COMPARISON OF NITROGEN REMOVAL BETWEEN CONVENTIONAL MEMBRANE BIOREACTOR AND ATTACHED GROWTH MEMBRANE BIOREACTOR

by

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Abstract

In this study two MBR systems were experimentally investigated. One was conventional suspended growth MBR with aeration and the other with attached growth MBR with sponge media to compare the nitrogen removal efficiencies and fouling characteristics. There were two types of media; namely cylindrical polypropylene and porous sponge (cubic). After a preliminary study sponge media was selected based on COD and TN removal efficiencies as the attached growth media. In most of the previous literature attached growth MBR used with a moving bed configuration. But in this study a partially fixed bed (media allowed to have a limited movement) was used under low dissolved oxygen (DO) concentration. Experiment was conducted for three different HRT values; namely 10 h, 7 h and 13 h and the organic loading rate (OLR) and nitrogen loading rate (NLR) were kept constants at 2.2 to 2.4 kg COD /m^3.d and 0.4 kg N/m^3.d respectively.

There was no significant difference in COD removal rate was observed during the MBR analysis for both conventional and attached growth (sponge media) MBR systems. Furthermore it was observed a similar COD removal rate for attached growth MBR and conventional MBR. In general the COD removal was not affected by the HRT variation during the study period. It was observed that the biomass assimilation was the major mechanism for total nitrogen (TN) removal in conventional MBR while simultaneous nitrification-denitrification (SND) was the dominating mechanism for sponge media MBR.

HRT 10 h was observed to be the most appropriate operational condition to operate the sponge media reactor. It was observed a 98% COD removal rate and 86% TN removal rate during the operation under 10 h HRT. Similarly it was observed a highest SND rate (around 70%) under 10 h HRT and SND rates for HRT 7 h and 13 h were observed as 20% and 42% respectively in the sponge reactor.

Both the systems were operated more than 70 days during the 10 h HRT, without membrane fouling. Attached growth system showed 1.5 times greater fouling propensity than the conventional reactor under the operation of 7 h HRT. Fouling rates for attached growth and conventional reactors were found to be 0.058 and 0.056 kPa/d respectively for 13 h HRT. The study further revealed that there was no significant relationship between EPS and membrane fouling for all HRT values.

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List of Abbreviations

A	Membrane surface area
AFM	Atomic Force Microscope
BAF	Biological Aerated Filter
BF	Biofilm
BOD	Biochemical Oxygen Demand
CAS	Conventional Activated Sludge
C_b	Concentration of the particles,
CFV	Cross Flow Velocity
COD	Chemical Oxygen Demand
CP	Cylindrical Polypropylene
CST	Capillary Suction Time
DO	Dissolved Oxygen
DOC	Dissolved Organic Compounds
EPS	Extracellular Polymeric Substances
FISH	Fluorescent Insitu Hybridization
HRT	Hydraulic Retention Time
J	Permeate Flux
LC	Low Calcium
MBR	Membrane Bioreactor
MCMBBR	Membrane Coupled Moving Bed Biofilm Reactor
MFI	Membrane Fouling Index
mg/L	Milligram per liter
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
MWCO	Molecular Weight Cut Off
OC	Optimum Calcium
OLR	Organic Loading Rate
OSBG	Optimum Support for Biological Growth
Pa.s	Pascal Seconds
PCR	Polymerase Chain Reaction
PE	Poly Ethylene
PS	Polyethylene Sponge
PUS	Polyester Urethane Sponge
PVDF	Polyvinylidene Fluoride
Q	Influent Flow Rate
R_c	Cake Resistance
R_f	Fouling Resistance
R_m	Intrinsic Membrane Resistance
R_t	Total Membrane Resistance
S_0	Influent BOD or COD Concentration
SBR	Sequencing Batch Reactor
SEM	Scanning Electron Microscope
SND	Simultaneous Nitrification Denitrification
SRT	Sludge Retention Time
SSMBR	Sponge Submerged Membrane Bio reactor
t/V	Time/Volume
TKN	Total Kjedahl Nitrogen

