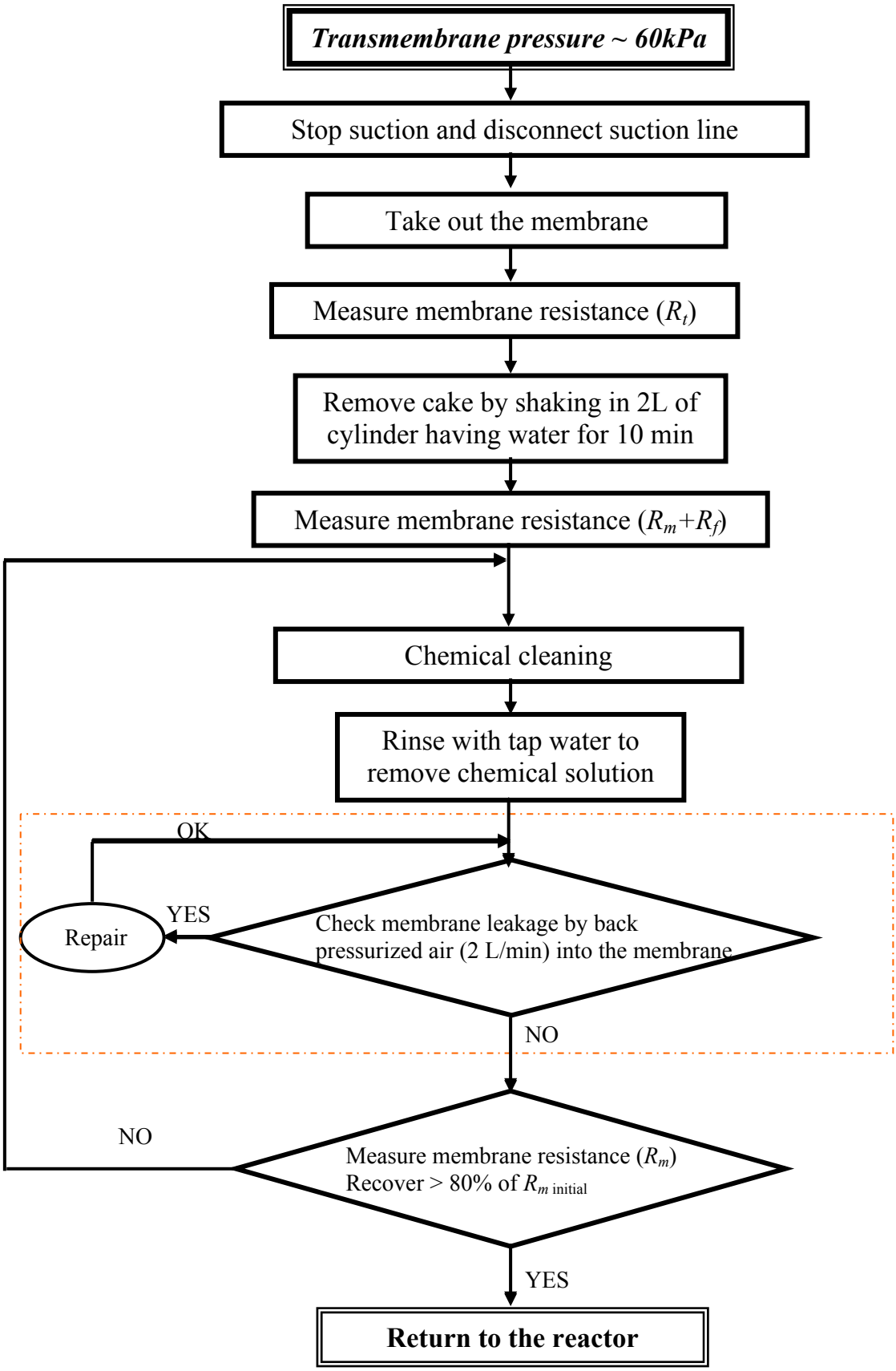


Figure 3.8 Protocol for membrane resistance measurement

Chapter 4

Results and Discussions

The experimental results were considered into two aspects; namely preliminary study and laboratory-scale MBR study. The preliminary study focused on the determination of suitable test conditions for EPS extraction and selection suitable media for attached growth reactor. For the laboratory-scale MBR, the effect of hydraulic retention time (HRT) and mixed liquor suspended solid (MLSS) on membrane performance was investigated. The performance of MBR was discussed in terms of removal efficiencies, fouling and sludge characteristics, and microscopic observations.

4.1 Preliminary Study

In order to examine suitable test conditions and to select suitable media for the attach growth reactor, a comparison of EPS production between suspended and attached growth systems by varying types of media used was made. A batch system was conducted for preliminary study. Five types of media were used, namely; polyethylene bead (PB), polyethylene granule (PG), polyethylene sheet (PS), cylindrical polypropylene (CP) and polyethylene sponge (S). The EPS production and the efficiencies of COD and TKN removal were monitored. The data for the EPS measurement in batch system are shown in Appendix A.

4.1.1 Selection of Media Type for Attached Growth Reactor

In this study, the MLSS in the experiment was maintained at SRT of 10 days with daily wasting of excess sludge. The sludge concentrations in the batch reactor with different types of media were maintained at MLSS of 4,000 mg/L.

A. COD and TKN Removal Efficiencies

Table 4.1 shows the removal efficiencies of COD and TKN for influent and effluent in the batch reactor for suspended and attached growth systems. It can be seen that the average COD and TKN concentrations of the influent were 460 mg/L and 30 mg/L, respectively whereas the COD and TKN concentrations of the effluent were reduced to less than 25 mg/L and 10 mg/L, respectively. For COD removal efficiency, there was no difference between these two growth systems, the average value being about 95%. For the TKN, the average efficiency of the attached growth system was in the range of 83 to 90%, which was greater than that of the suspended growth system due to biofilm formation on the media in the attached growth system which led to a nitrification/denitrification process, and increased nitrogen removal. However, with HRT of 6 hours, no significant difference in COD removal rate was noted between the suspended and attached growth systems. Previous work by Hoa *et al*. (2003) used the suspended growth system, and reported 90% of COD removal with an HRT of 6 h.

Table 4.1 Removal efficiencies of COD and TKN in batch reactors

Batch reactor	System	Sampling point	COD		TKN	
			mg/L	% removal	mg/L	% removal
-	-	Influent	460	-	30	-
Control (no media)	Suspended growth	Effluent	23	95	6	79
Polyethylene bead (PB)	Attached growth	Effluent	23	95	4	88
Polyethylene granule (PG)	Attached growth	Effluent	22	95	3	90
Polyethylene sheet (PS)	Attached growth	Effluent	21	95	4	86
Cylindrical polypropylene (CP)	Attached growth	Effluent	22	95	4	86
Polyethylene sponge (S)	Attached growth	Effluent	25	94	5	83

B. EPS Production

The production of bound EPS in the suspended biomass was measured using thermal extraction/solvent precipitation technique (Morgan *et al.,* 1990). The amount of bound EPS was analyzed by precipitating the extracted EPS solution. In this study, the main components of bound EPS to be considered were protein and carbohydrate, and the results of EPS in the suspended and attached growth systems are presented in Figure 4.1-4.2. In Figure 4.1, it can be seen that the average EPS in the attached growth system was between 36 and 41 mg/gVSS while that in the suspended growth system was about 47 mg/gVSS. These results indicated that there was no significant difference in EPS production in the suspended and attached growth systems.

Figure 4.2 illustrates the EPS compositions in terms of protein and carbohydrate contents for suspended growth (control sample) and attached growth (with media) systems. The average carbohydrate and protein contents were in the range from 13 to 16 mg/g VSS and from 7 to 12 mg/g VSS, respectively. Generally speaking, a reduction in EPS is reflected by reductions of both protein and carbohydrate. However, the reductions of protein and carbohydrate contents may not be in the same level as those of the total EPS. In this work, it seemed that the total EPS reduction was mainly caused by the protein reduction (20-30%), the carbohydrate content being similar among all the media used. This statement implied that there was a protein related biological nitrogen removal in the attached growth system. The principal mechanism for the nitrogen removal was assimilation and nitrification-denitrification. It was postulated that protein as organic nitrogen may convert to be inorganic nitrogen due to the presence of biofilm on the media. This was known as a nitrification reaction. During settling of batch reactor of this work, the biofilm could encounter anoxic condition which resulted in a denitrification. Thus, the

protein content and EPS production were reduced. In addition, it can be seen that the ratio of protein to carbohydrate (P/C) of the attached growth system give no difference although the media used were not the same. It was also noted that the P/C ratio in the suspended and the attached growth systems was not significantly different.

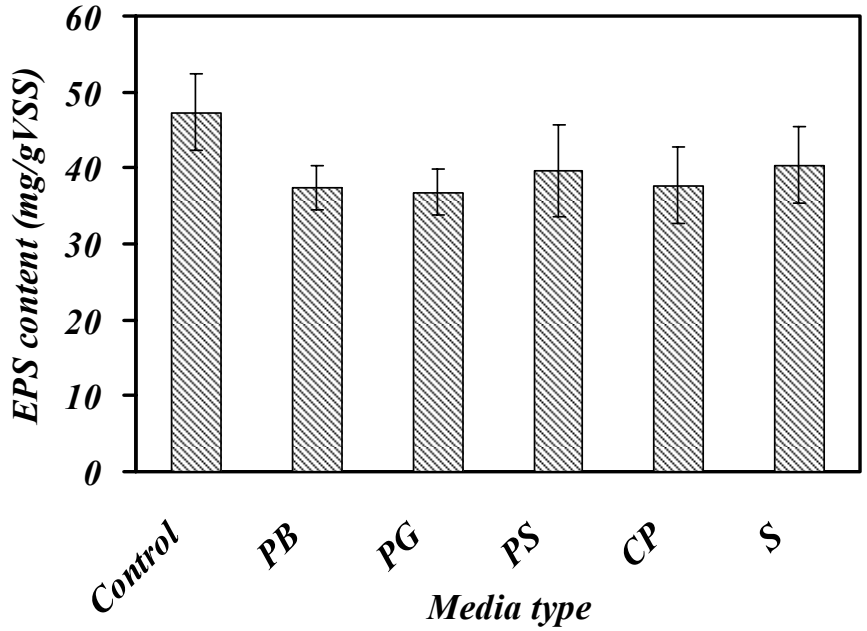


Figure 4.1 EPS content for different media types

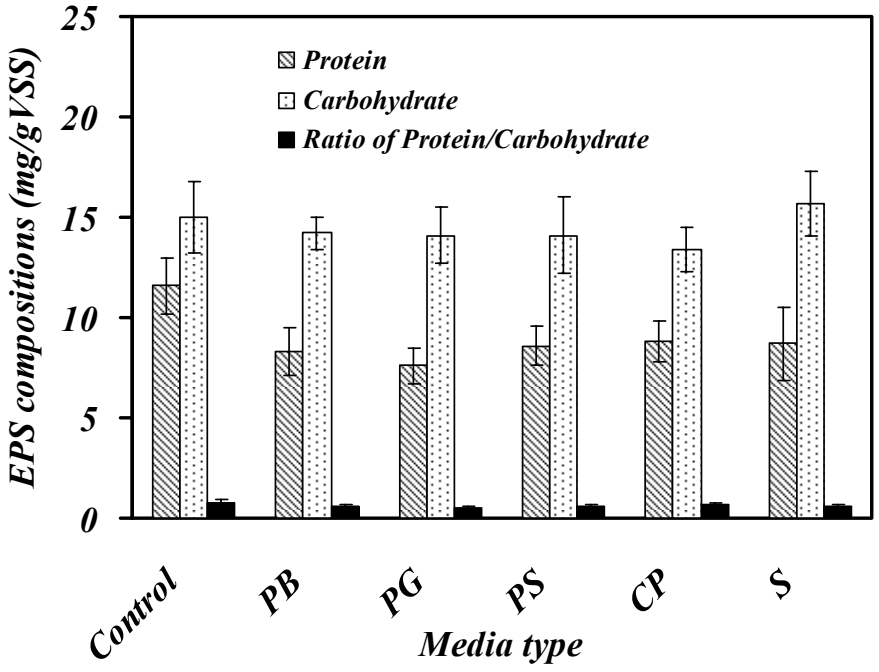


Figure 4.2 EPS compositions in different media types

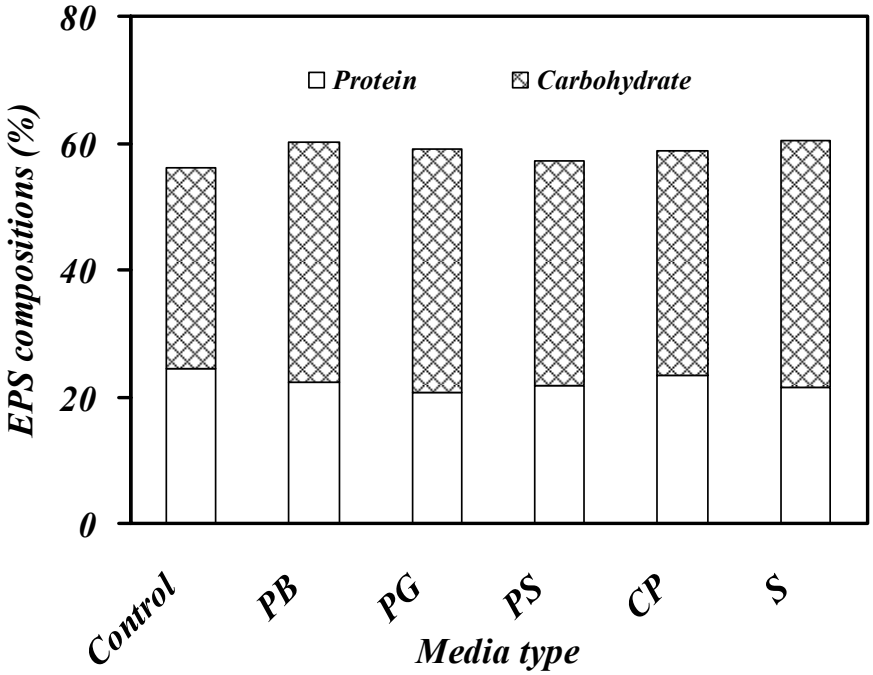


Figure 4.3 Percentage EPS compositions

Based on the amount of EPS content, the percentage of protein and carbohydrate are shown in Figure 4.3. It was clearly shown that the extracted EPS primarily consisted of carbohydrate, this being around 36%, whereas protein was 22%. On the contrary, the EPS analysis of activated sludge by Bura *et al.* (1998) and sewer biofilm by Jahn and Nielsen (1998) showed that the primary EPS material was protein. Lower protein EPS recovery found in this study may be due to the different extraction methods. Bura *et al.* (1998) used the sonication technique for EPS extraction and they suggested that large amount of protein content and minimum amount of cell lysis were obtained. Jahn and Nielsen (1998) used Dowex resin for extracting extracellular polymer (EPS) composition in sewer biofilm. They found that the major part in macromolecular composition of the biofilm was protein. Table 4.2 shows the component contents in EPS obtained from this study in comparison with those from other researchers (Liu and Fang, 2002; Sponza, 2002; Choi *et al.,* 2001). It can be seen that the component contents in EPS were different among different extraction methods. This can be concluded that the EPS composition was greatly dependent on the extraction methods used.

In order to evaluate the effectiveness of each media, it was reasonable for EPS production to be compared per a surface area. In this study, the apparent surface areas of S, CP, PB, PG, and PS media were calculated to be 1.22, 0.29, 0.11, 0.08 and 0.02 m^2, respectively. Figure 4.4 shows the comparison of EPS content/surface area for the five different types of media. It can be observed that PS media (lowest surface area) had the highest EPS production whereas S media (highest surface area) had the lowest. The differences in EPS productions for each media were due to the differences in the surface areas. This was because the EPS, which are mucous substances like glue, bind the bacteria cells together which will attach on the surface of the media (Li and Ganczarczyk, 1990). When high surface area media was used, there would be more bound bacteria cells on the

media, and thus low EPS in the suspended biomass. The experiment was extended to discuss the effect of shape characteristics of the media on EPS production. The productions of EPS and biofilm formation were affected by shape and size characteristics of media used. Greater surface area with sponge-shaped media tended to reduce EPS in the suspended biomass. In this work, the sponge media (S) appeared to give the lowest EPS production. However, the physical strength of the sponge media (S) was low and had shorter lifetime. Hence, the second choice of media was selected this is cylindrical polypropylene (CP) due to floating, well mixing, high surface area, non biodegradable nature and low EPS production.

Table 4.2 Component contents in EPS from this study in comparison with other works

Reference	Extraction method	Component contents in EPS (%)		
		Protein	Carbohydrate	Other
This study	Thermal extraction/solvent precipitation technique	22	36	N/A
Liu and Fang (2002)	EDTA	23	13	64
Sponza (2002)	Centrifugation with glutaraldehyde	75	18	7
Choi *et. al*.(2001)	Centrifugation and steaming	<1-10	40-70	<1-10

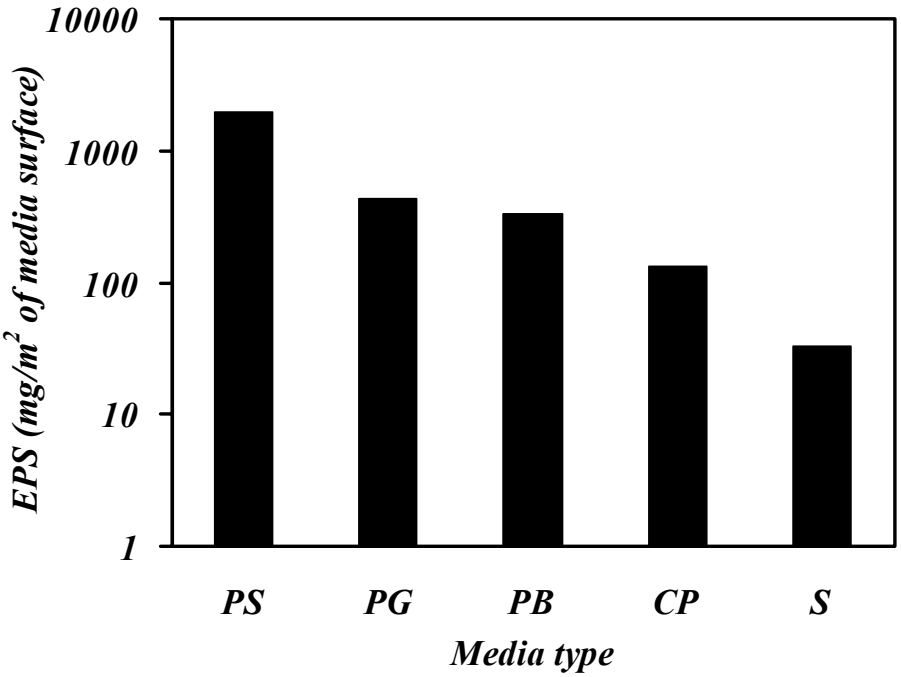


Figure 4.4 EPS content in terms of media surface at different media types

4.1.2 Extraction Conditions of EPS

A thermal extraction method was conducted to extract EPS to avoid any possible errors caused by disruption of intracellular polymer, which may be risked by a strong chemical extraction method. In order to obtain a reliable and reproducible EPS value, the extraction conditions, such as resuspended solution, centrifugation speed and centrifugation time, were considered.

A. Resuspended Solution

Three resuspended solutions (Distill water, Ringer's solution and 0.9 %NaCl) were compared for extraction of EPS. The thermal treatment was used to extract the EPS. The sludge from municipal wastewater treatment by the batch reactors with and without media (attached growth and suspended growth, respectively), and phenolic wastewater treatment by MBR (Thuy, 2003) was carried out. Sludge from the batch reactor without media was called SBR-control whereas that with media was called SBR-media. The other two reactors were activated sludge membrane bioreactor (AS-MBR) and granular activated carbon membrane bioreactor (GAC-MBR) (Thuy, 2003). The yields of EPS for different resuspended solutions in SBR and MBR systems are compared and shown in Table 4.3.

Table 4.3 Comparison of EPS yield for different resuspended solutions in SBR and MBR systems

System	Type of wastewater	Resuspended solution		
		Distill water	Ringer's solution	0.9% NaCl
		EPS (mg/gMLSS)	EPS (mg/gMLSS)	EPS (mg/gMLSS)
SBR-control	Synthetic wastewater (Glucose)	20.3	37.4	45.2
SBR-media	Synthetic wastewater (Glucose)	21.1	36.8	45.4
AS-MBR	Phenolic wastewater	26.0	49.6	43.8
GAC-MBR	Phenolic wastewater	17.8	44.6	44.1

The EPS results in Table 4.3 show that Ringer's and 0.9% NaCl solution methods gave higher EPS values than distilled water. The 0.9% NaCl solution gave double EPS value of the distilled water. It can be explained that the sodium chloride in both solutions gave Na^+ and Cl^- which are strong alkalinity ionic and acidic ionics. This resulted in a breaking of the Ca^{2+} and Mg^{2+} binding of EPS with bacteria (Forster and Newton, 1980). Ringer's and 0.9% NaCl solutions exhibited similar EPS yields. It can be concluded that NaCl solution for EPS extraction was more effective and gave stable EPS value. Hence, 0.9% NaCl was selected for further studies of analyzing EPS compositions.

B. Centrifugation Speed

EPS in the mixed liquor could be divided into two parts, bound and soluble EPSs. The soluble EPS is produced by microbial activity and cell lysis, which can be separated

from the bound EPS by a centrifugation technique. Soluble EPS measured in terms of TOC gives an overall soluble EPS measurement, but does not take into account EPS constituents, mainly protein and carbohydrate and it composition (Nielsen and Jahn, 1999). Therefore, the selection centrifugation speed was based on the TOC value as well as protein and carbohydrate measurements. The effect of centrifugation speed on soluble EPS is shown in Figures 4.5-4.7.