TMP	Transmembrane Pressure
TN	Total Nitrogen
TP	Total Phosphorous
UF	Ultra Filtration
V	Volume
VSS	Volatile Suspended Solids
α	Specific Resistance
ΔP	Transmembrane Pressure
μ	Viscosity

Chapter 1

Introduction

1.1 Background

Biological treatment of domestic wastewater by conventional activated sludge process (CAS) has been practicing for more than 100 years. Since then activated sludge process modified numerous times in order to produce higher quality effluent. Even at present conventional activated sludge process considered as one of the most widely used and most economical ways of treating wastewater containing organic pollutants. Due to the stringent rules and regulations in disposal of treated effluent to environment now a days there is a bloom in finding new treatment methods and process modifications to existing processes. Urbanization and increasing urban population increase the wastewater generation while reducing the available land area to build new treatment facilities. In order to face this challenge there is necessity of finding new treatment method which can produce higher quality effluent while having minimum foot print.

Operational problems drastically reduced the efficiency of conventional activated sludge process. Most common operational problems in CAS are sludge bulking, sludge rising and Nocardia foam. Therefore generally CAS needs more attention by conducting frequent analytical tests and having an experienced crew to look after the system. Higher hydraulic retention time requirement is another drawback of CAS and this leads to higher tank volumes, finally end up in large foot print. Situation becomes worse when treating wastewater for nutrients in wastewater such as nitrogen and phosphorus, because the removal takes more time compared to other organic matter.

Membrane bioreactor (MBR) was introduced in order to overcome some of the draw backs identified in the conventional activated sludge (CAS) process. MBR is nothing but an aeration tank having membrane units to recover water from the mixed liquor in the aeration tank. The MBR was originally introduced by Dorr-Olivier Inc. in late 1960s using Micro filtration membrane units (Le-Clech *et al*., 2006). Since then MBR is being used as an efficient way of solid liquid separation in treating wastewater.

There are many advantages of MBR over CAS systems. Mostly MBR processes are popular because of its less land requirement (smaller foot print) and reactor requirement, higher effluent quality (Judd, 2006) and easiness in upgrading. Basically operation problems like sludge bulking, sludge rising and Norcardia form do not occur in MBR process. Thus it needs minimum attention with compared to other biological processes. Other than these, MBR systems are highly tolerable to shock loadings and these systems produce less sludge. On the other hand higher capital cost and operation and maintenance cost are main disadvantages of the MBR system apart from membrane fouling.

Domestic wastewater consists both organic pollutants and inorganic pollutants such as nitrogen and phosphorous. While CAS process is being modified to treat nutrients (nitrogen and phosphorus) MBR is also under gone modifications to remove nutrients and control fouling. Introduction of media in MBR systems is such modification. Many researchers introduced different types of media and they all have their own advantages and disadvantage. Media in a MBR provide microorganisms a surface to attach and subsequently biofilm will be formed. Biofilm is very important in treating nitrogenous

compounds because it consists of both oxic and anoxic zones. In this case both nitrification and denitrification can take place in a single unit. Some of the researchers found out that polyethylene sponge media perform well in nitrogen and phosphorus removal as an attached growth media in MBRs. At the same time attached growth media will reduce the membrane fouling by reducing the extracellular polymeric substances (EPS) in MBR systems.

The use of attached growth MBRs for treating nitrogenous compounds is a fast growing research topic in present time. Again there are two type of systems depending on the media movement namely; moving bed and fixed bed. It is interesting to compare the performances of these systems in order to reach a conclusion.

In this study there were two MBRs; one was conventional suspended growth MBR with aeration and the other with attached growth MBR with sponge media to compare the nitrogen removal efficiencies and fouling characteristics. Selecting a suitable media for an attached growth MBR system was the starting point of this study. There were two types of media; namely cylindrical polypropylene and porous sponge (cubic). This preliminary study focused on the nitrogen removal efficiencies of the two media types in order to select better performance media. After the preliminary study sponge was selected as the attached growth media. In most of the previous literature attached growth MBR used with a moving bed configuration. But in this study a partially fixed bed (media allowed to have a limited movement) was used under low dissolved oxygen (DO) concentration.