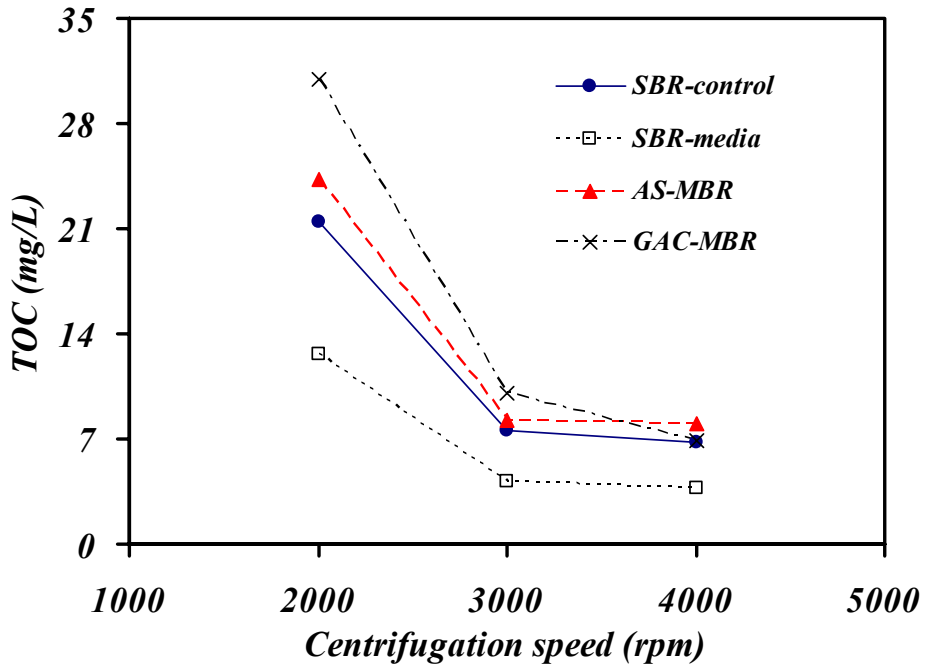


Figure 4.5 Centrifugation speed versus TOC

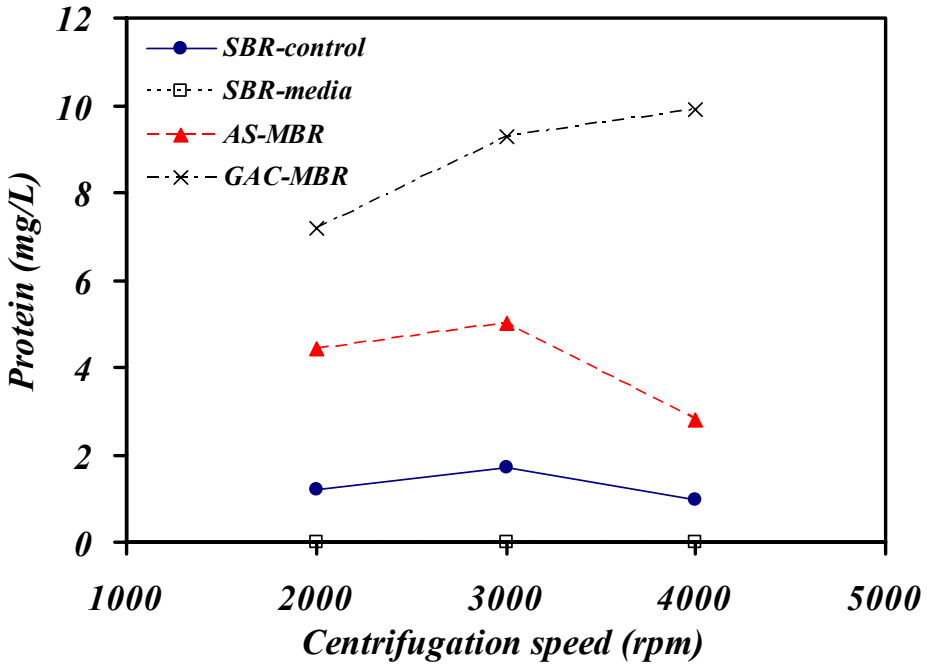


Figure 4.6 Centrifugation speed versus protein

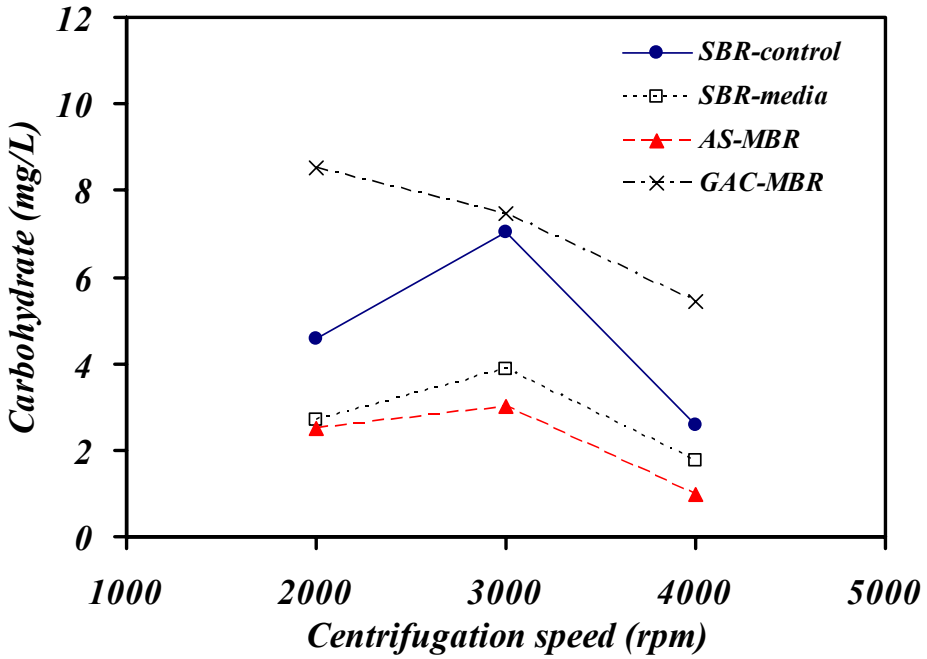


Figure 4.7 Centrifugation speed versus carbohydrate

In Figure 4.5, increasing centrifugation speeds from 2,000 to 3,000 rapidly decreased the TOC for all samples, while the centrifugation speeds of greater than 3,000 rpm gave a stable TOC. All reactors had the same trend of TOC reduction as the centrifugation speed was changed. This was because the soluble EPS, consisting of colloidal particle and some soluble macromolecules, were compacted by increasing the centrifugation speed until a maximum value, higher centrifugation speed not affecting the settling of that particle and macromolecules. Most soluble EPS exited was dissolved form in biomass and there was less soluble EPS attached on cell wall, which can be separated by centrifugation process. Therefore, the selected centrifugation range was found to comply with that suggested by Chang and Lee (1998). Finally, 4,000 rpm was selected as it gave the lowest protein, carbohydrate and TOC contents (Figures 4.5-4.7).

The relationships between TOC and bound and soluble EPS for the SBR and MBR systems are shown in Figures 4.8 and 4.9, respectively. It can be found that the change in TOC corresponded well with that in the bound and soluble EPS for both SBR and MBR systems. As a result, TOC could be used as a representative of EPS content.

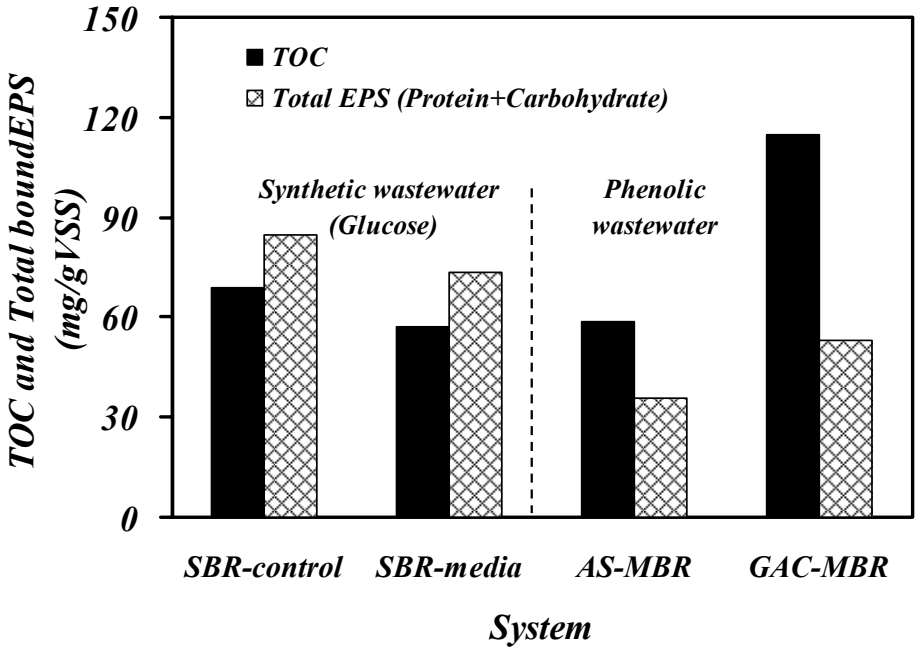


Figure 4.8 Relationship between TOC and total bound EPS for SBR and MBR systems

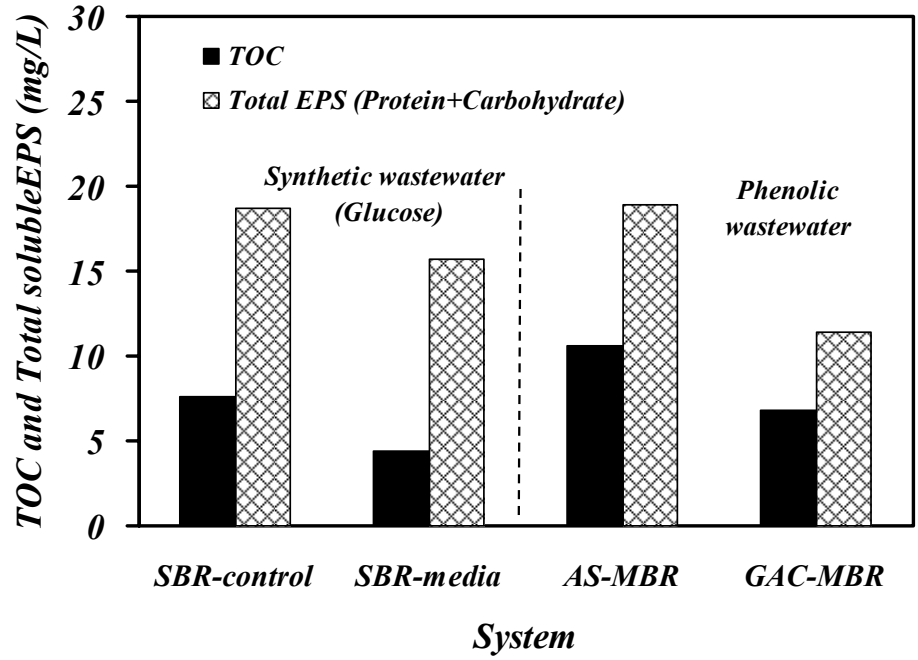


Figure 4.9 Relationship between TOC and total soluble EPS for SBR and MBR systems

C. Centrifugation Time

Two sludge samples were collected from the SBR-control and SBR with media reactors in order to investigate the effect of centrifugation time on soluble EPS. The centrifugation time was varied from 10 to 30 minutes using a constant centrifugation speed of 4,000 rpm, the results being shown in Table 4.4.

Table 4.4 Centrifugation time versus compositions of soluble EPS in SBR system

System	Centrifugation time (min)								
	10			20			30		
	TOC mg/L	Protein mg/L	Carbo-hydrate mg/L	TOC mg/L	Protein mg/L	Carbo-hydrate mg/L	TOC mg/L	Protein mg/L	Carbo-hydrate mg/L
SBR-control	8.7	7.7	50.8	9.2	7.1	45.7	9.0	4.4	44.7
SBR- media	10.0	6.6	5.1	10.1	4.9	5.0	10.2	4.6	4.7

It was indicated from Table 4.4 that the centrifugation time did not significantly affect soluble EPS content in terms of TOC, protein and carbohydrate. This can be explained with respect to colloidal fractions (~1 μm) which do not settled by increasing the centrifugation time beyond 10 min at the same centrifugation speed. Therefore, in this study, the centrifugation time of 20 min was suitable for separation of the soluble EPS.

4.2 Laboratory-Scale MBR Study

The objective of the laboratory–scale MBR study was to investigate the effects of operating conditions, such as, HRT and MLSS on membrane performance, fouling characteristics, EPS production and sludge properties, and to compare, membrane fouling behavior of the attached and suspended growth MBRs. In this study, laboratory-scale set up included two effects as follows;

Phase I: Effect of Hydraulic Retention Time (HRT);

HRT was varied at 2, 4, 6 and 8 h, with a fixed SRT of 20 days. The reduction of HRT led to increase sludge concentration (MLSS) that could influence sludge characteristics.

Phases II: Effect of MLSS:

MLSS was varied at 6, 10 and 15 g/L with controlled SRT values of 5, 20 and 50 days. HRT was also fixed at 2 h. The influence of different MLSS concentrations on fouling behavior and sludge properties was investigated.

Initial membrane resistance

At the start of the each experimental run, the initial membrane resistance was measured using pure water as per a protocol which was presented in the Section 3.5. The data for the membrane resistance are shown in Appendix B. Table 4.5 shows the initial resistance of new three hollow fiber membranes used for the suspended growth MBR and attached growth MBR with moving media and with fixed media.

Table 4.5 Initial membrane resistance for MBR systems

Reactor	Membrane Resistance (1/m)
Suspended growth MBR	$6.0*10^{11}$
Attached growth MBR with moving media	$5.4*10^{11}$
Attached growth MBR with fixed media	$4.7*10^{11}$

4.2.1 Effect of Hydraulic Retention Time (HRT)

MBR was operated for four different HRTs, such as 8, 6, 4 and 2 h. The first run was carried out at 8 h of HRT with a permeated flux of 1.8 $L/m^2.h$ for 80 days. After that, the second run was commenced for 6 hours of HRT for 90 days, while the permeate flux was increased to 2.4 $L/m^2.h$. The third run was operated at HRT 4 h for 40 days with a permeate flux of 3.6 $L/m^2.h$. Finally, the fourth run with HRT 2 hours was carried out for 40 days at permeate flux of 7.1 $L/m^2.h$. Based on the previous result in Section 4.1.1, the cylindrical polypropylene moving media was selected for the attached growth system while the loop media was used as the fixed media system.

A. Overall Performance of MBR Systems

Table 4.6 shows the COD concentration and removal efficiency of the MBR at different HRT conditions. The COD concentration of the influent was between 440 and 520 mg/L while the COD concentration of the effluent was between 10 and 25 mg/L. It can be seen that the removal efficiency was found to be greater than 90%, even with a short HRT. It was indicated that the MBR could provide consistently high COD removal efficiency. Similar observation was reported by Côté *et al.* (1997) who suggested that the effluent COD in a hollow fiber MBR was maintained at below 16 mg/L, despite a five–fold change in the HRT ranging from 2 to 24 h. The results in Tables 4.6 and 4.7 suggested that membrane bioreactor played an important role in providing the excellent and stable effluent quality at all HRTs. The membrane performance appeared to be insensitive to HRT values of between 2 and 8 h. Therefore, it can be said that changes in HRT had no effect on the water quality produced in terms of carbonaceous removal.

Table 4.6 COD removal in the MBRs with varying HRT

Item	COD (mg/L) (%Removal efficiency)			
	HRT 8 h	HRT 6 h	HRT 4 h	HRT 2 h
Influent	504	507	522	435
Effluent of suspended growth MBR	16 (97)	12 (98)	19 (96)	15 (97)
Effluent of attached growth MBR with moving media	13 (97)	10 (98)	16 (97)	10 (98)
Effluent of attached growth MBR with fixed media	19 (96)	15 (97)	23 (96)	25 (94)

Table 4.7 Nitrogen compound in different HRTs

Sample	TKN (mg/L) (%Removal efficiency)				NH_4-N (mg/L) (%Removal efficiency)				NO_3-N mg/L				NO_2-N mg/L			
	HRT (h)				HRT (h)				HRT (h)				HRT (h)			
	8	6	4	2	8	6	4	2	8	6	4	2	8	6	4	2
Influent	57.5	56.8	45.4	44.8	35.9	34.5	14.6	17.9	3.9	5.0	5.8	3.4	-	-	-	-
Effluent of suspended growth MBR	2.8 (95)	1.3 (98)	1.7 (96)	2.8 (94)	1.0 (97)	0.5 (99)	0.6 (96)	1.1 (94)	35.6	27.6	30.5	14.3	0.2	0.1	0.2	0.7
Effluent of attached growth MBR with moving media	2.9 (95)	1.3 (98)	1.7 (96)	2.5 (94)	1.2 (97)	0.4 (99)	0.6 (96)	1.1 (94)	34.0	27.7	24.5	17.5	0.1	0.1	0.1	0.9
Effluent of attached growth MBR with fixed media	3.3 (94)	1.9 (97)	2.1 (95)	3.4 (92)	1.4 (96)	0.5 (99)	0.8 (95)	1.1 (94)	30.4	25.4	22.8	20.5	0.2	0.1	0.5	0.8

Table 4.7 summarizes the concentrations of different nitrogen compounds in the influent and effluents for the MBRs at different HRTs. It can be seen that the TKN values of the influent for HRT 8, 6, 4 and 2 h were in the range of 44 to 60 mg/L. The TKN vlues of the effluent for the suspended and attached growth MBRs were less than 5 mg/L for all HRTs. The removal efficiency was greater than 90% even with 2 h of HRT. For the ammonia nitrogen (NH_4-N), the ammonia nitrogen of influent with the average concentration for all HRTs varied from 15 to 36 mg/L. The ammonia of the effluent was below 2 mg/L and the removal efficiency was greater than 94%. This implies that the TKN and ammonia removals were accomplished by the microorganism assimilation and nitrification reaction in the MBR. It can be seen that the ammonia nitrogen converted to nitrite, and, finally to nitrate this occurring under aerobic condition as called a nitrification reaction. It has been reported by Chiemchaisri *et al.* (1992) that, with an influent total nitrogen concentration of between 20 and 50 mg/L, a DO concentration of 1 mg/L supplied continuously gave a complete nitrification. It was found that the nitrite concentration was lower than 0.5 mg/L for 8, 6 and 4 h of HRT, but greater than 0.5 mg/L for HRT 2 hours. This would be caused by the reduction of strict aerobic bacteria activity and the number of nitrite bacteria at HRT 2 h, which led to high remained nitrite concentration in all reactors at short HRT of 2 h. It was concluded that the changes in HRT condition could disturb the removal of nitrogen compounds.

Based on nitrogen removal theory, nitrogen removal can be achieved by two principal processes, assimilation by microorganism and nitrification-denitrification as shown in Figure 4.10. The amount of nitrogen mass balance can be noted by Equation 4.1.

$$TKN_i + NO_2\text{-}N_i + NO_3\text{-}N_i = TKN_e + NO_2\text{-}N_e + NO_3\text{-}N_e + \text{Nitrogen assimilated} + \text{Nitrogen loss due to denitrification} \quad \text{Equation 4.1}$$

For nitrogen assimilation, it is accepted that during the aerobic process of organic matter removal, each 100 mg/L of BOD_5 needs 5 mg/L of nitrogen (N) and 1 mg/L of phosphorous. Based on this, BOD/N ratio (α) can be found to be 0.05. The term of α (BOD_{5i}-BOD_{5e}) represented the nitrogen removal by assimilation.

$$\text{Nitrogen assimilation} = \alpha\,(BOD_{5i}\text{-}BOD_{5e}) \quad \text{Equation. 4.2}$$

Where α is concentration factor (nitrogen to BOD_5 ratio), i is influent and e is effluent

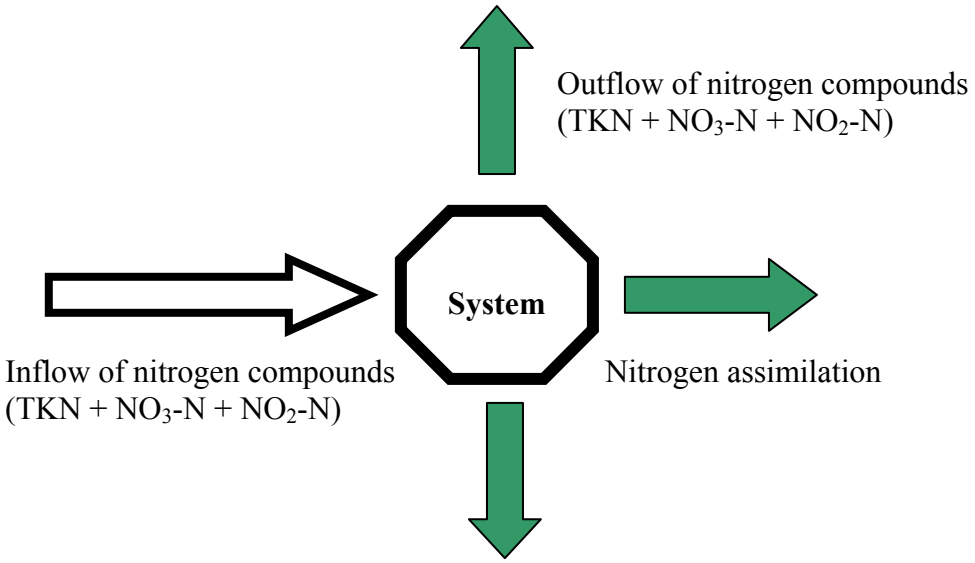


Figure 4.10 Nitrogen mass balances

In this work, there is no anoxic condition, therefore the denitrification can be neglected. The mass balance for this study is presented in Figure 4.11.

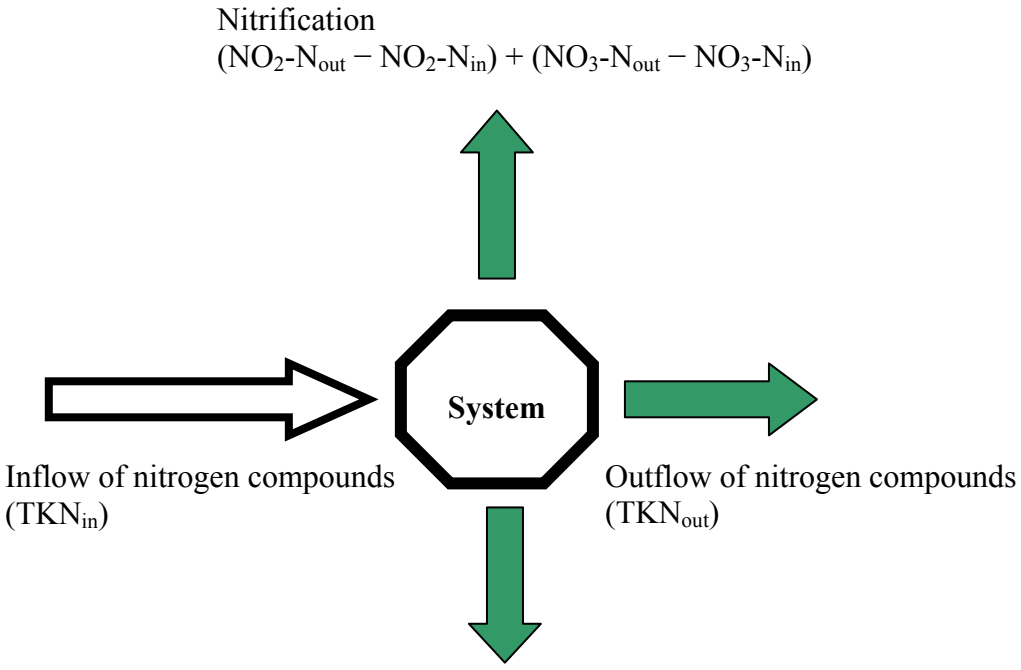


Figure 4.11 Nitrogen mass balances for this study

The mass balance of nitrogen in the MBR system in this study is presented as follows; and the calculations are noted in Appendix C.

$$TKN_{in} = TKN_{out} + (NO_2\text{-}N_e - NO_2\text{-}N_i) + (NO_3\text{-}N_e - NO_3\text{-}N_i) + \text{Assimilatio} \quad \text{Equation 4.3}$$

For nitrification process, the ammonium nitrogen converted to nitrite and nitrate by nitrifying bacteria under an aerobic condition. Therefore, the nitrification can be calculated as follows:

$$\text{Nitrification} = (NO_2\text{-}N_e - NO_2\text{-}N_i) + (NO_3\text{-}N_e - NO_3\text{-}N_i) \quad \text{Equation 4.4}$$

$$\text{Assimilation} = TKN_{in} - TKN_{out} - (NO_2\text{-}N_e - NO_2\text{-}N_i) - (NO_3\text{-}N_e - NO_3\text{-}N_i) \quad \text{Equation 4.5}$$

Figures 4.12-4.14 show the nitrogen mass balances for MBRs. It was found that the nitrogen removal was accomplished by the microorganism assimilation and nitrification reaction in the MBR at all HRTs used.