1.2 Objectives

In this study there are three main objectives.

1. To select the better performance media in terms of highest COD and TN removal out of cylindrical polypropylene and porous sponge media to be used in attached growth MBR
2. To compare the nitrogen removal in conventional MBR and attached growth MBR systems
3. To compare the fouling characteristics between the conventional and attached growth systems

1.3 Scope of study

In order to accomplish the objectives listed above following steps were under taken.

1. Two laboratory scale sequencing batch reactors (SBR) were installed under ambient conditions
2. Synthetic wastewater having a COD value of 850 mg/L was used as the carbon source and total nitrogen concentration was 190 mg/L for the reactors
3. Two laboratory scale MBRs were installed in the ambient condition; one simulated the conventional MBR and the other with the sponge media
4. Fouling characteristics and removal efficiencies were investigated for hydraulic retention times (HRT) 7, 10 and 13 h
5. Sludge characteristic tests (fouling potential, particle size and distribution and CST), EPS production, fouling rate and cake resistance were carried out in the two MBRs in order to evaluate the performance
6. Removal efficiencies were evaluated in terms of COD removal and nitrogenous compounds

Chapter 2

Literature Review

2.1 Nitrogen Removal

Nitrogen removal from domestic wastewater is a hot research topic during the last two decades. Total nitrogen in domestic wastewater consists of about 60% of ammonium nitrogen and 40% organic nitrogen. By using conventional primary and secondary treatment processes some part of the organic nitrogen which is associated with settleable solids can be removed. Most of the dissolved and colloidal organic and dissolved inorganic forms of nitrogen will be in the wastewater without affected. Nitrogen can be removed from the wastewater by advance biological processes, but addition of the tertiary treatment unit will increase the overall treatment cost as well as the land requirement. The removal of nitrogen can be achieved by two main processes; namely assimilation and nitrification-denitrification. In assimilation part of the total nitrogen is converted in to cell biomass by microorganisms. In nitrification-denitrification nitrogen removal takes place by two steps. In the first step ammonium nitrogen converts into nitrite by autotropic microorganisms called *Nitrosomanas* and further oxidized into nitrate by *Nitrobactor*. The second step is the conversion of nitrate in to nitrogen gas which is known as denitrification. Denitrification occurs under anoxic condition (dissolved oxygen concentration <0.5 mg/L). The transformation steps of the nitrogen removal presents in figure 2.1. Most of the biological nitrogen removal plants contain aerobic and anaerobic/anoxic processes separately.