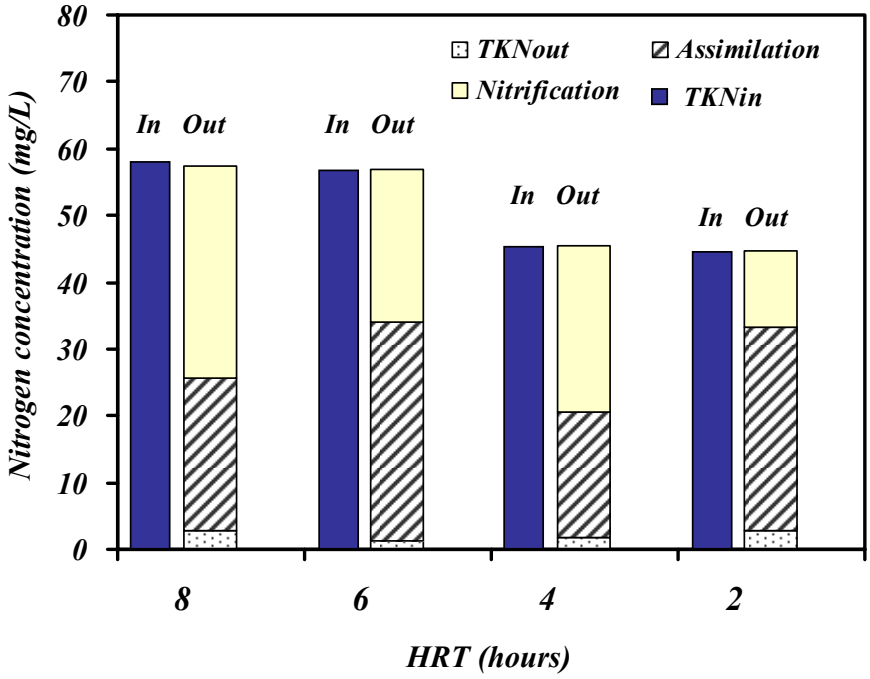


Figure 4.12 Nitrogen mass balance for suspended growth MBR

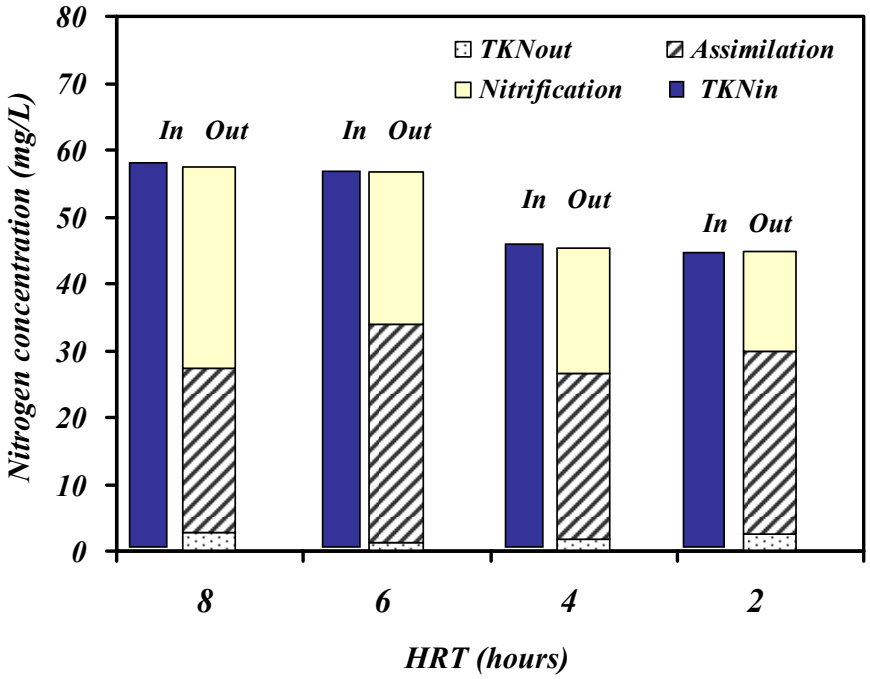


Figure 4.13 Nitrogen mass balance for attached growth MBR with moving media

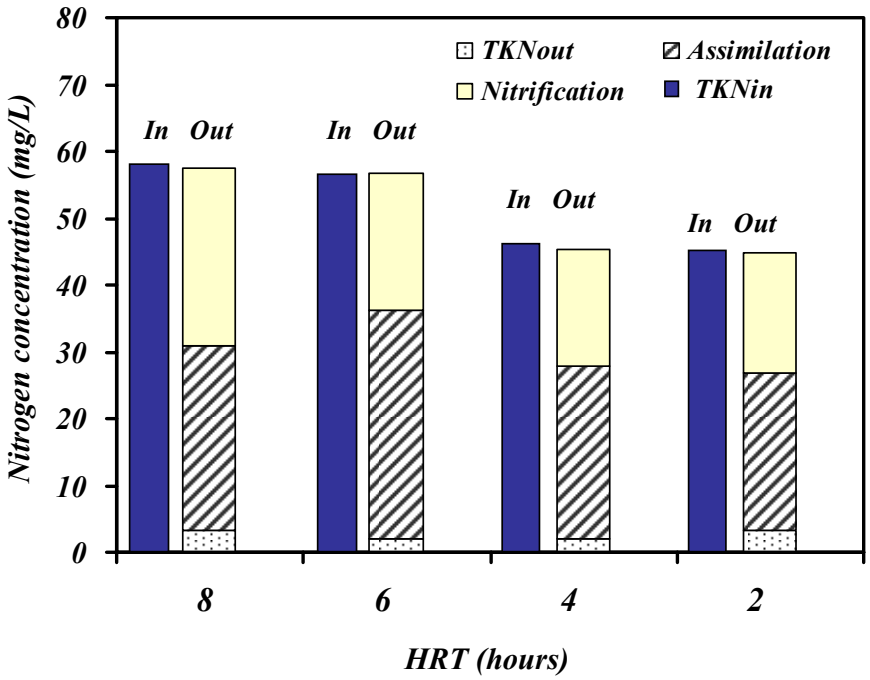


Figure 4.14 Nitrogen mass balance for attached growth MBR with fixed media

B. EPS Compositions

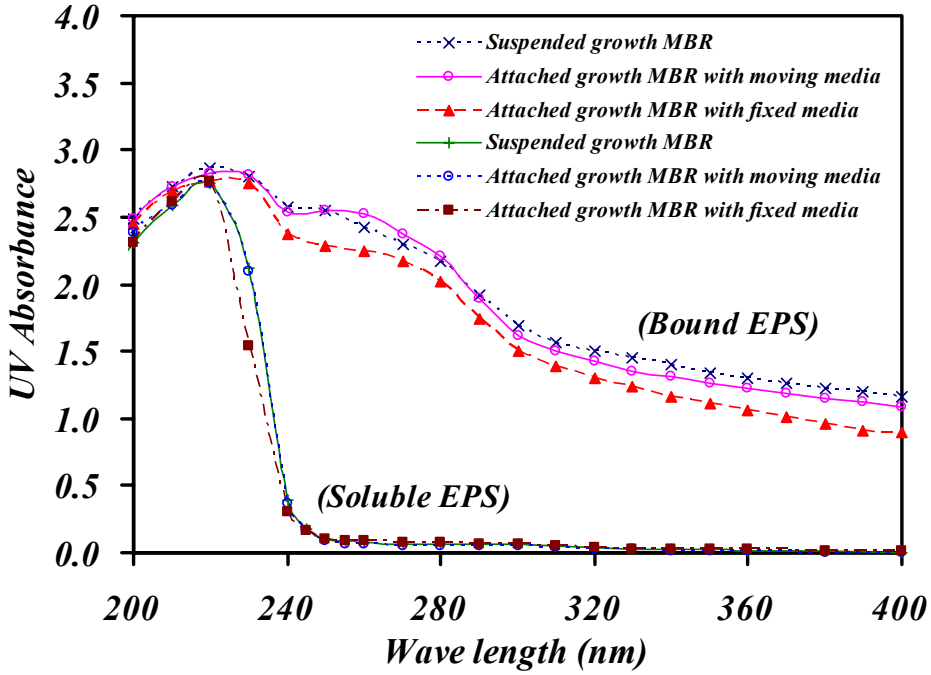


Figure 4.15 UV/vis absorbance of soluble and bound EPS

The sludge biomass was collected at HRT 8 h for evaluating the protein in terms of soluble and bound EPSs using UV/vis absorbance technique at wavelength between 200 and 400 nm, the results being shown in Figure 4.15 and Appendix D. The UV spectrum of the solution EPS was measured with a spectrophotometer (Hitachi-U2001). It can be clearly seen that UV absorbance peaked for the soluble EPS of around 220-230 nm whereas that for bound EPS of around 230-270 nm, this being agreed with Kim *et al.* (2001). The UV peak analysis indicated that the components of the soluble EPS had less protein content than those of the bound EPS in the bioreactor. However, the soluble and bound EPS of all sludges were similar for protein content. It can be said that both MBRs had similar quantities of protein in EPS though they were operated in different growth conditions.

The EPS production under various operating conditions was determined in terms of bound and soluble EPSs through the extraction method. Figures 4.16-4.17 show the bound and soluble EPSs with different HRTs. It can be found that there were no significant differences in bound EPS for all HRTs, taking account of the error bars. The amount of EPS production was independent of HRT in the suspended and the attached growth MBRs. It was clearly seen that the soluble EPS was quite high at short HRT (4 and 2 h). This was caused by an increase in the utilization of bound EPS in the floc by microorganisms as well as released from cell lysis. Barker *et al.* (1999) noted that soluble EPS could result from biomass decay and cell lysis by microbial cell.

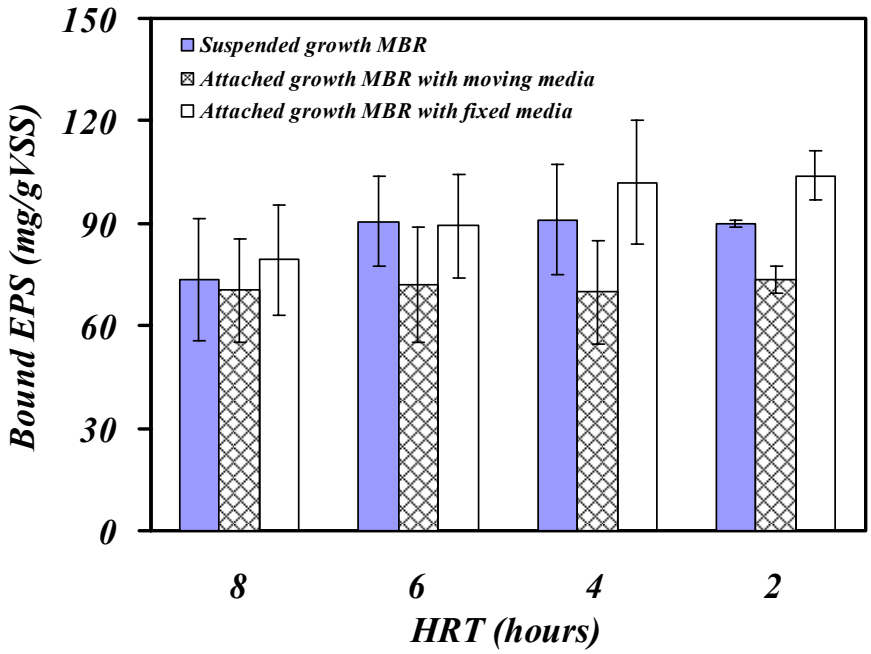


Figure 4.16 Bound EPS concentration in the MBR with varying HRT

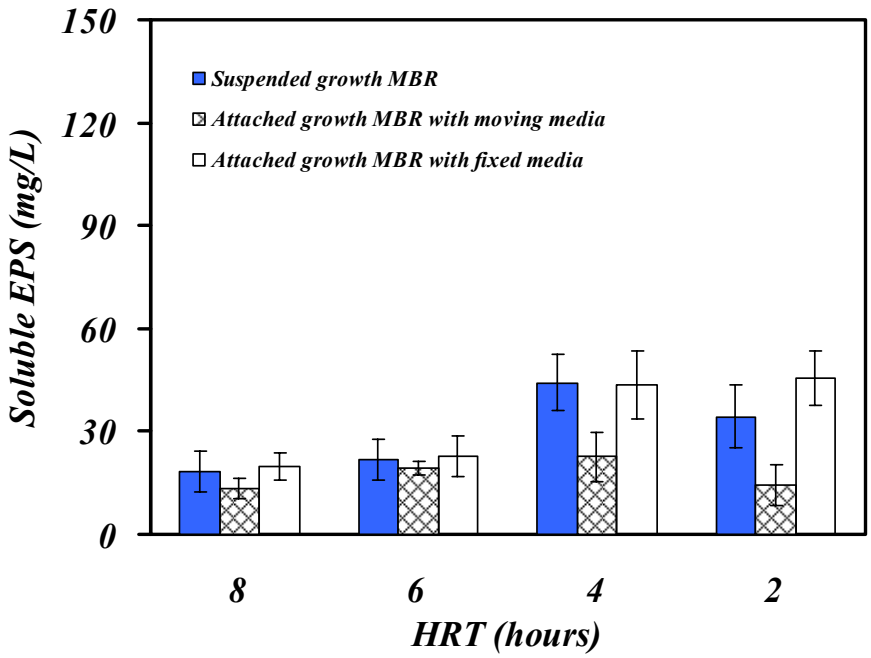


Figure 4.17 Soluble EPS concentration in the MBR with varying HRT

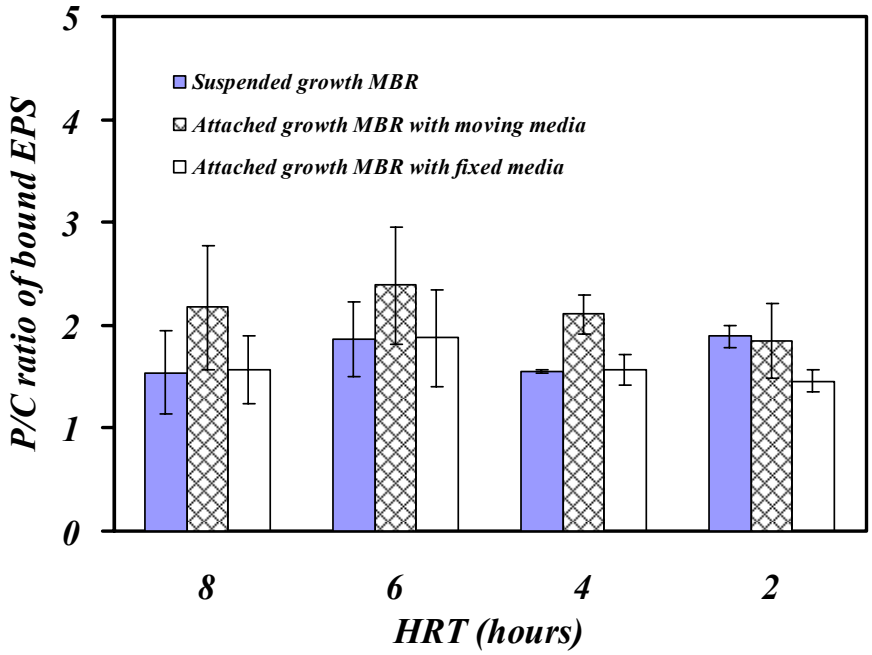


Figure 4.18 P/C ratio of bound EPS in the MBR with varying HRT

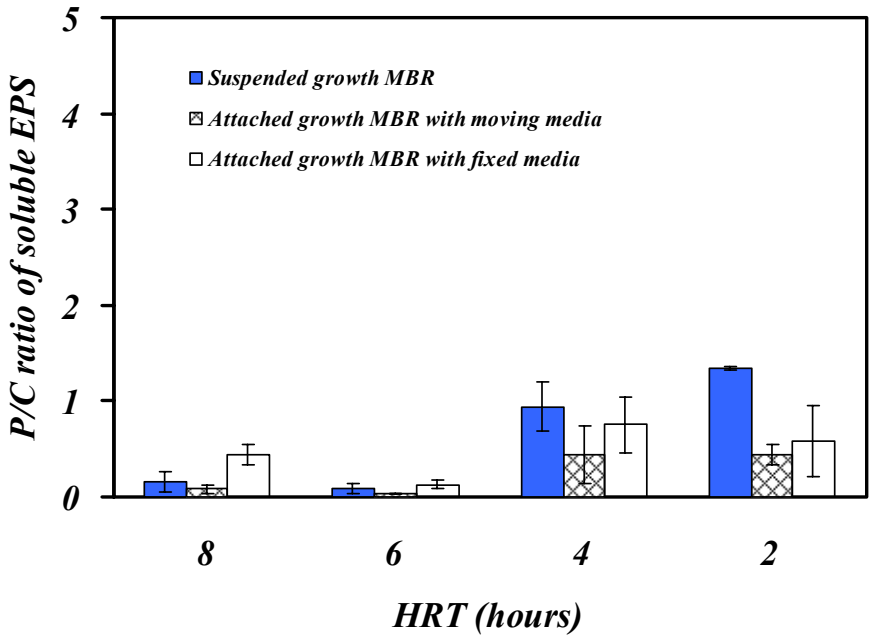


Figure 4.19 P/C ratio of soluble EPS in the MBR with varying HRT

The ratios of protein to carbohydrate (P/C) of bound and soluble EPS are presented in Figures 4.18-4.19. It can be seen that P/C ratio of bound EPS was similar for all HRT, this corresponding to the amount of bound EPS shown in Figure 4.16. The changing of HRT had an effect on the soluble EPS. The amount of soluble EPS or colloidal material in

the bioreactors increased because of biomass ineffectiveness in forming biological flocs (Ng *et at.,* 2004). This would lead to cell lysis and increase the colloidal material.

C. Sludge Concentration

Table 4.8 Sludge concentration in the MBR at different HRTs

Reactor	MLSS (mg/L) (MLVSS/MLSS)			
	HRT 8 h	HRT 6 h	HRT 4 h	HRT 2 h
Suspended growth MBR	6800 (0.91)	7700 (0.90)	9100 (0.89)	10800 (0.90)
Attached growth MBR with moving media	7600 (0.91)	7600 (0.91)	9200 (0.91)	11300 (0.90)
Attached growth MBR with fixed media	6500 (0.91)	7400 (0.90)	8900 (0.89)	9800 (0.89)

The sludge concentrations in the bioreactor during experimental were measured in terms of MLSS and the ratio of MLVSS/MLSS as shown in Table 4.8. The data of MLSS concentration are shown in Appendix D. The average MLSS was between 6,500 and 12,000 mg/L for HRT of 8 and 2 h, respectively. The ratio of MLVSS/MLSS of the sludge in the bioreactor was almost constant between 0.89 and 0.91, suggesting that there was no accumulation of inorganic matter in the bioreactor. This ratio of MLVSS/MLSS indicated that most suspended solids were microorganism. Lower concentration of MLSS was due to lower organic loading into the reactor and longer HRT. The MLSS concentration was found to change from 6,400 mg/L at HRT of 8 h to 12,000 mg/L at 2 h HRT. Shorter HRT provided more nutrients to biomass, leading to a greater biological growth and higher MLSS concentration.

D. Specific Cake Resistance and CST

It was observed that the amount of EPS content was indifferent (as in Section 4.2.1B), but the results on fouling potential presented in Figure 4.20-4.23 was higher in the attached growth MBRs. It implied that the fouling behavior was not influenced by the biological characteristics (EPS content). In other word, EPS was not the main factor to cause the membrane fouling. It was thought that the biological and physical characteristics of membrane (cake formation) could have an influence on the membrane fouling. These were evaluated by fouling potential and specific cake resistance values. Specific cake resistance is a cake resistance normalized to the mass of biosolids deposited on the unit area of cake layer. In this study, unstirrerd dead-end filtration was carried out to determine the specific cake resistance values (Chang and Kim, 2005). The specific cake resistance was calculated from the plot of elapsed time (t) versus volume (V). The slope of the filtration curve giving membrane fouling index (MFI) values represents the fouling potential, and the results are shown in Figure 4.20-4.23.

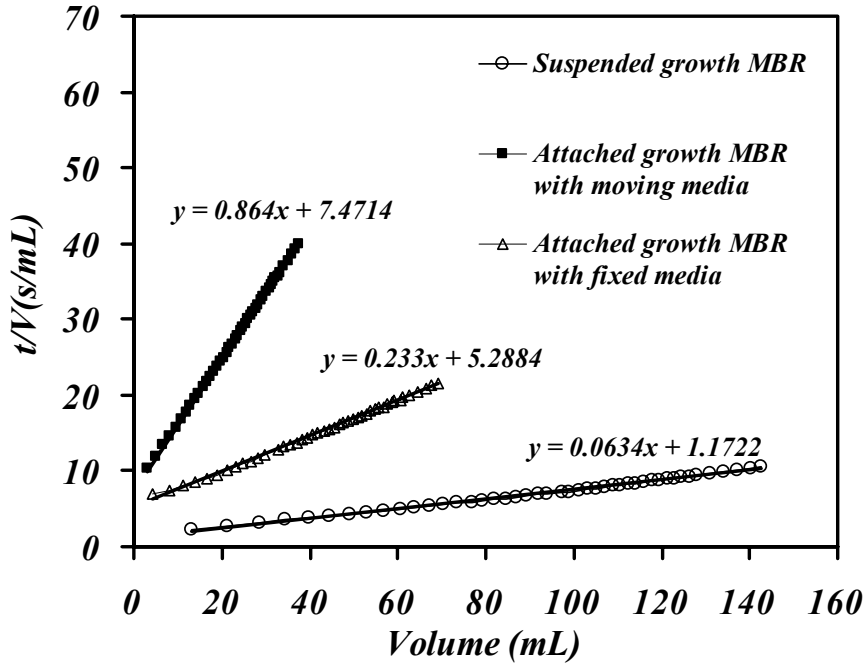


Figure 4.20 Filtration curve t/V versus V measured for HRT 8 h at constant TMP (0.2 bar), the slope giving the MFI value

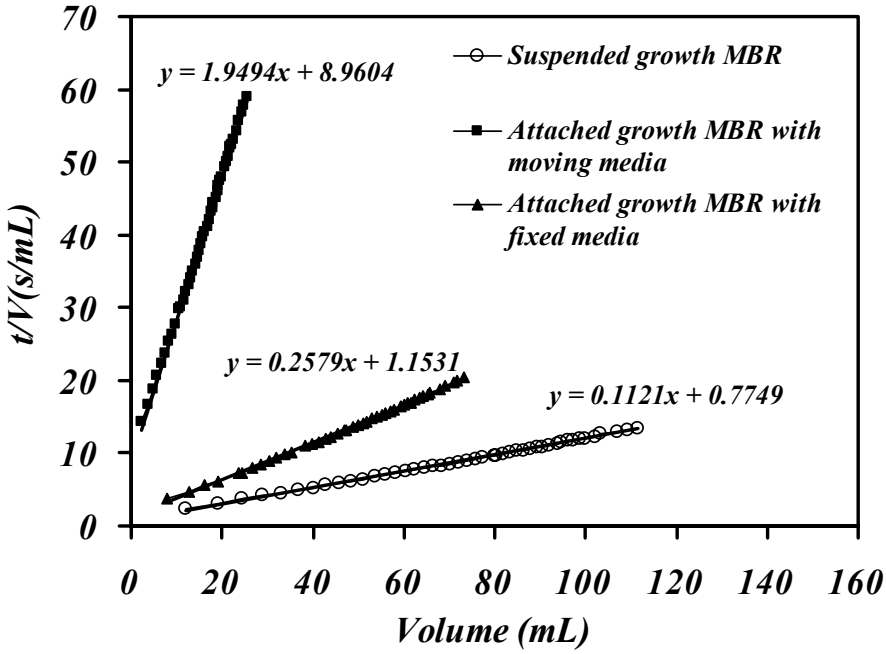


Figure 4.21 Filtration curve t/V versus V measured for HRT 6 h at constant TMP (0.2 bar), the slope giving the MFI value

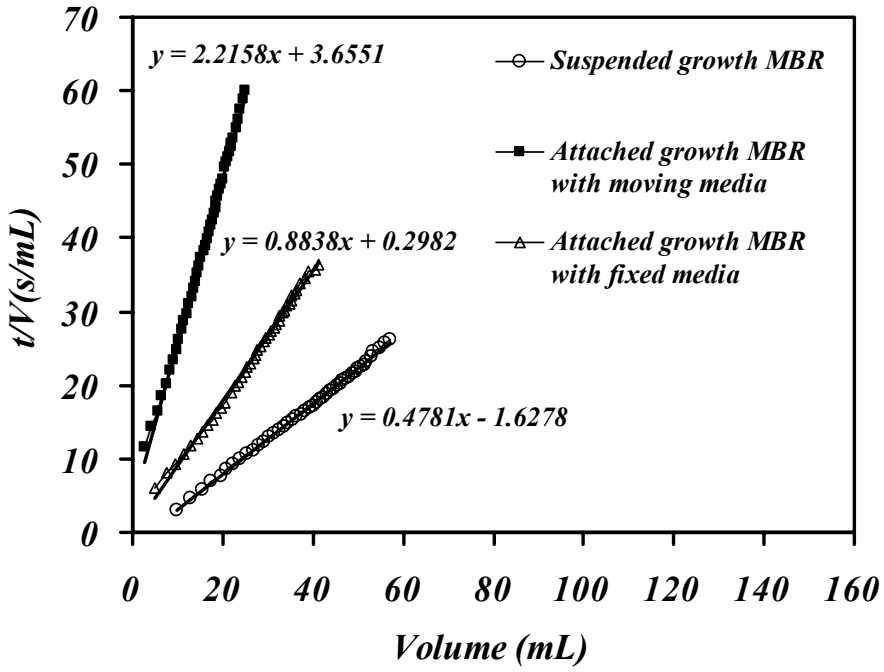


Figure 4.22 Filtration curve t/V versus V measured for HRT 4 h at constant TMP (0.2 bar), the slope giving the MFI value

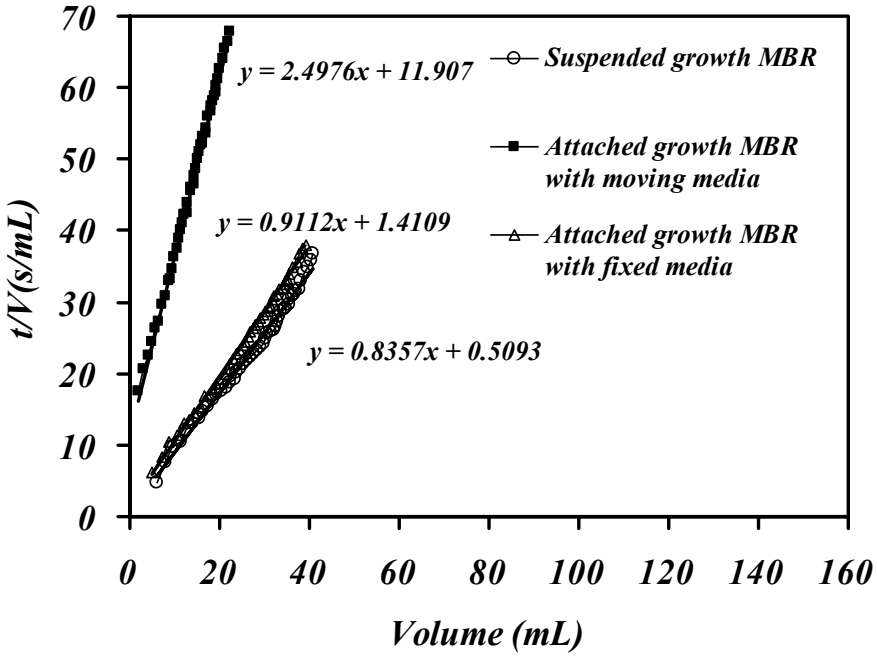


Figure 4.23 Filtration curve t/V versus V measured for HRT 2 h at constant TMP (0.2 bar), the slope giving the MFI value

Table 4.9 MFI value of the MBRs at different HRTs

Reactor	MFI * 10^5 (s/L^2)			
	HRT 8 h	HRT 6 h	HRT 4 h	HRT 2 h
Suspended growth MBR	0.06	0.11	0.48	0.84
Attached growth MBR with moving media	0.23	0.26	0.88	0.91
Attached growth MBR with fixed media	0.86	1.95	2.22	2.50

Table 4.9 shows MFI values for the attached and suspended growth MBRs at different HRTs. It can be seen that the attached growth MBR with moving media had higher MFI, which corresponded to particulate fouling potential, than the suspended growth MBR for all HRTs. In addition, the MFI increased with decreasing HRT because high biological growth led to a high deposition of suspended biomass.

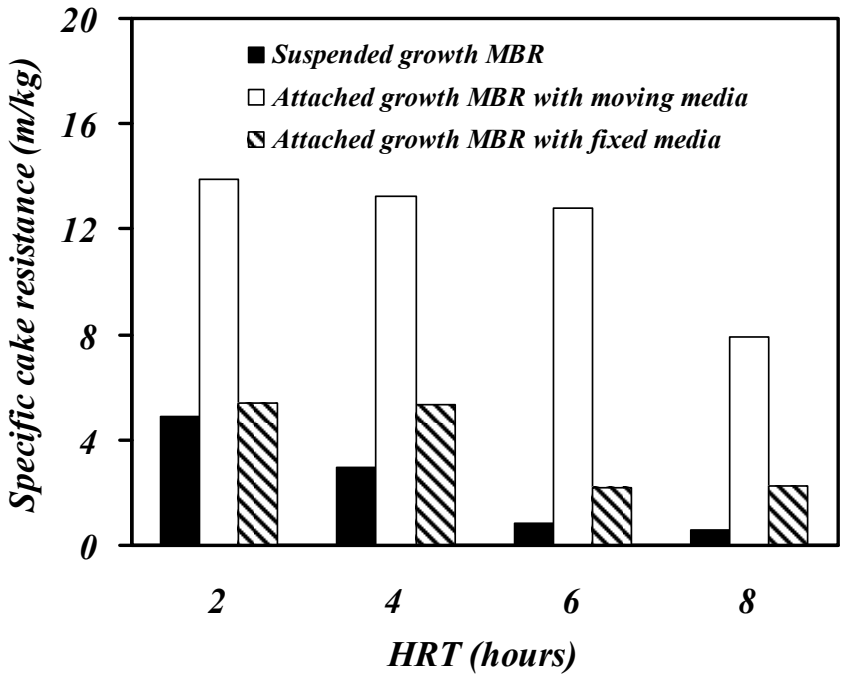


Figure 4.24 Specific cake resistance in suspended and attached growth MBRs at varying HRTs

Figure 4.24 shows the specific cake resistance at varying HRTs. It can be found that specific cake resistance decreased with increasing HRTs, and the cake resistance value in the attached growth MBR with moving media was the highest for all HRT values.

Table 4.10 Dewatering properties of sludge (CST-sec.) in the MBR for different HRTs

Reactor	HRT (h)			
	2	4	6	8
Suspended growth MBR	52.8	32.7	18.1	9.6
Attached growth MBR with moving media	101.3	86.0	78.3	50.0
Attached growth MBR with fixed media	30.2	20.6	17.9	10.0

A filterability of sludge suspension can be quickly tested by capillary suction time (CST) method. The CST test has been carried out as a relative indicator to characterize the performance of most sludge dewatering processes, and the CST results of the sludge in the MBR are shown in Table 4.10. It was noted that the CST value in the attached growth MBR with moving media was higher than that in the suspended growth MBR and the attached growth MBR with fixed media. It implied that the sludge in the moving media reactor was more difficult to dewatering than that in the other reactors. The reason was because of the presence of small sludge particles in the moving media reactor which can be seen in Figure 4.25. The sludge dewatering property was found to increase with decreasing HRT.

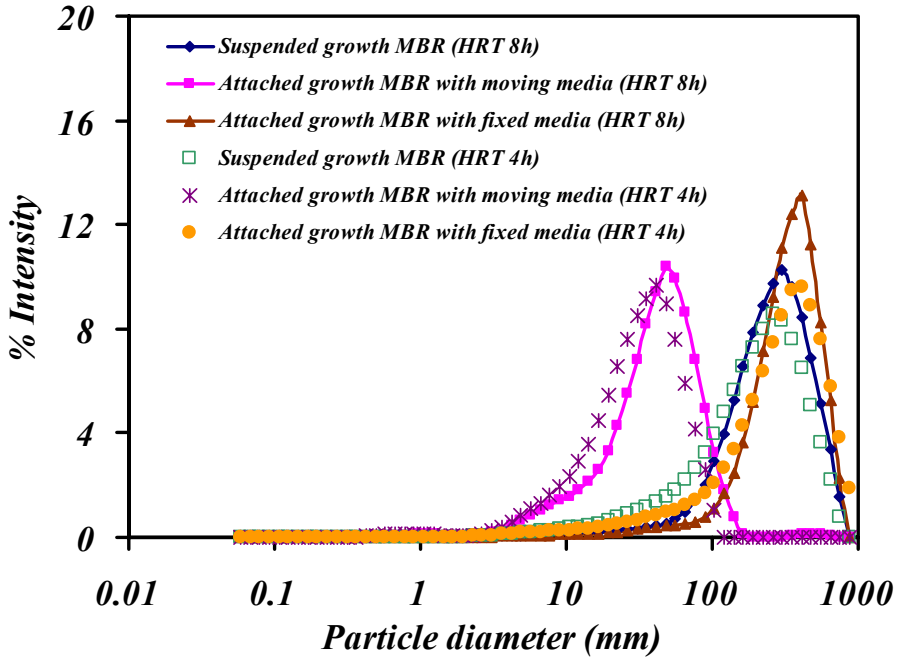


Figure 4.25 Particle size distribution of biological suspension in MBRs at HRT 4 and 8 h

Figure 4.25 shows the percentage intensity of sludge particle size from the three MBRs. The mean particle sizes of the suspended growth MBR, attached growth MBR with moving media and attached growth MBR with fixed media at HRT 8 h were 265, 45

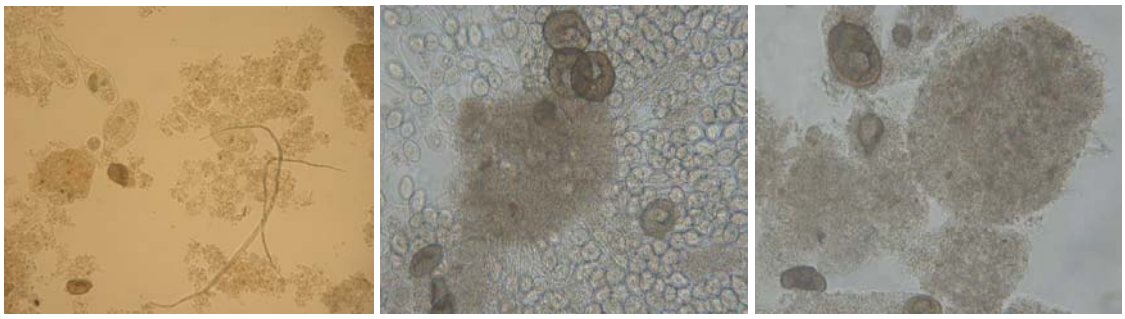
and 321 μm, respectively, and these at HRT 4 h were 219, 33, and 306 μm, respectively. Within the same MBR system, changing HRT had no effect on the particle size of the sludge. The attached growth system with the moving media was influenced more by the size distribution of biomass. This was because the movement of media which caused a floc breaking, and thus the small flocs produced.

E. Floc Morphology

The sludge morphologies were studied using an optical microscope, the results being shown in Figure 4.26. It was observed that the sludge morphologies of the three reactors were different in terms of floc shape, floc structure, floc size and type of microorganism. Three sludge samples with varying floc morphology and filamentous bacteria are described in Table 4.11. Filamentous fungi and protozoa organisms, including Ciliates and Rotifers were observed abundantly. Metazoas appeared in the suspended growth MBR and the attached growth MBR with fixed media. The amount of filamentous bacteria of the suspended growth MBR, and attached growth MBR with fixed media gave a good dewatering property as discussed earlier. This was because filamentous aggregated floc structure increased floc size while in the attached growth MBR with moving media had smaller floc size. The smaller floc size in the attached growth MBR with moving media resulted from the movement of media which broke the floc.

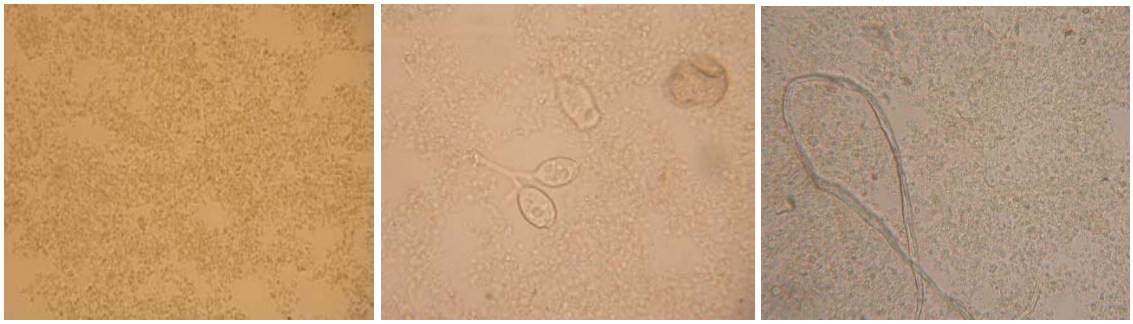
Table 4.11 Floc morphologies in MBR system

Sample	Filamentous Index	Description of floc morphology
Suspended growth MBR	2	Compact, round floc with some filamentous and some type of protozoa (Stalked ciliates and rotifer)
Attached growth MBR with moving media	1	Dense and matrix floc, irregular shape floc and small floc size
Attached growth MBR with fixed media	2	Compact, large and round floc with some filamentous embedded within floc and some protozoa



10X 40X 40X

(a) Suspended growth MBR



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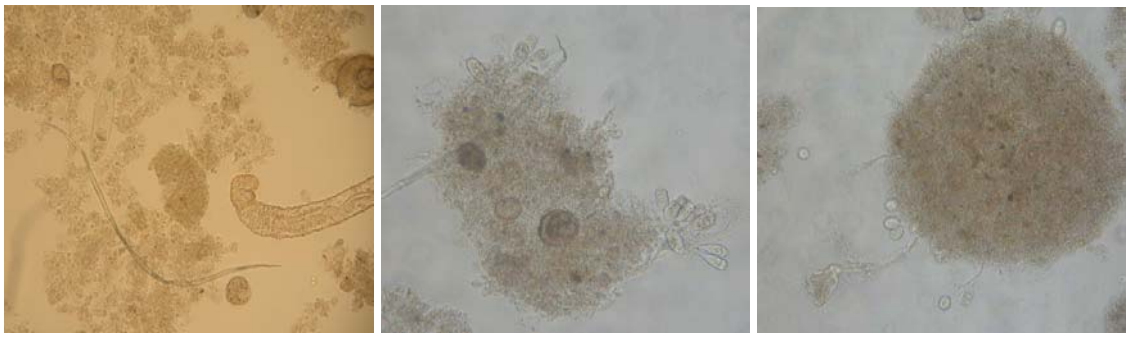
(b) Attached growth MBR with moving media



10X 40X 40X

(c) Attached growth MBR with fixed media

Figure 4.26 Sludge particle observed under optical microscope

4.2.2 Effect of Mixed Liquor Suspended Solid (MLSS)

This part describes the effect of MLSS on the removal efficiency and membrane fouling behavior. The MLSS was withdrawn frequently from the reactors in order to maintain the concentration of MLSS at 6, 10 and 15 g/L. The MLSS data is tabulated in Appendix E.

A. Overall Performance of MBR Systems

The influent and effluent qualities of the MBR in terms of COD and TKN are shown in Table 4.12. 94-98% of COD in the suspended growth MBR were removed and the COD concentration of effluent was between 15-32 mg/L. The effluent COD in the attached growth MBR with moving media was 11-18 mg/L, and the removal efficiency was found to be 97-98%. The effluent COD was relatively low and stabilized at less than 40 mg/L. This suggested the advantage of MBR system in having more biomass concentration, which resulted in a higher removal of COD (Chen and Chen, 2005). The removal efficiencies of TKN in the suspended growth MBR and attached growth MBR with moving media were in the range of 60-66% and 42-68%, respectively. The lowest TKN removal was found in the attached growth MBR with moving media at 15g/L of MLSS due to the limitation of DO concentration (< 2mg/L).

Table 4.12 Influent and effluent of COD and TKN in the MBRs with varying MLSS concentrations

Parameter / MLSS	COD (mg/L) (% Removal efficiency)			TKN (mg/L) (% Removal efficiency)		
	6 g/L	10 g/L	15 g/L	6 g/L	10 g/L	15 g/L
Influent	550	560	630	50	70	70
Effluent of suspended growth MBR	32 (94)	22 (96)	15 (98)	17 (66)	27 (60)	25 (62)
Effluent of attached growth MBR with moving media	18 (97)	11 (98)	14 (98)	N/A	22 (68)	38 (42)

B. Membrane Fouling Behavior

The change of TMP with time in the MBRs was monitored to investigate membrane fouling behavior at a constant flux of 7 L/m^2.h (HRT 2 h), the results being shown in Figures 4.27-4.29. Figure 4.27 shows that the TMP in the suspended growth reactor rapidly increased with time in exponential manner, ranging from 10 to 60 kPa in about 25 days at MLSS 6g/L. In fact, during the first period of 15 days the increase of TMP was very low and exponential increase started. Behavior of such phenomenon has been recently observed and proposed by Cho and Fane (2002). They explained the phenomenon of rapid TMP to progressive pore blocking with EPS. This eventually leads to local flux increase in remaining open pores and exceed the critical flux of the feed solution resulting in a rapid TMP rise. It is interesting to observe that the TMP in the attached growth reactor at MLSS 6 g/L was stable even after 25 days of operation. When MLSS was increased to 10g/L (Figure 4.28), the membrane clogging in the suspended growth reactor was faster (five times during 45 days of operation time). On the contrary, during the same period, it was found that the attached growth reactor had a TMP value of 30 kPa, which means that the clogging was rising at a much favorably slower pace. A similar trend was found at MLSS 15 g/L (Figure 4.29). The membrane clogging in the suspended growth reactor at 15 g/L of MLSS was very fast in which period the membrane was cleaned 11 times due to frequent fouling within a short period of 17 days. Higher TMP

value of nearly 80 KPa was noted after few days of operation. While on the attached growth, the increase in TMP was very slow and stable until 20 days of operation. However, after 20 days a sharp increase in TMPto nearly 80 KPa was noted. The observation implied a rapid acceleration of membrane clogging in the suspended growth than in the attached growth reactor in all MLSS concentrations. Additionally, increasing MLSS concentration exhibits higher TMP. It is interesting to note that after each membrane cleaning operation, the trend of rapid filter clogging within few days of operation was observed. However, the duration of filter cycle varied slightly which depends mostly on the membrane cleaning efficiency. Membrane cleaning was required when TMP increased up to 60 kPa. The procedure of membrane cleaning is commenced by disconnecting the suction lines from the membrane modules. Then, the membranes were taken out from the reactors in order to remove cake layers on the membrane by shaking in a 2L plastic cylinder which contains distilled water. After that, the membranes were cleaned as explained in Section 3.4. The effectiveness of membrane cleaning was evaluated by measuring the membrane resistance (R_m). R_m recovery value should be at least 80% of initial membrane resistance of a new membrane. If not, the above chemical cleaning process was repeated.

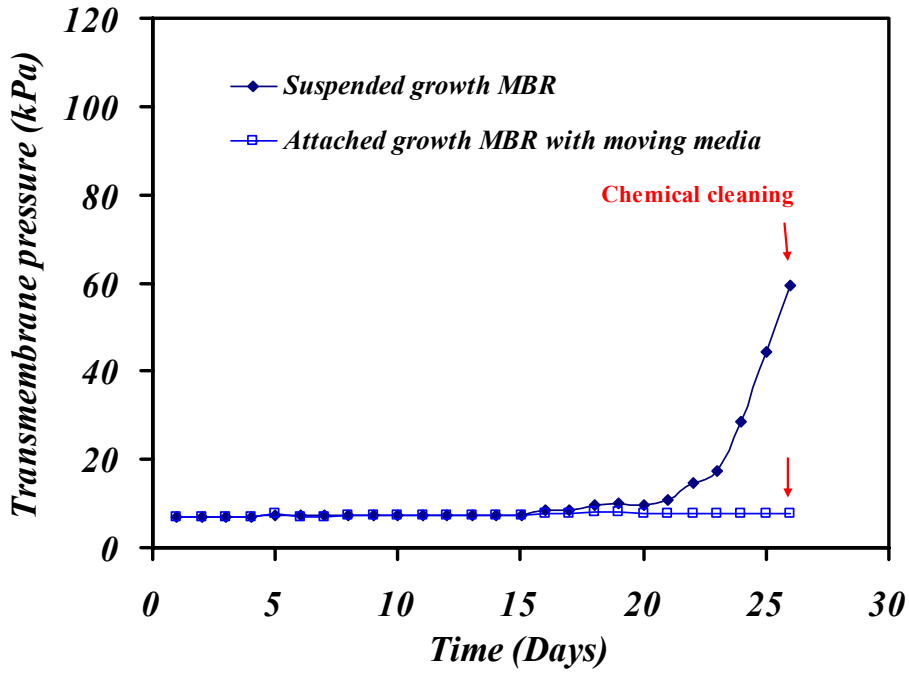


Figure 4.27 TMP changes with time at MLSS of 6 g/L in suspended and attached growth reactors (Membrane cleaning was conducted at point of arrows)

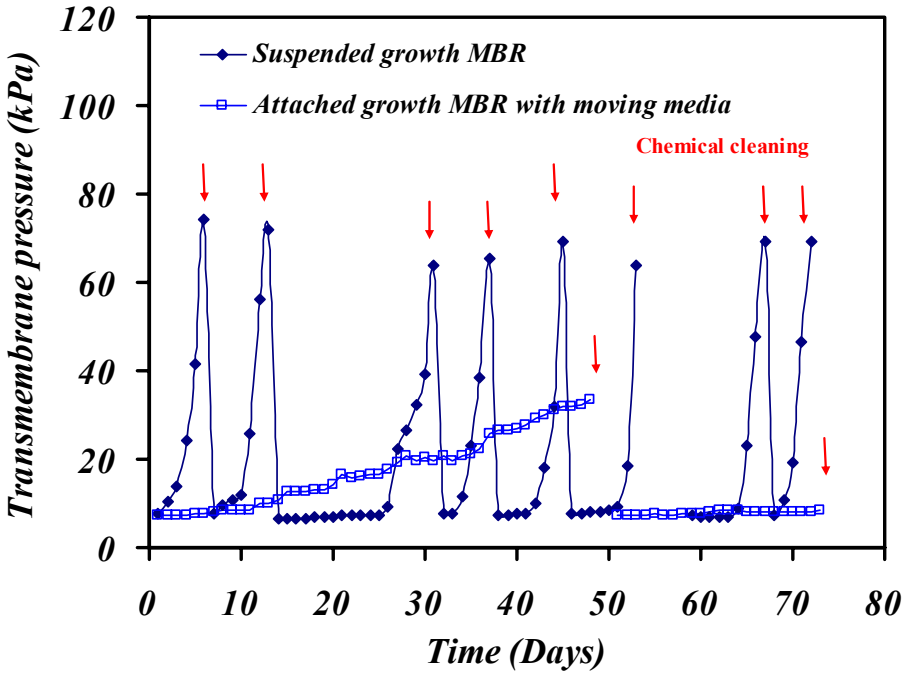


Figure 4.28 TMP changes with time at MLSS of 10 g/L in suspended and attached growth reactors (Membrane cleaning was conducted at point of arrows)

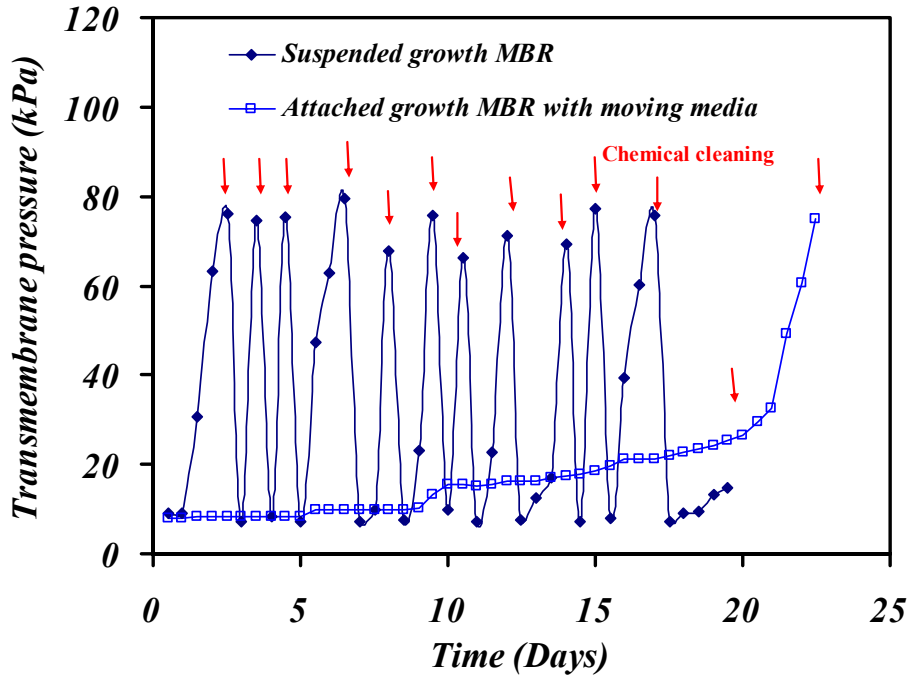


Figure 4.29 TMP changes with time at MLSS of 15 g/L in suspended and attached growth reactors (Membrane cleaning was conducted at point of arrows)

Table 4.13 Total cake formation on membrane surface for varying MLSS concentration

MLSS (g/L)	Total cake formation (g/m^2)*	
	Suspended growth reactor	Attached growth reactor
6	5.83	1.73
10	10.38	2.67
15	16.76	8.86

*(weight of the cake / membrane surface area)

The formation of gel and biological floc (cake layer) was observed on membrane surface of the suspended growth reactor during the clogging period. The total amount of cake formed on membrane surface which is expressed in terms of g/m^2 (weight of the cake /membrane surface area) was measured as shown in Table 4.13. It was noted that more cake formation was observed on membrane surface in the suspended growth as compared with the attached growth reactors for all MLSS concentrations. This indicates that the particle fouling in the attached growth reactor was lower than that in the suspended growth reactor. This was associated with the movement of the media present in the attached growth reactor which produced biomass with relatively small particles. The experimentally measured particle size distributions of the biomass for both reactors will be shown and discussed later. The formation of the cake layers from the two reactors can be quantitatively evaluated through the cake resistance (R_c) as presented in Table 4.14. In addition, the development of cake formation on the membrane surface depended on the MLSS concentrations in the reactor. It can be interpreted that MLSS concentration can be considered to impact directly on cake layer resistance which led to the flux decrease or the TMP increase as discussed earlier. This result was in agreement with Gui *et al.* (2002) who studied the effect of operational parameters on sludge accumulation on membrane surfaces in a submerged MBR at high biomass concentration of 10g/L and low biomass concentration of 1 g/L. They suggested that the biomass concentration was identified as a significant factor, influencing sludge accumulation on membrane surface.