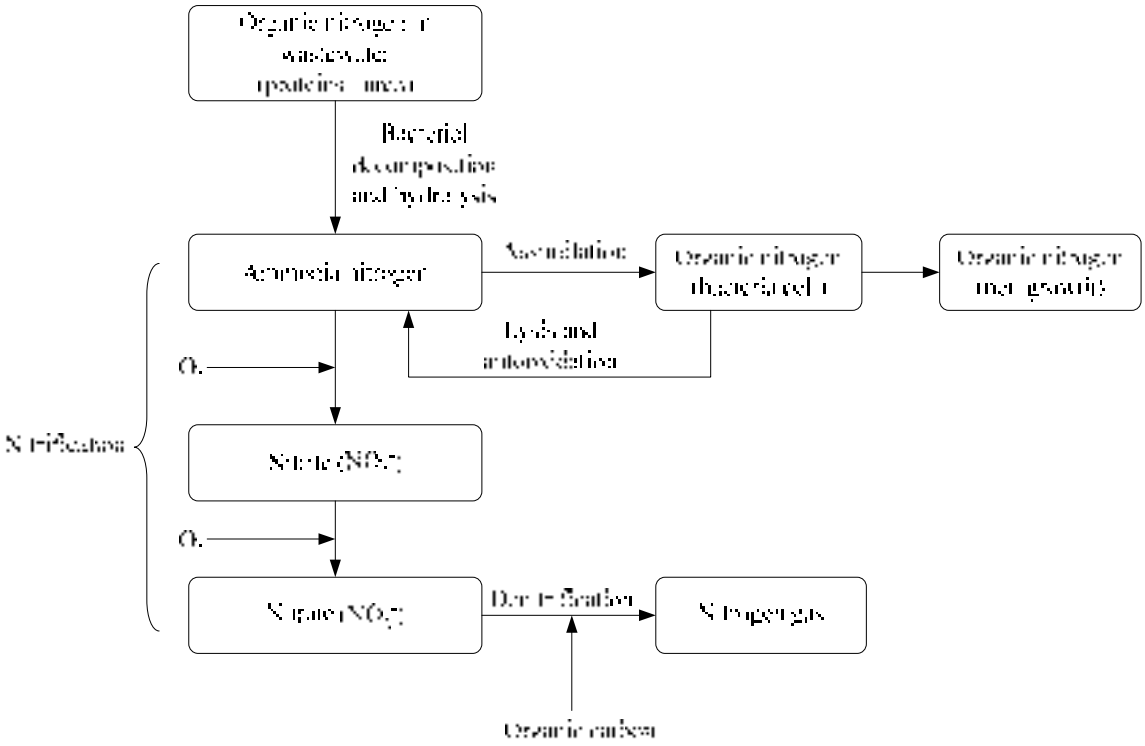

Figure 2.1 Various nitrogen removal mechanisms in biological treatment (Adopted from: Metcalf and Eddy, 2004)

At present, treating domestic wastewater using only biological processes in an urban city is a challenging task due to the land scarcity and higher effluent discharge standards. In this case membrane bioreactor (MBR) is an attractive solution due to its compactness in foot print and higher effluent quality. One of the main drawbacks of MBR is fouling of the membrane units. In early 1990s MBR studies mostly focused on achieving higher COD removal and the ways of reducing fouling. After that due to the stringent regulations in nitrogen disposal, MBR researches orient towards nitrogen removal in domestic wastewater. Researchers in the previous studies developed hybrid MBRs including moving media, fixed media, suspended growth, attached growth, etc in order to achieve higher removal efficiencies in terms of COD and nitrogen. Out of these researches it was found that the attached growth systems have better removal efficiencies and less fouling than the conventional suspended growth systems. In other words, it was observed that simultaneous nitrification denitrification (SND) occurred in a single bioreactor. Since then this new concept was being investigated by several researchers. But still the topic is open for more researches. In this study a new configuration for SND was investigated having polyethylene sponge (PS) as the attached growth media.

2.2 Membrane Process

2.2.1 Introduction to membrane technology

Membrane can be defined as a thin layer of material that is capable of separating materials as a function of their physical and chemical properties when a driving force is applied across it. Basic phases of a membrane process are illustrated in Figure 2.2. Driving force can be a difference in concentration, pressure, electrical charge or temperature.

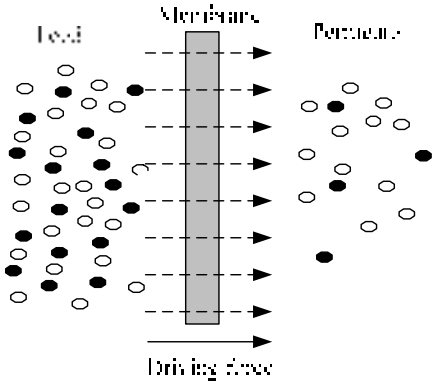

Figure 2.2 Basic phases of membrane process

Membrane processes divided in to four major categories depending on their rejected particle size; namely micro filtration, ultra filtration, nano filtration and reverse osmosis. Comparison of the above mentioned four membrane processes are shown in table 2.1. Membranes are manufactured by a large variety of materials. They are divided in to two main groups according to the material namely; inorganic membranes (sintered metals and ceramics) and organic membranes (polymers). Life span of inorganic membranes is higher than that of organic membranes due to higher thermal, mechanical and chemical stability. Organic membranes are widely used in water and wastewater treatment applications due to its flexibility. This property further leads to design more compact membrane modules providing higher surface area.

Synthetic polymeric membranes can be divided in to two main groups namely; hydrophilic (wet by water) and hydrophobic (cannot wet by water) membranes. Membranes which are made of hydrophobic materials have a greater propensity of membrane fouling (e.g. wastewater containing proteins).