Considering the membrane fouling rate in the suspended growth reactors (Figure 4.30) calculated from the slope of TMP versus operation time (days) (Basu and Huck, 2005, Ye *et al*., 2005), it was noted that the rate of average membrane fouling increased in the order of MLSS at 6 g/L (14.2 kPa/day), 10g/L (18.3 kPa/day) and 15g/L (31.3 kPa/day), respectively. This was because of the higher cake resistance value and higher sludge viscosity at MLSS 15g/L, which will be later elaborated in section 4.2.2 C. For the attached growth reactor, the rate of clogging at MLSS of 6 and 10 g/L was very low (0.1 and 0.3 kPa/day, respectively) because fouling did not occur during the period of this experiment, while the fouling rate at 15g/L MLSS was 11.9 kPa/day in which membrane was clogging during the experiment as discussed earlier. Moreover, the clogging of membrane that occurred at MLSS 15 g/L in the attached growth reactor but the fouling rate was still low, as compared with that in the suspended growth reactor. It was noted in Figure 4.30 that the fouling rate of the suspended growth reactor was much higher than that of the attached growth reactor. This result was conflicting with Lee *et al.* (2001) who used fixed media for attached growth reactor at HRT 8 h. The difference between this work and Lee and co-worker's study was related to the movement of the media in the reactor. Nevertheless, this study was optimistic to suggest that with respect to the frequency of membrane cleaning and membrane fouling rate, the performance and lifetime of the membrane could be improved by the using attached growth system incorporated with moving media.

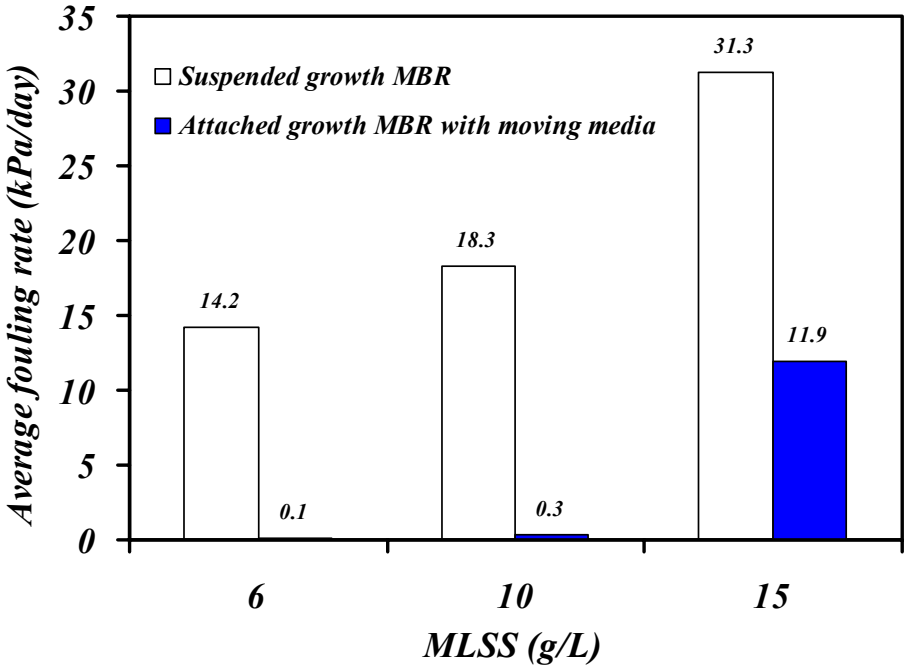


Figure 4.30 Fouling rate at MLSS of 6, 10 and 15 g/L

Table 4.14 Resistance values for suspended and attached growth reactors at 6, 10 and 15 g/L MLSS

Reactor	MLSS (g/L)	R_t ($*10^{12}$ m^{-1})	R_c ($*10^{12}$ m^{-1})	R_f ($*10^{12}$ m^{-1})	R_m ($*10^{12}$ m^{-1})	R_c/R_t
Suspended growth	6	34.7	33.1	0.98	0.63	0.95
	10	43.5	42.4	0.46	0.63	0.97
	15	51.4	49.7	1.18	0.54	0.97
Attached growth	6	2.09	0.66	0.82	0.62	0.32
	10	2.55	0.84	1.06	0.65	0.33
	15	16.7	14.0	2.09	0.58	0.84

Table 4.14 shows the results of all resistances in the suspended and attached growth reactors. It can be seen that the total resistance ($R_t = R_m+R_c+R_f$) in the suspended growth reactor was higher than that in the attached growth reactor. The majority of the membrane fouling in suspended growth reactor was caused by the cake resistance (R_c). Moreover, it was found that the cake resistance (R_c) increased with the MLSS concentration. This result was in agreement with Chang *et al.* (2001) that MLSS concentration was considered to impact upon cake layer resistance. Membrane fouling increased with increasing MLSS concentration, depending on the nature of biological process (Hong *et al.,* 2002). In addition, the fouling on the membrane can be quantitatively considered through the ratio of cake resistance (R_c) to total resistance (R_t) at MLSS of 6, 10 and 15g/L. Generally, greater R_c to R_t ratio indicates more cake layers accumulated on the membrane surface. It was found that the ratio of R_c to R_t in the suspended growth reactor was higher than that in the attached growth reactor at all MLSS concentrations. This would decline the permeated flux. These results corresponded well to the increase of TMP as discussed earlier. Based on the above results, it denotes that the lifetime of membrane for the attached growth MBR will be longer than that for the suspended growth MBR, and thus less maintenance and low operating costs for membrane application.

Alternatively, the difference in the cake layer resistance (R_c) in the attached and suspended growth reactors can be analyzed and explained by considering the effects of specific cake resistance (α) and the cake thickness (δ_c), which can be explained by Kozeny-Carman relationship (Equation 4.1) as given below (Bai and Leow, 2002):

$$R_c = \alpha \delta_c \qquad \text{Equation 4.1}$$

$$\alpha = \frac{180(1-\varepsilon_c)}{\rho_p . d_p^2 . \varepsilon_c^3} \qquad \text{Equation 4.2}$$

Where ε_c is the porosity of the cake layer, ρ_p is the density of the particles and d_p is the mean diameter of the particles.
The thickness of the cake, δ_c, can be given as Equation 4.3 (Bowen and Jenner, 1995):

$$\delta_c = \frac{m_p}{A_m} \qquad \text{Equation 4.3}$$

Where m_p is the mass of deposited particles and A_m the membrane area.

Based on Kozeny-Carman relationship (Equation 4.2) the specific cake resistance is inversely proportional to the porosity of the cake layer (ε_c) and average particle size (d_p). In the attached growth reactor, the colloidal particles (<5 μm) combined with the suspended particles (5–100 μm) resulted in relatively higher porosity of the cake layer as compared to that of the suspended growth reactor having very large range of suspended particles (1–1,000 μm) (Figure 4.32). The high porosity of attached growth cake layer resulted in small cake thickness (δ_c) and correspondingly low cake resistance (R_c) as compared to that of the suspended growth reactor (Table 4.13 and Table 4.14).

In the suspended growth reactor, the gel matrix constitutes the EPS and biomass particles leading to low porosity of the cake layer. However, in the attached growth reactor the gel matrix mainly EPS matrix is broken by the moving media and results in small particles without gel condition resulting in high porosity. This argument can be substantiated by the viscosity values at each biomass concentration for both reactors which will be discussed in section 4.2.2C. Graphically, the combination of particles and EPS gel matrix for both reactors is shown in Figure 4.31.

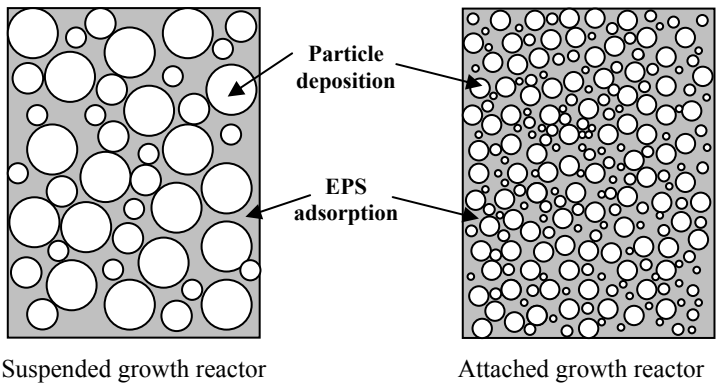


Figure 4.31 Combination of particles and EPS gel matrix

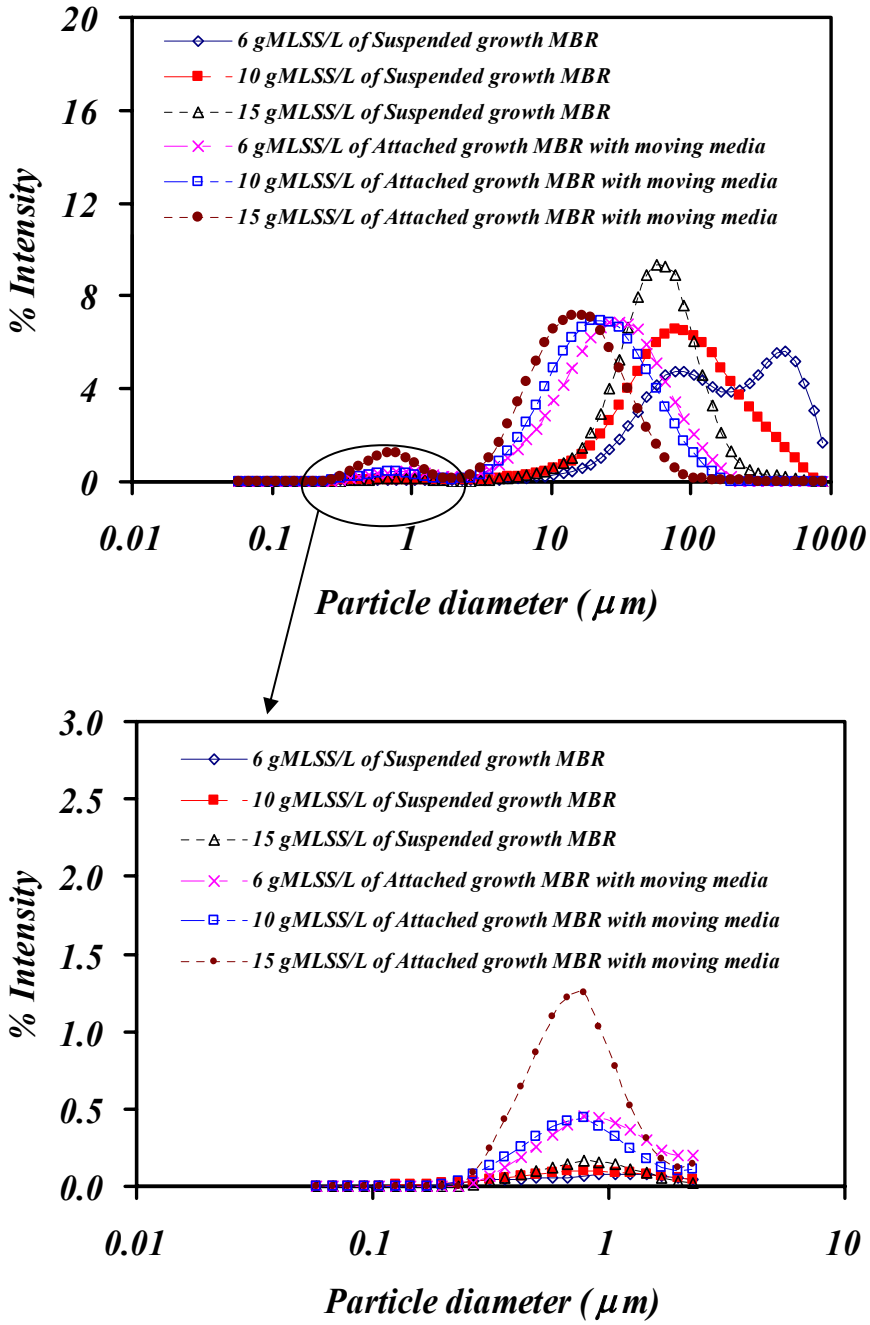


Figure 4.32 Relationship between particle size and MLSS concentration
(Top: normal scale, Bottom: enlarged scale)

Figure 4.32 shows particle size distribution of sludge from the suspended growth and attached growth reactors at different MLSS concentrations during a steady state operation. The data are shown in Appendix E. It can be observed that the particle sizes in the suspended growth reactor were larger than that in the attached growth reactor. It was worthy noting that the mean particle sizes of the suspended growth at 6, 10 and 15 g/L of MLSS were 226, 116 and 65 μm, respectively while those of the attached growth reactor at 6, 10 and 15 g/L were 33, 27 and 17 μm, respectively. Moreover, the particle size distributions in the attached growth reactor could be separated in two regions, the colloidal range (<5 μm) and the suspended particle range. However, the particle size distributions in

the suspended growth reactors could be considered as consisting of only suspended particle range as the intensity of colloidal range was very low. The results of the particle size distributions could be used to substantiate the proposed mechanism of membrane fouling as previously discussed.

C. Sludge Characteristics

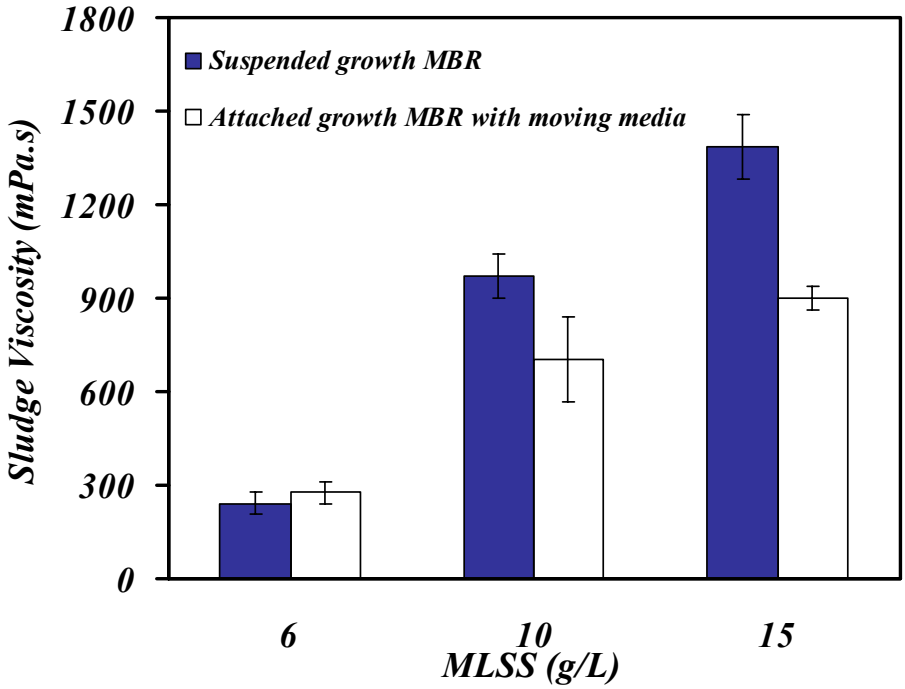


Figure 4.33 Relationship between sludge viscosity and MLSS concentration

Figure 4.33 shows the sludge viscosity and its relationship in three different MLSS concentrations. It can be seen that the sludge viscosities in the suspended growth reactor at MLSS 6, 10 and 15 g/L were 242, 970 and 1387 mPa.s., respectively, while the sludge viscosities in the attached growth reactor at MLSS 6, 10 and 15 g/L were 277, 705 and 900 mPa.s, respectively. It was expected that the sludge viscosity increased with increasing MLSS concentration. This result was supported by Itonaga *et al.* (2003). In addition, adding of media in the attached growth reactor increased shear stress in the system that would decrease sludge viscosity in the attached growth reactor as compared to suspended growth reactor. However, higher biomass concentration increased the sludge viscosity. It can be said that the suspended biomass in the reactor was psuedoplastic non-Newtonian model due to the viscosity change with the change in the environmental conditions (shear stress).

Figure 4.34 shows the CST values with time during experimental period and its relationship with MLSS concentration. It can be seen that the CST value in the attached growth reactor was higher than that in the suspended growth reactor due to the presence of the small floc in the attached growth reactor (as discussed in Figure 4.32), leading to a decrease in the sludge dewatering property. The sludge dewatering property was found to increase with MLSS concentration.

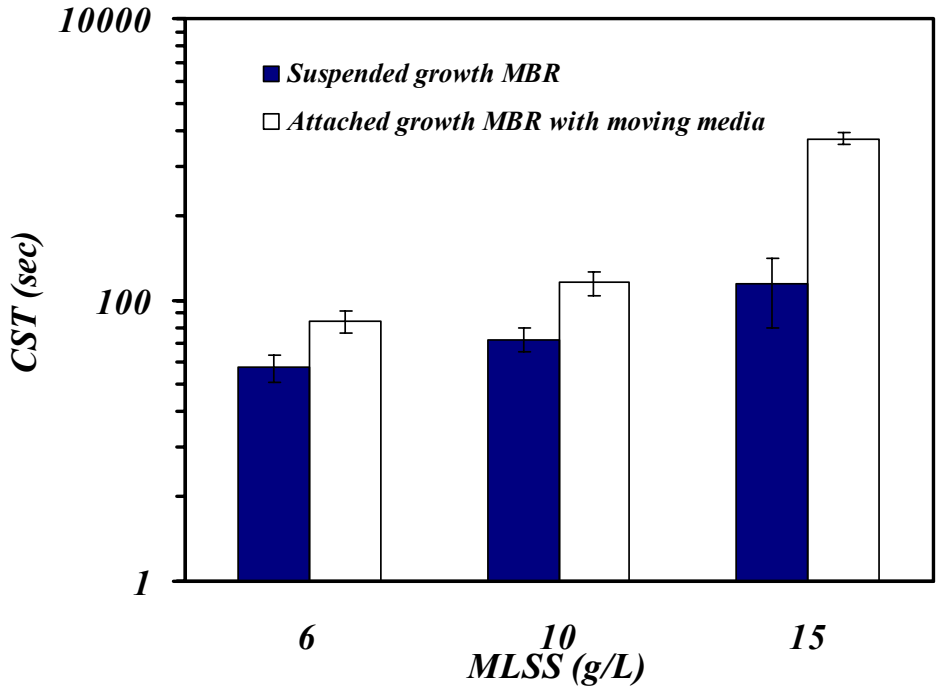


Figure 4.34 Relationship between CST and MLSS concentration

D. Bound and Soluble EPS Compositions

Another factor to consider, for the cause of clogging, was bound and soluble EPS components. Figures 4.35-4.38 show the bound and soluble EPS components for MLSS of 6, 10 and 15 g/L. For bound EPS (Figures 4.35 and 4.37), it was indicated that 70% of EPS composition was protein. The high content of protein led to hydrophobic sludge and was attributed to membrane fouling by adsorption, a specific interaction between protein and membrane, and by deposition during filtration (Kelly *et al.*, 1993). The amounts of bound EPS at MLSS 6, 10 and 15 g/L were similar. It was also found that the bound EPS contents in the suspended growth and attached growth reactors were nearly the same.

The soluble EPS in the laboratory-scale MBR arose from two origins. One was induced by cell lysis, and the other was by the EPS released from activated sludge floc. These matters were non-biodegradable or very slowly biodegradable matters compared with the glucose in synthetic wastewater. Therefore, it can be assumed that there were almost no substrate residuals from glucose in the supernatant. The soluble EPS was collected directly from the bioreactors. The soluble EPS was obtained by removing the activated sludge using the centrifugation. It should be noted that this soluble EPS differs from the bound EPS, which entrapped on the microbial cell. Figures 4.36 and 4.38 show the values of soluble EPS for the different MLSS. It was noted that the main composition in soluble EPS was carbohydrate, which resulted from substrate metabolism, biomass decay and cell lysis (Barker *et al.*, 1999). It was clearly found that the soluble EPS values in the suspended growth MBR at MLSS 6, 10 and 15 g/L were similar with those in the attached growth MBR at MLSS 6 and 10 g/L. It was clearly seen that the soluble EPS in the attached growth MBR at MLSS 15 g/L was the highest. This would be caused by the breaking of EPS matrix on the microorganism cell in the attached growth MBR. On the other hand, the amount of soluble EPS at 15 g/L MLSS was higher than that at 6 and 10 g/L MLSS. This suggested that the EPS was not the main factor to cause the fouling in

this work, but the particle size of the biomass, which was influenced by the movement of the media, had a significant effect on the formation of cake layers on the membrane.

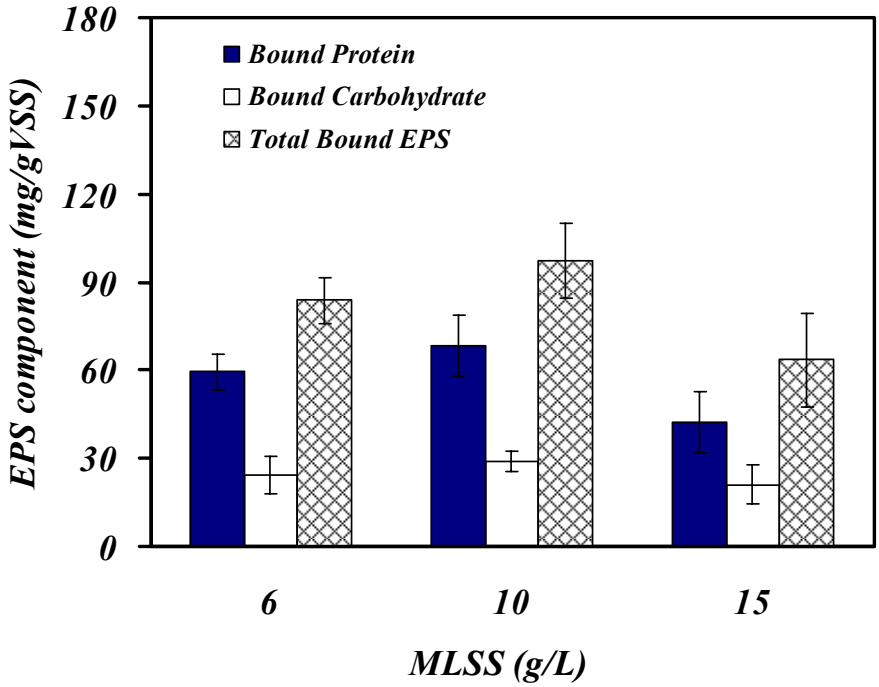


Figure 4.35 Bound EPS components in suspended growth MBR at varying MLSS concentrations

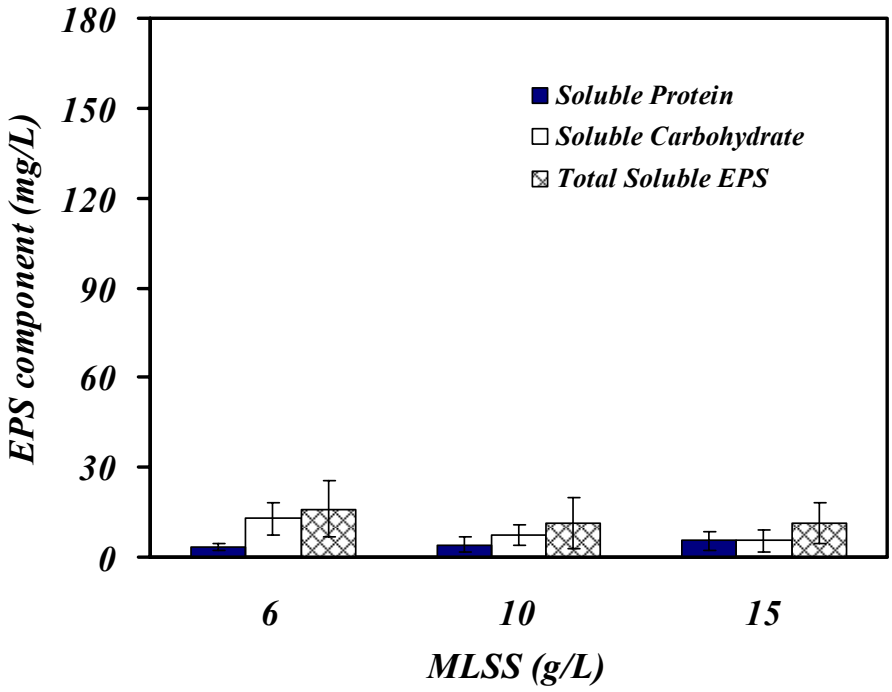


Figure 4.36 Soluble EPS components in suspended growth MBR at varying MLSS concentrations

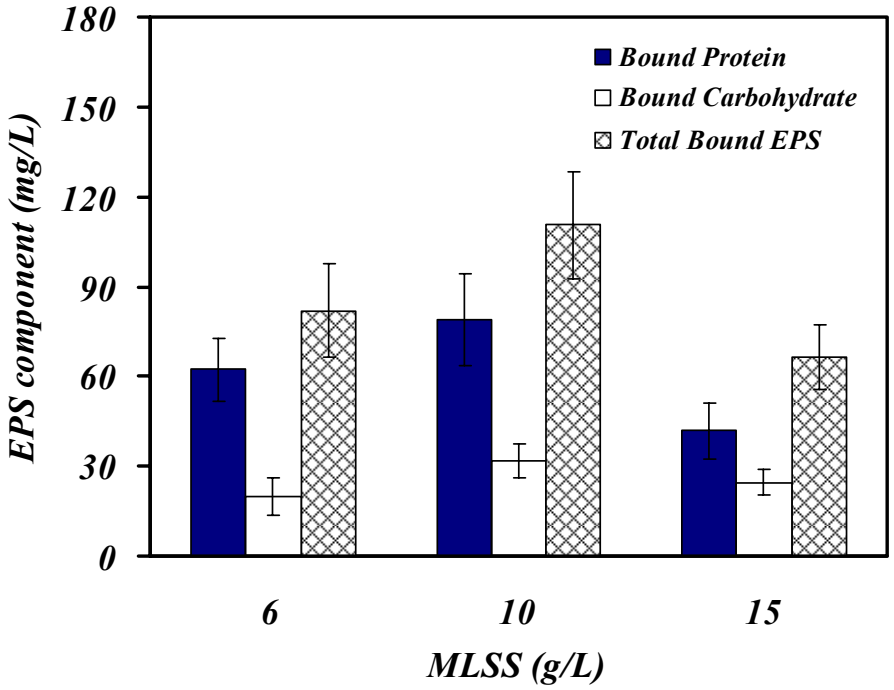


Figure 4.37 Bound EPS components in attached growth MBR with moving media at varying MLSS concentrations

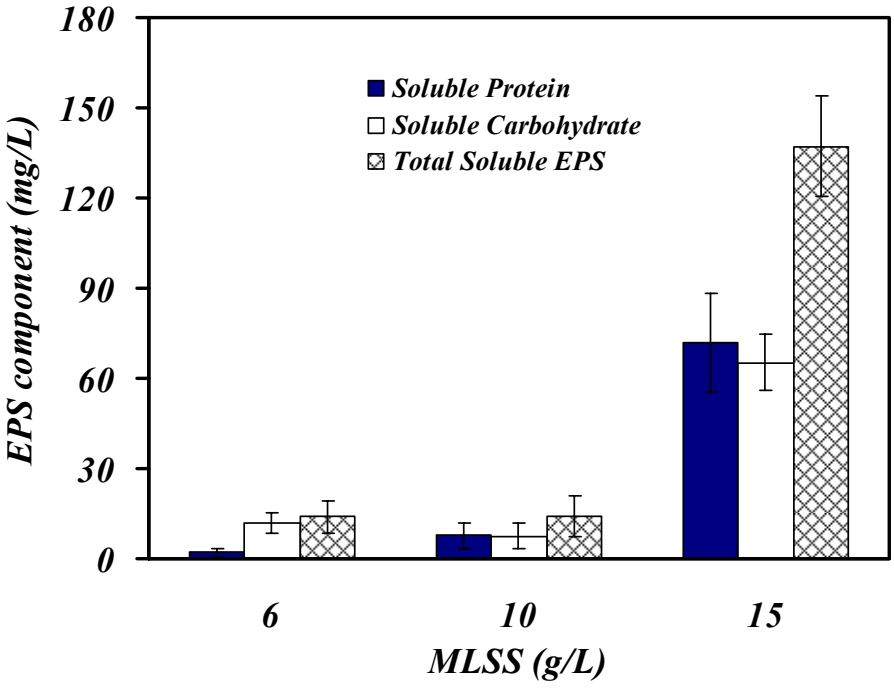


Figure 4.38 Soluble EPS components in attached growth MBR with moving media at varying MLSS concentrations

Chapter 5

Conclusions and Recommendations

This work investigated the effects of operating conditions on removal efficiency and biofouling phenomena in the suspended and the attached growth systems. The work can be divided into two separate parts; preliminary study and laboratory-scale membrane bioreactor study. The preliminary study was carried out to select a suitable media for the attached growth reactor. The laboratory-scale membrane bioreactor study was focused on an understanding of fouling mechanism in the attached and suspended growth MBRs. The effects of operational conditions, such as HRT and MLSS, were evaluated. The summary and conclusions drawn from the experimental results are noted below.

5.1 Conclusions

Preliminary Study

1. No significant difference in COD removal efficiency was found between the suspended and the attached growth systems, and the average value of COD was about 95%. The average TKN removal efficiency in the attached growth system was in the range of 83 to 90% which was greater than that in the suspended growth system, this being associated with a biofilm formation on the media in the attached growth system.

2. There was no significant difference in EPS production in the suspended and the attached growth systems. The compositions of EPS in terms of protein and carbohydrate were in the range from 13 to 16 mg/gVSS and from 7 to 12 mg/gVSS, respectively. In this research, the total EPS reduction was mainly caused by the protein reduction (20-30%) due to biological nitrogen removal in the attached growth system. The carbohydrate content was similar among all the media used, and the extracted EPS primarily consisted of carbohydrate (around 36%), and protein (around 22%). Cylindrical polypropylene (CP) was selected as the most suitable media for attached growth system due to low EPS production.

3. NaCl solution was found to be most effective for EPS extraction. The centrifugation speed of 4,000 rpm for 20 min was the optimum condition for EPS extraction as it gave the lowest protein, carbohydrate and TOC content.

Effect of Hydraulic Retention Time (HRT)

1. The COD removal efficiency was greater than 90% even with a short HRT. The removal efficiencies of TKN and ammonia were greater than 90% and 94%, respectively, at HRT of 2 h. It can be observed that there was no significant difference in bound EPS for all HRT while the soluble EPS was high at short HRT (2 and 4 h). This was caused by an increase in utilization of bound EPS in the floc by microorganism as well as released from cell lysis, and thus increased soluble EPS.

2. It was found that the CST value in the attached growth MBR with moving media was higher than that in the suspended growth MBR, and attached growth MBR with fixed media. The movement of media in the attached growth MBR could cause floc breakage, and produce the small floc, which resulted in poor dewatering. The sludge dewatering property increased with decreasing HRT.

3. It was found that the sludge morphologies of the three reactors were different in terms of floc shape, floc size and type of microorganism. Filamentous fungi, ciliates and rotifers were observed. Metazoas was found to appear in the suspended growth MBR and the attached growth MBR with fixed media.

Effect of Mixed Liquor Suspended Solid (MLSS)

1. As the MLSS was increased from 6, 10 and 15 g/L, the TMP values were found to increase due to clogging of the membrane. More membrane fouling in the suspended growth MBR was greater than that in the attached growth MBR. More cake formation was observed on membrane surface in the suspended growth as compared with the attached growth reactors for all MLSS concentrations. This indicated that the particle fouling in the attached growth reactor was lower than that in the suspended growth reactor.

2. The total resistance (R_t) in the suspended growth reactor was higher than that in the attached growth reactor. The majority of the membrane fouling in suspended growth reactor was caused by the cake resistance which increased with increasing MLSS concentration. The fouling on the membrane was found to be affected by the design of operating system.

3. The attached growth reactor with moving media was found to have lower fouling and prolong filtration as compared to the suspended growth reactor due to the difference in particle size distribution of biomass. In the attached growth reactor, the smaller suspended particles resulted in higher porosity of the cake layer and lower cake thickness.

4. The bound EPS contents in the suspended growth and attached growth reactors were similar. The amount of soluble EPS at 15 g/L MLSS was higher than that at 6 and 10 g/L MLSS. The EPS was not the main factor to cause fouling. The particle size of the biomass influenced by the movement of the media had a significant effect on the formation of cake layers on the membrane.

5.2 Recommendations for Further Study

The following studies are recommended for further studies.

1. Conducting pilot scale or full scale to verify the laboratory-scale results.
2. Comparing removal efficiency and fouling performance between moving bed MBR and anaerobic MBR in the condition of high organic loadings.
3. Considering bio-mechanisms of microbial activity and bio-kinetics in the moving bed MBR in more detail, and identifying microbial species and quantifications through microbial techniques (FISH, PCR and DGGE).

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Appendix-A

EPS Measurement in Batch Reactor

Table A.1 EPS content (mg/gVSS) in batch reactor

Time	Control	PB	PG	PS	CP	S
1	41.5	42.3	35.8	35.3	43.2	33.8
2	45.8	35.3	34.7	29.4	32.3	45.2
3	54.5	37.7	43.5	46.4	34.4	40.1
4	44.9	40.7	38.2	38.4	45.4	42.1
5	43.9	37.1	33.1	48.2	38.1	33.6
6	54.8	32.8	35.6	40.1	31.1	46.5
7	45.6	36.1	37.0	39.2	39.1	41.5
Average	**47.3**	**37.4**	**36.8**	**39.6**	**37.7**	**40.4**
Std.	**5**	**3**	**3**	**6**	**5**	**5**

Table A.2 Protein content (mg/gVSS) in batch reactor

Time	Control	PB	PG	PS	CP	S
1	11.5	6.6	6.6	9.4	9.4	6.7
2	12.6	8.3	8.5	7.8	9.6	10.6
3	9.4	7.9	8.7	7.5	8.4	9.4
4	11.8	7.0	6.3	8.9	7.3	6.9
5	12.9	9.1	8.1	9.3	7.6	7.0
6	12.9	9.6	7.2	9.9	9.1	10.7
7	10.2	9.5	7.9	7.7	9.9	9.7
Average	**11.6**	**8.3**	**7.6**	**8.6**	**8.8**	**8.7**
Std	**1.4**	**1.2**	**0.9**	**1.0**	**1.0**	**1.8**

Table A.3 Carbohydrate content (mg/gVSS) in batch reactor

Time	Control	PB	PG	PS	CP	S
1	14.9	12.6	15.0	11.2	11.8	13.9
2	13.9	13.7	12.1	14.5	12.9	15.4
3	13.4	14.7	15.2	15.9	12.1	14.4
4	12.7	14.3	15.6	12.6	14.1	14.7
5	16.0	15.2	14.4	12.8	13.9	15.9
6	16.2	14.6	13.6	15.8	14.4	17.1
7	17.9	14.6	12.5	15.7	14.7	18.4
Average	**15.0**	**14.2**	**14.1**	**14.1**	**13.4**	**15.7**
Std	**1.8**	**0.8**	**1.4**	**1.9**	**1.1**	**1.6**

Table A.4 Percentage of protein and carbohydrate in EPS

Media	EPS mg/gVSS	Protein mg/gVSS	% Protein	Carbohydrate mg/gVSS	% Carbohydrate
PB	37.4	8.3	22.2	14.2	38.0
PG	36.8	7.6	20.7	14.1	38.3
PS	39.6	8.6	21.7	14.1	35.6
CP	37.7	8.8	23.3	13.4	35.5
S	40.4	8.7	21.5	15.7	38.9
Control	47.3	11.6	24.5	15.0	31.7

Table A.5 EPS in the unit of media surface

Media	Media Surface m^2	EPS mg/gVSS	EPS/Surface (mg/m^2 of media surface)
PB	0.114	37.4	328.1
PG	0.084	36.8	438.1
PS	0.020	39.5	1975.0
CP	0.288	38.0	131.9
S	1.220	40.2	33.0

Table A.6 Relationship between TOC and total bound EPS

Reactor	TOC (mg/gVSS)	Protein (mg/gVSS)	Carbohydrate (mg/gVSS)	Total EPS (mg/gVSS)
SBR-control	69.1	40.8	43.9	84.7
SBR-media	57.1	25.9	47.8	73.6
AS-MBR	58.6	17.2	18.7	35.9
GAC-MBR	114.6	24.0	29.4	53.3

Table A.7 Relationship between TOC and total soluble EPS

Reactor	TOC (mg/L)	Protein (mg/L)	Carbohydrate (mg/L)	Total EPS (mg/L)
SBR-control	7.6	5.0	13.7	18.7
SBR-media	4.4	2.5	13.2	15.7
AS-MBR	10.6	8.2	10.7	18.9
GAC-MBR	6.8	6.7	4.7	11.4

Table A.8 Centrifugation speed versus compositions of soluble EPS

Sample	Centrifugation speed (rpm)								
	2000			3000			4000		
	TOC mg/L	Protein mg/L	Carbohydrate mg/L	TOC mg/L	Protein mg/L	Carbohydrate mg/L	TOC mg/L	Protein mg/L	Carbohydrate mg/L
SBR-control	21.4	1.2	4.6	7.6	1.7	7.1	6.8	1.0	2.6
SBR-media	12.6	0.0	2.7	4.1	0.0	3.9	3.7	0.0	1.7
AS-MBR	24.3	4.4	2.5	8.2	5.0	3.0	8.0	2.8	1.0
GAC-MBR	31.0	7.2	8.5	10.0	9.3	7.5	6.9	9.9	5.4

Appendix-B

Initial Membrane Resistance Measurement

Table B.1 Initial membrane resistance for suspended growth MBR

Flux (mL/min)	Different TMP (mmHg)	Filtration flux ($L/m^2.h$)	TMP (kPa)
99	40	14.1	5.3
178	50	25.5	6.7
238	60	33.9	8.0
301	70	42.9	9.3
386	80	55.1	10.7

Initial membrane resistance (#4241507) = $6.03*10^{11}$ 1/m
Note: Viscosity of the water at 30°C is $0.798*10^{-3}$ $N.s/m^2$

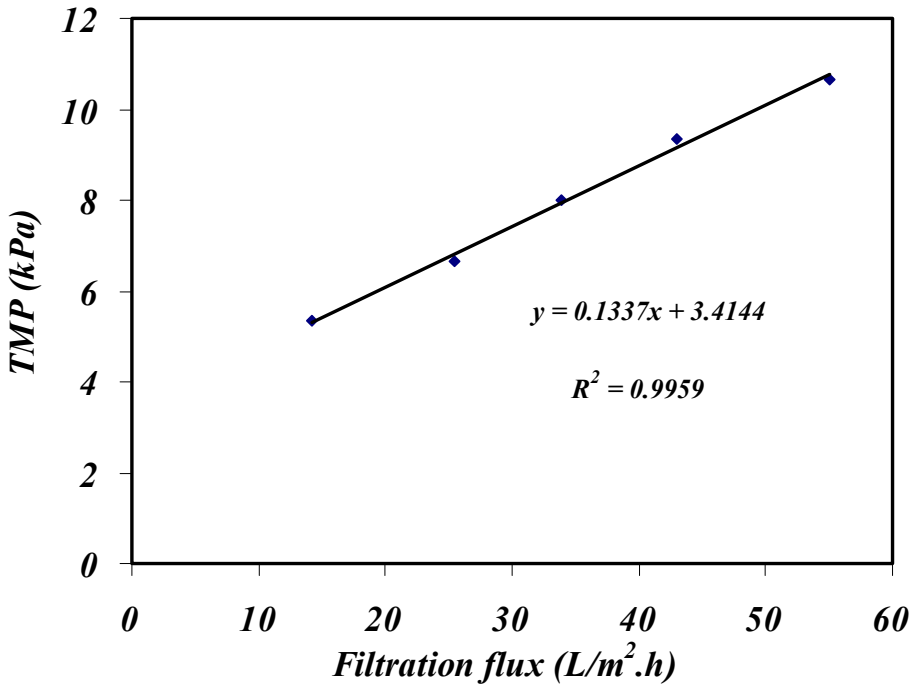

Figure B.1 Variation of TMP with filtration flux for suspended growth MBR

Table B.2 Initial membrane resistance for attached growth MBR with moving media

Flux (mL/min)	Different TMP (mmHg)	Filtration flux ($L/m^2.h$)	TMP (kPa)
80	40	11.4	5.3
159	50	22.8	6.7
255	60	36.4	8.0
315	70	45.0	9.3
388	80	55.4	10.7

Initial membrane resistance (#4241503) = $5.43*10^{11}$ 1/m
Note: Viscosity of the water at 30°C is $0.798*10^{-3}$ $N.s/m^2$

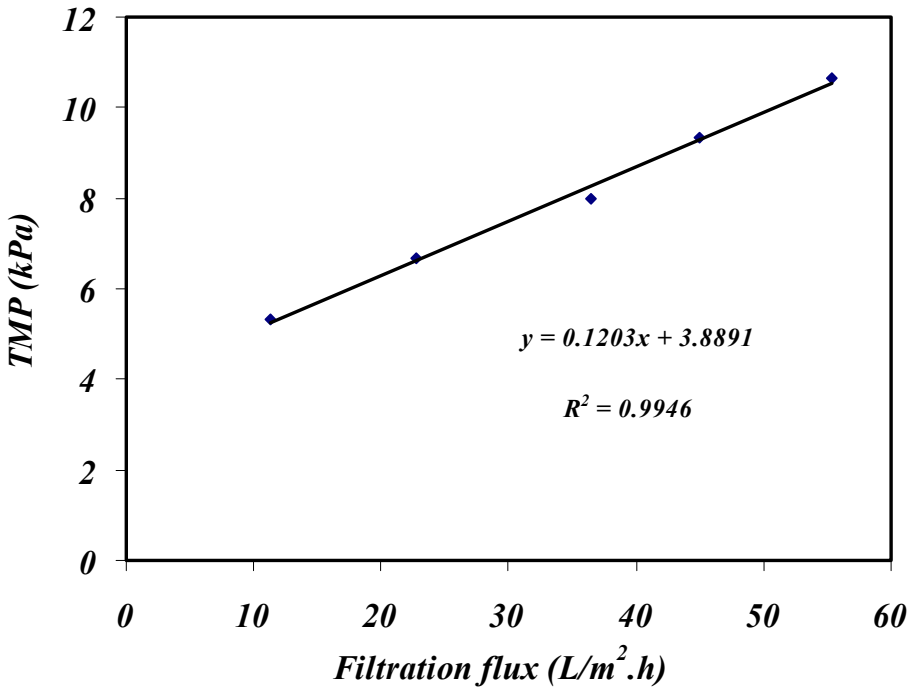

Figure B.2 Variation of TMP with filtration flux for attached growth MBR with moving media

Table B.3 Initial membrane resistance for attached growth MBR with fixed media

Flux (mL/min)	Different TMP (mmHg)	Filtration flux ($L/m^2.h$)	TMP (kPa)
97	40	13.9	5.3
195	50	27.9	6.7
285	60	40.6	8.0
380	70	54.2	9.3
449	80	64.1	10.7

Initial membrane resistance (#4241432) = $4.73*10^{11}$ 1/m
Note: Viscosity of the water at 30°C is $0.798*10^{-3}$ $N.s/m^2$

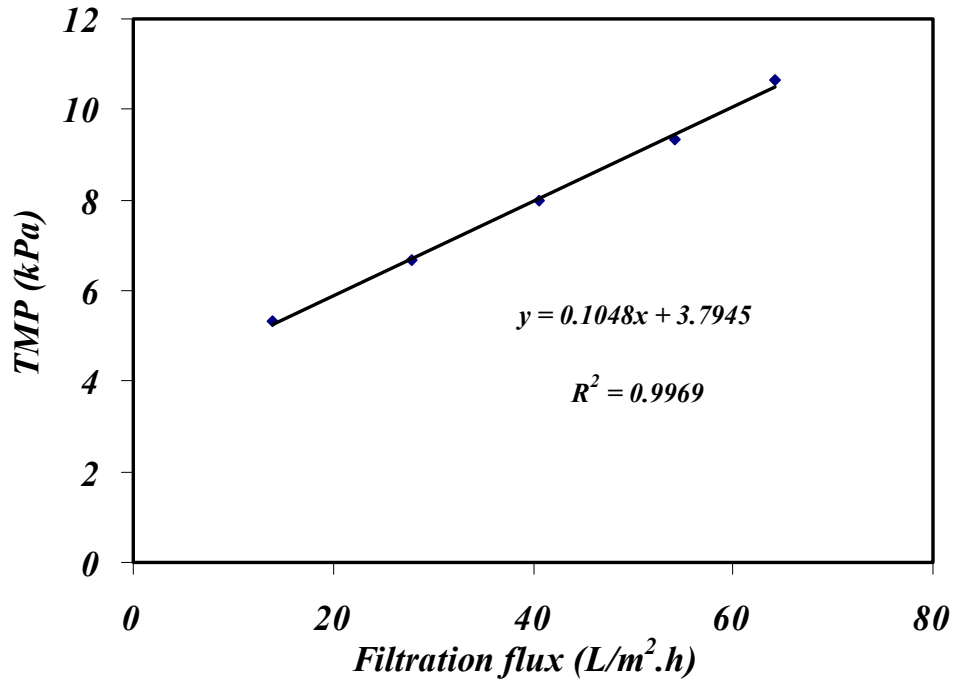

Figure B.3 Variation of TMP with filtration flux for attached growth MBR with fixed media

Appendix-C

Nitrogen Mass Balance

Example: Nitrogen balance for suspended growth MBR at HRT 8 h. are shown below.

Nitrogen compounds in influent:

TKN (mg/L)	= 57.5
NO_3-N (mg/L)	= 3.9
NO_2-N (mg/L)	= 0
	= 61.4

Nitrogen compounds in effluent:

TKN (mg/L)	= 2.8
NO_3-N (mg/L)	= 35.6
NO_2-N (mg/L)	= 0.2
	= 38.6

Nitrogen lost by assimilation:

BOD_5-Inffluent (mg/L)	= 458
BOD_5-effleunt (mg/L)	= 5

Nitrogen lost by assimilation (mg/L) = 0.05(458-5)
= 22.65

According to the Equation.4.1

$TKN_i + NO_2\text{-}N_i + NO_3\text{-}N_i = TKN_e + NO_2\text{-}N_e + NO_3\text{-}N_e$ + Nitrogen assimilated
+Nitrogen loss due to denitrification Equation 4.1

Nitrogen lost by denitrification
=Total nitrogen to influent - Total nitrogen in effluent
- Nitrogen assimilated into biomass

= 61.4 – 38.6 – 22.7
= 0.1 mg/L

Appendix-D

EPS and Biomass Measurement at Different HRT

Table D.1 UV/vis absorbance of bound EPS

Wave length (nm)	Absorbance		
	Suspended growth MBR	Attached growth MBR with moving media	Attached growth MBR with fixed media
190	1.929	1.906	1.894
200	2.481	2.480	2.448
210	2.723	2.723	2.691
220	2.866	2.831	2.761
230	2.804	2.814	2.753
240	2.570	2.538	2.378
250	2.545	2.552	2.290
260	2.427	2.523	2.246
270	2.300	2.373	2.173
280	2.175	2.207	2.017
290	1.924	1.897	1.740
300	1.689	1.611	1.498
310	1.561	1.498	1.387
320	1.503	1.427	1.301
330	1.450	1.354	1.236
340	1.396	1.312	1.167
350	1.335	1.258	1.110
360	1.304	1.223	1.058
370	1.266	1.187	1.008
380	1.222	1.146	0.965
390	1.196	1.123	0.912
400	1.160	1.091	0.891

Table D.2 UV/vis absorbance of soluble EPS

Wave length (nm)	Absorbance		
	Suspended growth MBR	Attached growth MBR with moving media	Attached growth MBR with fixed media
190	1.848	1.910	1.758
200	2.309	2.379	2.311
210	2.593	2.588	2.610
220	2.747	2.757	2.767
230	2.123	2.100	1.535
240	0.397	0.372	0.302
245	0.182	0.166	0.158
250	0.107	0.092	0.107
255	0.084	0.068	0.090
260	0.075	0.061	0.084
270	0.069	0.055	0.077
280	0.066	0.053	0.072
290	0.065	0.053	0.067
300	0.062	0.051	0.061
310	0.052	0.043	0.052
320	0.039	0.031	0.041
330	0.028	0.021	0.031
340	0.023	0.017	0.027
350	0.021	0.015	0.023
360	0.017	0.012	0.020
380	0.011	0.006	0.013
400	0.004	0.002	0.009

Table D.3 P/C ratio of bound EPS at different HRT

Reactor	HRT 8 h	HRT 6 h	HRT 4 h	HRT 2 h
Suspended growth MBR	1.5±0.4	1.9±0.4	1.6±0.0	1.9±0.1
Attached growth MBR with moving media	2.2±0.6	2.4±0.6	2.1±0.2	1.9±0.4
Attached growth MBR with fixed media	1.6±0.3	1.9±0.5	1.6±0.2	1.5±0.1

Table D.4 P/C ratio of soluble EPS at different HRT

Reactor	HRT 8 h	HRT 6 h	HRT 4 h	HRT 2 h
Suspended growth MBR	0.2±0.1	0.1±0.1	0.9±0.3	1.3±0.0
Attached growth MBR with moving media	0.1±0.1	0.0±0.0	0.4±0.3	0.4±0.1
Attached growth MBR with fixed media	0.4±0.1	0.1±0.1	0.8±0.3	0.6±0.4

Table D.5 Bound EPS at different HRT

Reactor	HRT 8 h	HRT 6 h	HRT 4 h	HRT 2 h
Suspended growth MBR	73.4±18.0	90.6±13.0	91.1±16.0	89.7±1.0
Attached growth MBR with moving media	70.4±15.0	71.9±17.0	69.9±15.0	73.6±4.0
Attached growth MBR with fixed media	79.3±16.0	89.2±15.0	102.0±18.0	104.0±7.0

Table D.6 Soluble EPS at different HRT

Reactor	HRT 8 h	HRT 6 h	HRT 4 h	HRT 2 h
Suspended growth MBR	18.5±6.0	22.0±6.0	44.3±8.0	34.4±9.0
Attached growth MBR with moving media	13.2±3.0	19.3±2.0	22.5±7.0	14.3±6.0
Attached growth MBR with fixed media	20.0±4.0	22.6±6.0	43.7±10.0	45.5±8.0

Table D.7 MLSS concentration at HRT 2 h

Date	Day	MLSS			MLVSS			MLVSS/MLSS		
		SG-MBR	AG-MBR (moving media)	AG-MBR (fixed media)	SG-MBR	AG-MBR (moving media)	AG-MBR (fixed media)	SG-MBR	AG-MBR (moving media)	AG-MBR (fixed media)
30/1/2004	1	10850	N/A	N/A	9680	N/A	N/A	0.89	N/A	N/A
2/2/2004	4	N/A	N/A	N/A	6820	N/A	N/A	0.90	N/A	N/A
4/2/2004	6	11280	9190	9130	9980	8230	8050	0.88	0.90	0.88
7/2/2004	9	11630	11450	11090	10440	10190	9770	0.90	0.89	0.88
9/2/2004	11	11390	10820	11260	10300	9620	9960	0.90	0.89	0.88
11/2/2004	13	11500	11780	9740	10430	10610	8730	0.91	0.90	0.90
12/2/2004	14	9550	9280	8780	8620	8360	7810	0.90	0.90	0.89
14/2/2004	16	10080	10680	7990	9090	9710	7150	0.90	0.91	0.89
16/2/2004	18	11040	11830	9460	10030	10720	8500	0.91	0.91	0.90
17/2/2004	19	10650	11460	9890	9620	10380	8920	0.90	0.91	0.90
18/2/2004	20	10610	12600	9600	9740	11400	8650	0.92	0.90	0.90
19/2/2004	21	10590	12000	9780	9640	10880	8830	0.91	0.91	0.90
23/2/2004	25	10950	12840	11050	9960	11670	10040	0.91	0.91	0.91
	Avg.	**10843**	**11266**	**9797**	**9794**	**10161**	**8765**	**0.90**	**0.90**	**0.89**
	Std.dev	**603**	**1194**	**1014**	**534**	**1112**	**906**	**0.01**	**0.01**	**0.01**

Note: SG-MBR: Suspended growth MBR
AG-MBR (moving media): Attached growth MBR with moving media
AG-MBR (fixed media): Attached growth MBR with fixed media

Table D.8 MLSS concentration at HRT 4h

Date	Day	MLSS			MLVSS			MLVSS/MLSS		
		SG-MBR	AG-MBR (moving media)	AG-MBR (fixed media)	SG-MBR	AG-MBR (moving media)	AG-MBR (fixed media)	SG-MBR	AG-MBR (moving media)	AG-MBR (fixed media)
19/12/2003	1	7520	7750	9070	6400	7080	7790	0.85	0.91	0.86
23/12/2003	5	9850	10040	10730	8940	9200	9550	0.91	0.92	0.89
25/12/2003	7	9630	9250	9770	8670	8500	8710	0.90	0.92	0.89
31/12/2003	13	9840	9580	10800	8830	8700	9620	0.90	0.91	0.89
7/1/2004	20	8630	N/A	8950	N/A	N/A	N/A	N/A	N/A	N/A
12/1/2004	25	10120	9080	8930	8990	8210	7930	0.89	0.90	0.89
13/1/2004	26	9430	9440	8000	8350	8480	7140	0.89	0.90	0.89
14/1/2004	27	9120	8920	7230	8030	8050	6490	0.88	0.90	0.90
15/1/2004	28	9020	9130	7400	8020	8190	6690	0.89	0.90	0.90
21/1/2004	34	8310	N/A	8390	7370	6110	7320	0.89	N/A	0.87
	Avg.	**9147**	**9149**	**8927**	**8178**	**8058**	**7916**	**0.89**	**0.91**	**0.89**
	Std.dev	**807**	**664**	**1241**	**851**	**927**	**1157**	**0.02**	**0.01**	**0.01**

Table D.9 MLSS concentration at HRT 6h

Date	Day	MLSS			MLVSS			MLVSS/MLSS		
		SG-MBR	AG-MBR (moving media)	AG-MBR (fixed media)	SG-MBR	AG-MBR (moving media)	AG-MBR (fixed media)	SG-MBR	AG-MBR (moving media)	AG-MBR (fixed media)
22/9/2003	1	8140	7890	7560	7240	7020	6720	0.89	0.89	0.89
23/9/2003	2	8260	8060	7210	N/A	N/A	N/A	N/A	N/A	N/A
24/9/2003	3	8100	8180	6390	N/A	N/A	N/A	N/A	N/A	N/A
25/9/2003	4	8240	8390	7940	7240	7530	7060	0.88	0.90	0.89
26/9/2003	5	8070	8380	6790	7170	7660	6010	0.89	0.91	0.89
29/9/2003	8	8320	8040	6970	7390	7270	6130	0.89	0.90	0.88
1/10/2003	10	7500	8120	6070	6680	7300	5590	0.89	0.90	0.92
3/10/2003	12	6980	7670	7430	6270	6960	6580	0.90	0.91	0.89
6/10/2003	15	6470	6620	7300	6230	6350	6690	0.96	0.96	0.92
8/10/2003	17	6840	8270	6660	6040	7490	5930	0.88	0.91	0.89
10/10/2003	19	7010	7520	7620	6320	6830	6790	0.90	0.91	0.89
13/10/2010	22	7240	8370	8080	6490	7520	7210	0.90	0.90	0.89
15/10/2003	24	7460	8340	7040	6670	7430	6230	0.89	0.89	0.88
17/10/2003	26	7400	7160	6530	6380	6580	5700	0.86	0.92	0.87
18/10/2003	27	7500	7210	6420	N/A	N/A	N/A	N/A	N/A	N/A
20/10/2003	29	7380	7600	6470	6620	6880	5880	0.90	0.91	0.91
22/10/2003	31	8450	7730	8190	7580	7090	7440	0.90	0.92	0.91
24/10/2003	33	7690	7450	7510	7300	6710	6770	0.95	0.90	0.90
27/10/2003	36	7560	6700	7650	6830	6120	6950	0.90	0.91	0.91
28/10/2003	37	7550	6900	7540	6850	6270	6810	0.91	0.91	0.90

Table D.9 MLSS concentration at HRT 6h (Cont')

Date	Day	MLSS			MLVSS			MLVSS/MLSS		
		SG-MBR	AG-MBR (moving media)	AG-MBR (fixed media)	SG-MBR	AG-MBR (moving media)	AG-MBR (fixed media)	SG-MBR	AG-MBR (moving media)	AG-MBR (fixed media)
1/11/2003	41	7940	6070	7720	7150	5570	6980	0.90	0.92	0.90
6/11/2003	46	8080	5330	7470	7300	4970	6780	0.90	0.93	0.91
7/11/2003	47	7990	5720	8130	7190	5240	7360	0.90	0.92	0.91
9/11/2003	49	8050	6690	8220	7280	6160	7560	0.90	0.92	0.92
10/11/2003	50	7840	6630	8140	7050	6130	7340	0.90	0.92	0.90
12/11/2003	52	8670	7550	8990	7740	6930	8190	0.89	0.92	0.91
15/11/2003	55	7350	7490	8370	6610	6810	7510	0.90	0.91	0.90
17/11/2003	57	7630	7240	8380	6840	6640	7550	0.90	0.92	0.90
20/11/2003	60	7510	7700	7620	6590	6840	6800	0.88	0.89	0.89
24/11/2003	64	6700	8100	7970	6080	7340	7170	0.91	0.91	0.90
25/11/2003	65	7370	7950	6100	6590	7230	5520	0.89	0.91	0.90
27/11/2003	67	7010	7360	5990	6300	6720	5270	0.90	0.91	0.88
1/12/2003	71	8030	9630	7090	7220	8800	6440	0.90	0.91	0.91
3/12/2003	73	8190	8460	6770	7400	7710	6160	0.90	0.91	0.91
4/12/2003	74	8060	7870	6570	7100	7340	6060	0.88	0.93	0.92
8/12/2003	78	8760	8540	7570	7850	7860	6910	0.90	0.92	0.91
11/12/2003	81	8240	8060	7920	7400	7420	7100	0.90	0.92	0.90
13/12/2003	83	7750	8000	8470	7010	7390	7630	0.90	0.92	0.90
16/12/2003	86	8280	9120	9290	7452	8299	8361	0.90	0.91	0.90
	Avg.	**7734**	**7644**	**7440**	**6929**	**6956**	**6755**	**0.90**	**0.91**	**0.90**
	Std.dev	**542**	**864**	**806**	**479**	**781**	**736**	**0.02**	**0.01**	**0.01**

Table D.10 MLSS concentration at HRT 8h

Date	Day	MLSS			MLVSS			MLVSS/MLSS		
		SG-MBR	AG-MBR (moving media)	AG-MBR (fixed media)	SG-MBR	AG-MBR (moving media)	AG-MBR (fixed media)	SG-MBR	AG-MBR (moving media)	AG-MBR (fixed media)
25/6/2003	1	8960	10220	9600	N/A	N/A	N/A	N/A	N/A	N/A
27/6/2003	3	9860	10600	8530	8830	9480	7610	0.90	0.89	0.89
30/6/2003	6	7850	10450	7320	7040	9280	6570	0.90	0.89	0.90
3/7/2003	9	6930	9090	4850	6280	8140	4470	0.91	0.90	0.92
6/7/2003	12	6670	8840	4150	6090	8000	3910	0.91	0.90	0.94
8/7/2003	14	6740	8940	6440	5960	8520	6180	0.88	0.95	0.96
9/7/2003	15	6420	8100	4950	5770	7340	4550	0.90	0.91	0.92
12/7/2003	18	5810	7470	3700	5300	6770	3530	0.91	0.91	0.95
15/7/2003	21	5980	7980	5050	5510	7240	4590	0.92	0.91	0.91
18/7/2003	24	7030	7480	5670	6280	6740	5110	0.89	0.90	0.90
21/7/2003	27	6470	5700	4130	6090	5200	3840	0.94	0.91	0.93
24/7/2003	30	7810	6180	4520	6980	5660	4160	0.89	0.92	0.92
27/7/2003	33	7620	7090	6050	6900	6470	5380	0.91	0.91	0.89
29/7/2003	35	7460	6890	5480	6880	6370	4960	0.92	0.92	0.91
2/8/2003	39	7490	7390	6690	6910	6680	5980	0.92	0.90	0.89
4/8/2003	41	6590	7580	7540	5960	6920	6770	0.90	0.91	0.90
5/8/2003	42	6090	7310	7620	5440	6620	6850	0.89	0.91	0.90
6/8/2003	43	8160	7260	8450	7350	6310	7480	0.90	0.87	0.89
8/8/2003	45	6480	8620	9120	6180	8000	8420	0.95	0.93	0.92
9/8/2003	46	6200	7980	8420	N/A	N/A	N/A	N/A	N/A	N/A

Table D.10 MLSS concentration at HRT 8h (Cont')

Date	Day	MLSS			MLVSS			MLVSS/MLSS		
		SG-MBR	AG-MBR (moving media)	AG-MBR (fixed media)	SG-MBR	AG-MBR (moving media)	AG-MBR (fixed media)	SG-MBR	AG-MBR (moving media)	AG-MBR (fixed media)
10/8/2003	47	5910	8520	8380	N/A	N/A	N/A	N/A	N/A	N/A
12/8/2003	49	6700	9100	7910	N/A	N/A	N/A	N/A	N/A	N/A
13/8/2003	50	6190	8810	7920	N/A	N/A	N/A	N/A	N/A	N/A
15/8/2003	52	6140	7740	7220	5530	7230	6290	0.90	0.93	0.87
16/8/2003	53	6020	6800	7070	5490	6190	6350	0.91	0.91	0.90
20/8/2003	57	6520	7450	6910	5860	6720	6220	0.90	0.90	0.90
25/8/2003	62	6560	7690	6020	5960	6990	5520	0.91	0.91	0.92
28/8/2003	65	5980	7150	6060	5480	6530	5440	0.92	0.91	0.90
29/8/2003	66	6110	7010	5440	5480	6350	4940	0.90	0.91	0.91
30/8/2003	67	6130	6780	5170	5520	6130	4580	0.90	0.90	0.89
2/9/2003	69	6530	6390	5930	5860	5870	5370	0.90	0.92	0.91
3/9/2003	70	6220	6550	4580	5610	6000	4130	0.90	0.92	0.90
	Avg.	**6801**	**7582**	**6465**	**6168**	**6954**	**5526**	**0.91**	**0.91**	**0.91**
	Std.dev	**932**	**903**	**1597**	**791**	**1040**	**1260**	**0.02**	**0.02**	**0.02**

Appendix-E

Experimental Results at Different MLSS

Table E.1 Experimental result of TMP in suspended growth MBR at MLSS 6g/L

Date	Time (Days)	TMP (kPa)	Flux ($L/m^2.h$)	pH	DO (mg/L)
7/10/2004	1	6.93	7.14	7.75	2.6
8/10/2004	2	6.93	7.14	7.76	2.1
9/10/2004	3	6.93	7.14	7.65	2.2
10/10/2004	4	6.93	7.14	7.74	2.1
11/10/2004	5	7.47	7.14	7.64	2.5
12/10/2004	6	7.47	7.29	7.74	2.5
13/10/2004	7	7.47	7.14	7.52	3.5
14/10/2004	8	7.47	7.14	7.64	2.6
15/10/2004	9	7.47	7.14	7.45	2.6
16/10/2004	10	7.47	7.14	7.56	1.7
17/10/2004	11	7.47	7.14	7.65	2.1
18/10/2004	12	7.47	7.14	7.72	2.2
19/10/2004	13	7.47	7.14	7.46	2.3
20/10/2004	14	7.47	7.14	7.61	2.4
21/10/2004	15	7.47	7.14	7.27	2.0
22/10/2004	16	8.53	7.00	7.80	2.4
23/10/2004	17	8.53	7.00	7.52	2.6
24/10/2004	18	9.47	7.14	7.40	4.2
25/10/2004	19	10.00	7.14	7.61	2.5
26/10/2004	20	9.60	7.14	7.67	2.3
27/10/2004	21	10.94	7.00	7.61	5.2
28/10/2004	22	14.80	7.29	7.58	2.0
29/10/2004	23	17.34	7.00	7.56	2.5
30/10/2004	24	28.54	7.14	7.63	1.7
31/10/2004	25	44.27	7.14	7.58	1.8
1/11/2004	26	59.34	7.14	7.56	2.0
Average				**7.60**	**2.5**
Std.dev				**0.12**	**0.8**

Table E.2 Experimental result of TMP in attached growth MBR with moving media at MLSS 6g/L

Date	Time (Days)	TMP (kPa)	Flux ($L/m^2.h$)	pH	DO (mg/L)
7/10/2004	1	6.93	7.43	7.69	1.0
8/10/2004	2	6.93	7.43	7.65	0.8
9/10/2004	3	6.93	7.43	7.60	1.2
10/10/2004	4	6.93	7.43	7.62	1.8
11/10/2004	5	7.60	7.14	7.60	0.5
12/10/2004	6	6.93	7.14	7.76	1.8
13/10/2004	7	6.93	7.29	7.70	2.6
14/10/2004	8	7.20	7.29	7.63	1.8
15/10/2004	9	7.20	7.29	7.51	1.9
16/10/2004	10	7.33	7.29	7.52	1.8
17/10/2004	11	7.33	7.29	7.57	1.5
18/10/2004	12	7.33	7.29	7.60	1.4
19/10/2004	13	7.33	7.29	7.54	3.0
20/10/2004	14	7.33	7.29	7.63	2.3
21/10/2004	15	7.33	7.29	7.34	1.9
22/10/2004	16	7.60	7.43	7.77	3.0
23/10/2004	17	7.60	7.43	7.65	2.7
24/10/2004	18	8.00	7.14	7.50	3.4
25/10/2004	19	8.00	7.14	7.53	2.5
26/10/2004	20	7.87	7.14	7.56	2.6
27/10/2004	21	7.73	7.14	7.55	2.5
28/10/2004	22	7.87	7.14	7.51	2.0
29/10/2004	23	7.87	7.29	7.53	2.5
30/10/2004	24	7.87	7.14	7.51	2.0
31/10/2004	25	7.87	7.14	7.58	1.6
1/11/2004	26	7.87	7.14	7.65	1.8
Average				**7.59**	**2.0**
Std.dev				**0.09**	**0.7**

Table E.3 Experimental result of TMP in suspended growth MBR at MLSS 10 g/L

Date	Time (Days)	TMP (kPa)	Flux ($L/m^2.h$)	pH	DO (mg/L)
3/11/2004	1	7.87	6.86	7.65	3.4
4/11/2004	2	10.54	6.86	7.78	3.4
5/11/2004	3	13.74	7.14	7.86	2.5
6/11/2004	4	24.14	7.14	7.82	3.6
7/11/2004	5	41.61	7.14	7.78	2.9
8/11/2004	6	74.28	5.00	7.73	5.3
9/11/2004	7	7.87	7.14	7.70	1.8
10/11/2004	8	9.60	7.14	7.85	3.3
11/11/2004	9	10.94	7.00	7.75	5.8
12/11/2004	10	12.00	7.14	7.81	2.6
13/11/2004	11	25.87	7.14	7.78	2.0
14/11/2004	12	56.01	7.14	7.71	1.9
15/11/2004	13	72.01	5.29	7.71	1.9
16/11/2004	14	6.67	7.14	7.79	1.0
17/11/2004	15	6.67	7.14	7.75	1.2
18/11/2004	16	6.67	7.14	7.82	1.4
19/11/2004	17	6.67	7.14	7.83	1.5
20/11/2004	18	7.07	7.14	7.75	2.1
21/11/2004	19	7.07	7.00	7.75	2.0
22/11/2004	20	7.07	7.14	7.71	2.9
23/11/2004	21	7.47	7.14	7.76	2.4
24/11/2004	22	7.47	7.14	7.75	2.4
25/11/2004	23	7.47	7.14	7.84	2.8
26/11/2004	24	7.47	7.14	7.76	3.5
27/11/2004	25	7.47	7.14	7.79	3.2
28/11/2004	26	9.33	7.14	7.69	3.2
29/11/2004	27	22.27	7.14	7.85	2.3
30/11/2004	28	26.54	7.14	7.81	2.3
1/12/2004	29	32.14	7.14	7.80	3.2
2/12/2004	30	39.21	7.14	7.61	2.5
3/12/2004	31	64.01	5.00	7.74	2.5
4/12/2004	32	7.87	7.14	7.61	3.3
5/12/2004	33	7.73	7.14	7.41	2.0
6/12/2004	34	11.60	7.14	7.82	2.5
7/12/2004	35	22.94	7.14	7.60	2.2
8/12/2004	36	38.27	7.14	7.78	2.7
9/12/2004	37	65.34	5.00	7.50	3.0
10/12/2004	38	7.47	7.14	6.99	3.5

Table E.3 Experimental result of TMP in suspended growth MBR at MLSS 10 g/L (Cont')

Date	Time (Days)	TMP (kPa)	Flux ($L/m^2.h$)	pH	DO (mg/L)
11/12/2004	39	7.47	7.00	7.62	3.8
12/12/2004	40	7.87	7.14	7.74	3.9
13/12/2004	41	7.87	7.14	7.66	3.6
14/12/2004	42	10.14	7.00	7.40	4.5
15/12/2004	43	18.14	7.14	7.73	2.0
16/12/2004	44	32.01	7.14	7.74	2.7
17/12/2004	45	69.34	5.71	7.89	2.7
18/12/2004	46	7.87	7.29	7.58	4.5
19/12/2004	47	7.87	7.14	7.53	2.4
20/12/2004	48	8.00	7.14	7.49	3.3
21/12/2004	49	8.00	7.14	7.75	3.5
22/12/2004	50	8.53	7.14	7.74	3.8
23/12/2004	51	9.07	7.14	7.71	2.5
24/12/2004	52	18.40	7.14	7.61	2.8
25/12/2004	53	64.01	5.71	7.80	3.7
26/12/2004	54	N/A	N/A	N/A	N/A
27/12/2004	55	N/A	N/A	N/A	N/A
28/12/2004	56	N/A	N/A	N/A	N/A
29/12/2004	57	N/A	N/A	N/A	N/A
30/12/2004	58	N/A	N/A	N/A	N/A
31/12/2004	59	7.33	7.14	7.83	3.3
1/1/2005	60	7.07	7.14	7.92	2.4
2/1/2005	61	6.80	7.14	7.81	1.0
3/1/2005	62	6.80	7.14	7.87	5.9
4/1/2005	63	6.80	7.14	7.91	1.2
5/1/2005	64	8.93	7.14	7.76	2.2
6/1/2005	65	22.94	7.14	7.75	2.6
7/1/2005	66	47.87	7.14	7.73	2.5
8/1/2005	67	69.21	6.29	7.68	2.0
9/1/2005	68	7.33	7.14	6.30	5.5
10/1/2005	69	10.94	7.14	7.79	2.2
11/1/2005	70	19.07	7.29	7.76	2.3
12/1/2005	71	46.54	7.14	7.76	2.4
13/1/2005	72	69.34	4.00	7.65	3.2
Average				**7.70**	**2.8**
Std.dev				**0.22**	**1.0**

Table E.4 Experimental result of TMP in attached growth MBR with moving media at MLSS 10 g/L

Date	Time (Days)	TMP (kPa)	Flux ($L/m^2.h$)	pH	DO (mg/L)
3/11/2004	1	7.33	7.29	7.76	2.3
4/11/2004	2	7.33	7.14	7.84	2.5
5/11/2004	3	7.33	7.14	7.89	2.3
6/11/2004	4	7.33	7.14	7.81	3.4
7/11/2004	5	7.60	7.14	7.68	2.3
8/11/2004	6	7.60	7.14	7.78	1.2
9/11/2004	7	8.00	7.14	7.63	2.7
10/11/2004	8	8.40	7.14	7.81	2.1
11/11/2004	9	8.40	7.14	7.82	1.9
12/11/2004	10	8.40	7.14	7.85	1.8
13/11/2004	11	8.40	7.14	7.85	2.1
14/11/2004	12	9.87	7.14	7.82	1.8
15/11/2004	13	9.87	7.14	7.77	2.0
16/11/2004	14	10.80	7.00	7.88	3.1
17/11/2004	15	12.67	7.00	7.75	2.2
18/11/2004	16	12.67	7.00	7.84	1.9
19/11/2004	17	12.67	7.14	7.80	2.4
20/11/2004	18	12.94	7.14	7.69	1.6
21/11/2004	19	13.07	7.14	7.81	2.0
22/11/2004	20	14.14	7.14	7.70	2.4
23/11/2004	21	16.67	7.14	7.71	2.6
24/11/2004	22	15.60	7.14	7.69	2.4
25/11/2004	23	16.14	7.00	7.85	2.4
26/11/2004	24	16.67	7.14	7.73	3.5
27/11/2004	25	16.40	7.14	7.78	3.2
28/11/2004	26	17.74	7.14	7.64	2.3
29/11/2004	27	19.07	7.14	7.83	2.2
30/11/2004	28	20.80	7.14	7.85	2.8
1/12/2004	29	19.74	7.14	7.82	3.4
2/12/2004	30	20.27	7.00	7.58	0.8
3/12/2004	31	19.74	7.14	7.47	3.2
4/12/2004	32	20.67	7.14	7.56	1.3
5/12/2004	33	19.74	7.14	7.42	1.5
6/12/2004	34	20.80	7.00	7.82	1.2
7/12/2004	35	21.20	7.14	7.76	1.2
8/12/2004	36	22.67	7.14	7.73	1.8
9/12/2004	37	25.60	7.00	7.53	2.2
10/12/2004	38	26.67	7.14	7.75	1.0

Table E.4 Experimental result of TMP in attached growth MBR with moving media at MLSS 10 g/L (Cont')

Date	Time (Days)	TMP (kPa)	Flux ($L/m^2.h$)	pH	DO (mg/L)
11/12/2004	39	26.67	7.00	7.56	0.9
12/12/2004	40	26.94	7.14	7.72	2.0
13/12/2004	41	27.87	7.14	7.58	2.0
14/12/2004	42	29.07	7.00	7.37	2.2
15/12/2004	43	30.14	7.14	7.65	1.0
16/12/2004	44	31.21	7.14	7.66	1.9
17/12/2004	45	32.01	7.14	7.92	2.4
18/12/2004	46	31.87	7.29	7.76	1.8
19/12/2004	47	32.41	7.14	7.60	1.6
20/12/2004	48	33.34	7.14	7.45	1.8
21/12/2004	49	55.48	5.00	7.64	2.7
22/12/2004	50	7.33	7.29	7.52	2.1
23/12/2004	51	7.33	7.14	7.58	1.6
24/12/2004	52	7.47	7.14	7.60	5.7
25/12/2004	53	7.47	7.14	7.55	0.3
26/12/2004	54	7.47	7.14	7.23	0.2
27/12/2004	55	7.60	7.14	7.33	1.5
28/12/2004	56	7.47	7.14	7.21	2.0
29/12/2004	57	7.47	7.14	7.10	1.8
30/12/2004	58	7.87	7.14	7.47	1.9
31/12/2004	59	7.60	7.14	7.78	4.9
1/1/2005	60	7.60	7.14	7.88	4.9
2/1/2005	61	8.27	7.14	7.83	5.6
3/1/2005	62	8.40	7.14	7.85	6.0
4/1/2005	63	8.53	7.14	7.87	2.0
5/1/2005	64	8.40	7.14	7.72	1.9
6/1/2005	65	8.13	7.14	7.76	1.1
7/1/2005	66	8.13	7.29	7.74	1.4
8/1/2005	67	8.13	7.14	7.70	2.0
9/1/2005	68	8.13	7.14	7.73	1.7
10/1/2005	69	8.13	7.29	7.68	1.4
11/1/2005	70	8.13	7.14	7.68	1.0
12/1/2005	71	8.13	7.29	7.66	1.1
13/1/2005	72	8.13	7.14	7.79	2.1
Average				**7.78**	**2.3**
Std.dev				**0.07**	**0.5**

Table E.5 Experimental result of TMP in suspended growth MBR at MLSS 15 g/L

Date	Time (Days)	TMP (kPa)	Flux ($L/m^2.h$)	pH	DO (mg/L)
7/2/2005	1.0	9.07	7.14	7.49	3.5
7/2/2005	1.5	30.67	7.14		
8/2/2005	2.0	63.34	5.43	7.50	1.7
8/2/2005	2.5	76.01	3.57		
9/2/2005	3.0	7.07	7.14	7.55	1.3
9/2/2005	3.5	74.41	2.86		
10/2/2005	4.0	8.40	7.14	7.54	1.1
10/2/2005	4.5	75.21	3.57		
11/2/2005	5.0	7.20	7.14	7.72	1.2
11/2/2005	5.5	47.21	6.43		
12/2/2005	6.0	62.94	4.57	7.51	1.1
12/2/2005	6.5	79.35	4.29		
13/2/2005	7.0				
13/2/2005	7.5	N/A	N/A	N/A	N/A
14/2/2005	8.0				
14/2/2005	8.5	7.33	7.14	7.69	1.8
15/2/2005	9.0	10.00	7.14	7.71	1.2
15/2/2005	9.5				
16/2/2005	10.0	67.61	3.57	7.55	2.0
16/2/2005	10.5				
17/2/2005	11.0	7.73	7.14	7.55	3.2
17/2/2005	11.5	23.07	7.14		
18/2/2005	12.0	75.61	4.71	7.70	1.2
18/2/2005	12.5	10.00	7.14		
19/2/2005	13.0	66.41	4.14	7.60	1.0
19/2/2005	13.5	7.07	7.14		
20/2/2005	14.0	22.67	7.14	7.65	1.4
20/2/2005	14.5				
21/2/2005	15.0	71.08	6.00	7.58	1.9
21/2/2005	15.5	7.73	7.14		
22/2/2005	16.0	12.67	7.14	7.72	3.5
22/2/2005	16.5				
23/2/2005	17.0	17.07	7.00	7.79	2.0
23/2/2005	17.5				
24/2/2005	18.0	69.21	4.43	7.64	1.0
24/2/2005	18.5	7.33	7.14		
25/2/2005	19.0	77.35	3.57	7.64	1.1
25/2/2005	19.5	8.13	7.14		
26/2/2005	20.0	39.34	7.14	7.76	1.2
26/2/2005	20.5				

Table E.5 Experimental result of TMP in suspended growth MBR at MLSS 15 g/L (Cont')

Date	Time (Days)	TMP (kPa)	Flux ($L/m^2.h$)	pH	DO (mg/L)
27/2/2005	21.0	60.01	5.71	7.64	2.0
27/2/2005	21.5				
28/2/2005	22.0	75.61	4.29	7.72	1.2
28/2/2005	22.5	7.07	7.14		
1/3/2005	23.0	8.93	7.14	7.69	1.0
1/3/2005	23.5				
2/3/2005	24.0	9.60	7.14	7.72	2.0
2/3/2005	24.5				
3/3/2005	25.0	13.20	7.14	7.73	0.8
3/3/2005	25.5				
4/3/2005	26.0	14.80	7.14	7.74	2.2
4/3/2005	26.5				
5/3/2005	27.0	16.54	7.14	7.72	1.3
5/3/2005	27.5				
Average				**7.65**	**1.7**
Std.dev				**0.09**	**0.8**

Table E.6 Experimental result of TMP in attached growth MBR with moving media at MLSS 15 g/L

Date	Time (Days)	TMP (kPa)	Flux ($L/m^2.h$)	pH	DO (mg/L)
7/2/2005	1.0	8.13	7.14	7.70	1.1
7/2/2005	1.5	8.25			
8/2/2005	2.0	8.40	7.14	7.68	1.8
8/2/2005	2.5	8.40			
9/2/2005	3.0	8.40	7.14	7.62	4.4
9/2/2005	3.5	8.40			
10/2/2005	4.0	8.40	7.14	7.74	1.0
10/2/2005	4.5	8.40			
11/2/2005	5.0	8.40	7.14	7.75	1.5
11/2/2005	5.5	10.00			
12/2/2005	6.0	10.00	7.14	7.72	1.0
12/2/2005	6.5	10.00			
13/2/2005	7.0	10.00	7.14	7.70	1.3
13/2/2005	7.5	10.00			
14/2/2005	8.0	9.73	7.00	7.78	1.3
14/2/2005	8.5	10.00			
15/2/2005	9.0	10.27	7.00	7.64	1.4
15/2/2005	9.5				
16/2/2005	10.0	13.34	7.14	7.64	1.5
16/2/2005	10.5				
17/2/2005	11.0	15.34	7.14	7.68	1.2
17/2/2005	11.5	15.34			
18/2/2005	12.0	15.07	7.14	7.63	0.8
18/2/2005	12.5	15.34			
19/2/2005	13.0	16.27	7.14	7.60	1.2
19/2/2005	13.5	16.27			
20/2/2005	14.0	16.40	7.14	7.62	1.6
20/2/2005	14.5				
21/2/2005	15.0	17.20	7.14	7.57	1.7
21/2/2005	15.5	17.40			
22/2/2005	16.0	17.60	7.14	7.66	1.0
22/2/2005	16.5				
23/2/2005	17.0	18.54	7.14	7.74	1.2
23/2/2005	17.5				
24/2/2005	18.0	19.87	7.14	7.59	1.2
24/2/2005	18.5				
25/2/2005	19.0	21.20	7.14	7.72	1.2
25/2/2005	19.5	21.20			
26/2/2005	20.0	21.20	7.14	7.74	2.0
26/2/2005	20.5	22.00			

Table E.6 Experimental result of TMP in attached growth MBR with moving media at MLSS 15 g/L (Cont')

Date	Time (Days)	TMP (kPa)	Flux ($L/m^2.h$)	pH	DO (mg/L)
27/2/2005	21.0	22.67	7.14	7.51	1.5
27/2/2005	21.5	23.50			
28/2/2005	22.0	24.40	7.14	7.63	1.6
28/2/2005	22.5				
1/3/2005	23.0	25.20	7.14	7.66	1.1
1/3/2005	23.5				
2/3/2005	24.0	26.54	7.14	7.68	1.0
2/3/2005	24.5				
3/3/2005	25.0	29.34	7.14	7.65	1.2
3/3/2005	25.5				
4/3/2005	26.0	32.54	7.14	7.68	1.0
4/3/2005	26.5				
5/3/2005	27.0	49.34	7.00	7.70	0.8
5/3/2005	27.5				
Average				**7.67**	**1.4**
Std.dev				**0.06**	**0.7**

Table E.7 MLSS and MLVSS concentration at the condition of 6g/L MLSS

Date	Time	MLSS (mg/L)		MLVSS (mg/L)		MLVSS/MLSS	
	(Days)	SG-MBR	AG-MBR	SG-MBR	AG-MBR	SG-MBR	AG-MBR
7/10/2004	1	7000	6940	6220	6120	0.89	0.88
8/10/2004	2	7400	8640	6840	7700	0.92	0.89
12/10/2004	6	8340	7880	N/A	N/A	N/A	N/A
13/10/2004	7	7100	8140	6440	7460	0.91	0.92
14/10/2004	8	5920	5700	5540	5400	0.94	0.95
15/10/2004	9	6040	6120	5760	5660	0.95	0.92
18/10/2004	12	6800	7320	6300	6620	0.93	0.90
19/10/2004	13	6000	5760	5660	5380	0.94	0.93
20/10/2004	14	5820	6060	5360	5560	0.92	0.92
21/10/2004	15	6760	6800	6240	6220	0.92	0.91
24/10/2004	18	5460	5440	5060	5120	0.93	0.94
26/10/2004	20	6220	5900	5840	5700	0.94	0.97
28/10/2004	22	6060	6280	5880	5640	0.97	0.90
30/10/2004	24	6760	6420	6100	5900	0.90	0.92
Average		**6549**	**6671**	**5942**	**6037**	**0.93**	**0.92**
Std.		**765**	**992**	**481**	**791**	**0.02**	**0.02**

Note: SG-MBR (Suspended growth MBR)
AG-MBR (Attached growth MBR with moving media)

Table E.8 MLSS and MLVSS concentration at the condition of 10g/L MLSS

Date	Time	MLSS (mg/L)		MLVSS (mg/L)		MLVSS/MLSS	
	(Days)	SG-MBR	AG-MBR	SG-MBR	AG-MBR	SG-MBR	AG-MBR
4/11/2004	1	8720	10140	8240	9440	0.94	0.93
5/11/2004	2	10560	12360	9800	11360	0.93	0.92
6/11/2004	3	11020	9460	10280	8760	0.93	0.93
8/11/2004	5	10280	9560	9740	8860	0.95	0.93
9/11/2004	6	10520	10220	9780	9400	0.93	0.92
10/11/2004	7	11500	10080	10680	9400	0.93	0.93
12/11/2004	9	9900	9520	9140	8700	0.92	0.91
16/11/2004	13	9180	9360	8960	8600	0.98	0.92
17/11/2004	14	10260	9760	9400	8840	0.92	0.91
20/11/2004	17	9300	8800	8760	8020	0.94	0.91
23/11/2004	20	11200	9580	9480	8520	0.85	0.89
29/11/2004	26	9460	10000	8780	9120	0.93	0.91
30/11/2004	27	9960	9900	9220	9060	0.93	0.92
2/12/2004	29	9940	9800	9000	8800	0.91	0.90
7/12/2004	34	9120	10500	8340	9560	0.91	0.91
9/12/2004	36	8360	9460	7760	8640	0.93	0.91
10/12/2004	37	7320	9920	6760	9060	0.92	0.91
13/12/2004	40	7320	8140	6760	7520	0.92	0.92
14/12/2004	41	8240	9160	7580	8320	0.92	0.91
15/12/2004	42	9060	10040	8360	9200	0.92	0.92
17/12/2004	44	9380	10320	8740	9600	0.93	0.93
20/12/2004	47	8640	9360	8000	8660	0.93	0.93
23/12/2004	50	10180	9600	9500	9000	0.93	0.94
6/1/2005	64	8040	10680	7620	9760	0.95	0.91
7/1/2005	65	9680	11880	8720	10860	0.90	0.91
Average		**9486**	**9904**	**8776**	**9082**	**0.93**	**0.92**
Std.		**1118**	**858**	**998**	**795**	**0.02**	**0.01**

Note: SG-MBR (Suspended growth MBR)
AG-MBR (Attached growth MBR with moving media)

Table E.9 MLSS and MLVSS concentration at the condition of 15g/L MLSS

Date	Time	MLSS (mg/L)		MLVSS (mg/L)		MLVSS/MLSS	
	(Days)	SG-MBR	AG-MBR	SG-MBR	AG-MBR	SG-MBR	AG-MBR
1/2/2005	1	N/A	15240	N/A	N/A	N/A	N/A
2/2/2005	2	N/A	15200	N/A	N/A	N/A	N/A
7/2/2005	7	12820	12760	11860	11840	0.93	0.93
9/2/2005	9	11820	11560	10940	10500	0.93	0.91
11/2/2005	11	11640	14960	10476	13464	0.90	0.90
15/2/2005	15	12480	16800	11540	15660	0.92	0.93
16/2/2005	16	13480	18400	12820	17260	0.95	0.94
17/2/2005	17	14700	16780	13580	15500	0.92	0.92
21/2/2005	21	15080	16020	12900	13120	0.86	0.82
22/2/2005	22	14580	15620	13360	13960	0.92	0.89
25/2/2005	25	13940	13560	13040	12460	0.94	0.92
28/2/2005	28	13100	14540	11790	13240	0.90	0.91
1/3/2005	29	17000	15960	15540	14520	0.91	0.91
4/3/2005	32	16960	15680	14100	13700	0.83	0.87
9/3/2005	37	19760	16800	17780	15120	0.90	0.90
Average		**14412**	**15325**	**13056**	**13873**	**0.91**	**0.90**
Std.		**2342**	**1725**	**1968**	**1779**	**0.03**	**0.03**

Note: SG-MBR (Suspended growth MBR)
AG-MBR (Attached growth MBR with moving media)

Appendix-F

Sludge Management in MBR

Sludge Management in MBR

Excess Sludge Production in MBR

The biological process of wastewater results in the generation of an excess activated sludge that has to be wasted. Excess sludge has to be properly treated prior to final disposal, even though the cost of sludge treatment is extremely high. The treatment of the excess sludge may account up to 50-60% of the total plant operation cost (Egemen *et al.* 2001). It should be noted that biomass production is an important economic factor because the sludge generated in the form of secondary waste must be disposed in an environmentally sound and cost effective manner. The excess sludge production in the suspended and attached growth MBRs can be calculated by the following equations below.

Excess sludge production = [Q_w (L/d) x MLSS (g/L)]/ Q (L/d)

where Q is influent flow rate and Q_w is wastage sludge. The amount of excess sludge produced per volume of wastewater treated in MBR operation is given in Table 4.16.

Table F.1 Amount of excess sludge production per volume of wastewater treated

MLSS (g/L)	Influent flow rate (L/d)	Suspended growth MBR		Attached growth MBR	
		Sludge Wastage (L/d)	Excess sludge production (kg/m^3)	Wastage sludge (L/d)	Excess sludge production (kg/m^3)
6	72	0.8	0.07	1.0	0.08
10	72	0.4	0.06	0.5	0.07
15	72	0.1	0.02	0.15	0.03

According to Table F.1, it was found that excess sludge production in the attached and suspended growth MBRs was found to be relatively similar. Table F.2 compares excess sludge production in MBR system of this study with other recent studies. It can be observed that excess sludge production varied according to the operating conditions. Therefore, considering the variability of reactor operation and assumptions used in the calculation, it is difficult to ascertain that attached growth results in higher sludge production as compare to suspended growth system.

Table F.2 Excess sludge production (ESP) in MBR system

System	Operating conditions	ESP (kg/d)	Reference
Suspended growth MBR	HRT 2 h: MLSS 6 g/L	0.005	This study
	MLSS 10 g/L	0.004	
	MLSS 15 g/L	0.002	
Attached growth MBR	HRT 2 h: MLSS 6 g/L	0.006	
	MLSS 10 g/L	0.005	
	MLSS 15 g/L	0.002	
Suspended growth MBR	HRT 12h: MLSS 7 g/L	0.003	Han *et al.* (2005)
	MLSS 10 g/L	0.002	
	MLSS 14 g/L	0.002	
	MLSS18 g/L	0.002	
Suspended growth MBR	HRT 5 hrs, SRT 30 d	0.075	Xing *et al.* (2003)
	HRT 5 hrs, SRT 60 d	0.054	
	HRT 5 hrs, SRT 100 d	0.039	
Suspended growth MBR (Pilot scale)	HRT 6 hrs, SRT 30 d.	0.014	Cicek *et al.* (1999)

4.3.2 Sludge Management Plan

The application of this work can be applied to a compact wastewater treatment plant providing the attached growth MBR with the ability to withstand high organic loading. As an example, one can apply this MBR concept to a residential complex building in Bangkok, Thailand. Figure F.1 shows concept of the attached growth MBR to full scale application. The sludge management plan for the excess sludge produced from this system is proposed as follows:

Assume five buildings in a residential complex with one building having 20 floors and each floor having five units. Further, it can be assumed that each unit can accommodate two persons on average. So, total population can be 1,000 persons for residential complex.

Assumptions:

1. Maximum wastewater production is 200 L/d per person
2. BOD concentration of wastewater is 100 mg/L
3. Maximum organic loading rate is 6.3 kg COD/m^3.d (Loading rate based on 500 mg-COD/L and HRT 2 h in laboratory-scale MBR)

Calculation: For five buildings in a residential complex

Total wastewater production is 200 L/d per person x 1000 persons = 200 m^3/d

Total BOD concentration is 100 mg/L = 0.1 kg/m^3

Volume of MBR reactor based on loading rate of 6.3 kg COD/m^3.d (Assume COD=BOD)

$$\text{Loading rate (kgCOD/m}^3\text{.d)} = \text{COD (kg/m}^3\text{) x Q (m}^3\text{/d) / V (m}^3\text{)}$$

$$6.3\ \text{(kgCOD/m}^3\text{.d)} = [0.1\ \text{kg/m}^3 \times 200\ \text{m}^3\text{/d}\ ] / V(\text{m}^3)$$

$$V = 3.2\ \text{m}^3$$

This MBR system can be installed in the basement of each building which should have an estimated working volume of (3.2m^3/5) 0.64 m^3

From this research work (Table 4.18), excess sludge production was about 0.07 kg/m^3 at 10g/L of MLSS from the attached growth MBR.

So, Total excess sludge produced for the population of 1,000 persons is

$$0.07\ \text{kg/m}^3 \times 200\ \text{m}^3\text{/d} = 14\ \text{kg/d}$$

The anaerobic digester and subsequent filter press can be designed based on sludge loading of 28 kg/d. The two fold increase in the design loading is based on incorporating addition of residential buildings to the current complex setup. Addition of new building with same residential capacity would require an installation of an MBR in the basement and connecting it to the excess sludge treatment zone.

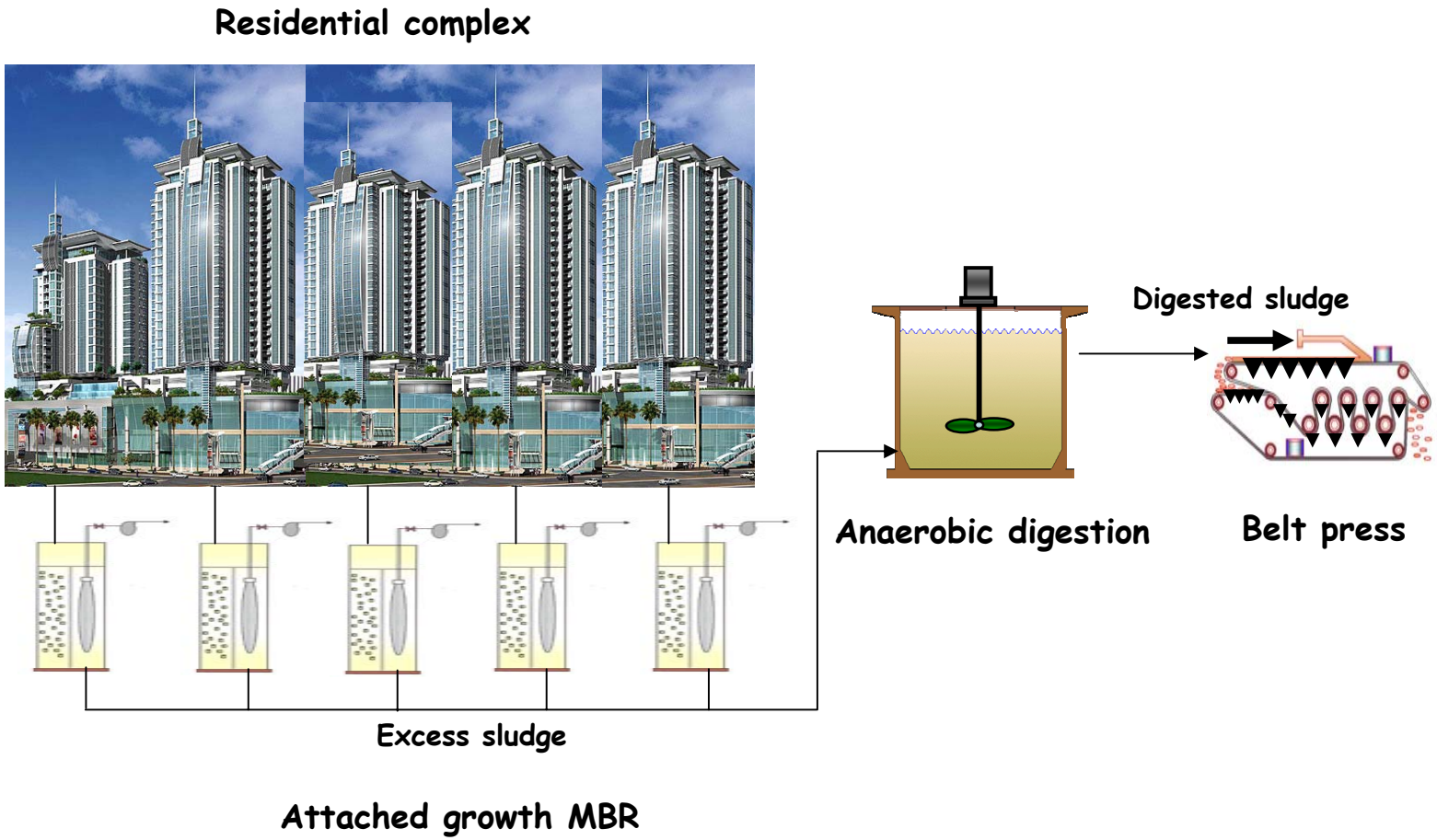

Figure F.1 Concept of the attached growth MBR to full scale application