Membrane can be further classified in to two groups according to the operational mode namely; dead end filtration and cross flow filtration. The schematic diagrams of the two modes are shown in figure 2.3.

Table 2.1 Comparison between Main Membrane Processes (Modified from: Metcalf and Eddy, 2004)

Process	Separation potential	Applied pressure (bar)	Flux range (L/m^2 .h.)	Typical operating range (µm)
Microfiltration	Suspensions, Emulsions	0.1 to 2	20 - 70	0.08 – 2.0
Ultrafiltration	Macromolecula solutions, emulsions	1 to 5	20 to 40	0.005 – 0.2
Nanofiltration	Low to medium molar mass solutions	5 to 20	10 to 40	0.001 – 0.01
Reverse osmosis	Aqueous low molar mass solutions	10 to 100	14 to 20	0.0001 – 0.001

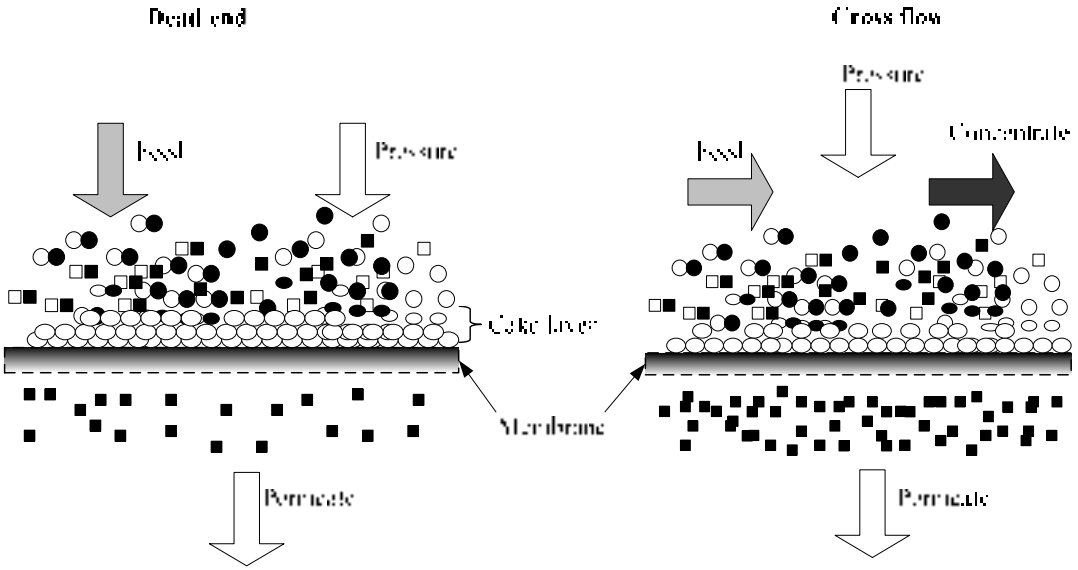

Figure 2.3 Membrane operational configurations

In dead end operation feed is pumped perpendicular to the membrane and in cross flow configuration feed is pumped tangential to the surface of the membrane. Membrane fouling due to the cake layer formation is reduced due to the high velocity gradient near to

the surface of the membrane, in cross flow mode. As a result of less fouling of the membrane in cross flow mode, permeate flux is considerably higher than dead end mode. In dead end filtration mode, the thickness of the cake layer will increase with time. This leads to a decrease of permeate flux. However dead end filtration has lower pumping requirement, which reduces the energy consumption.

2.2.2 Membrane operational parameters

In membrane operation the most important parameters are transmembrane pressure, permeate flux and membrane resistance. The relationship between these parameters is given in equation 2.1 and 2.2.

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

$$R_t = R_m + R_c + R_f \qquad \text{Equation 2.2}$$

Where, J: permeate flux ($L/m^2.h$)
ΔP: transmembrane pressure (kPa)
μ: viscosity of the permeate (Pa.s)
R_t: Total resistance (1/m)
R_m: intrinsic membrane resistance (1/m)
R_c: cake resistance (1/m)
R_f: fouling resistance caused by solute adsorption (1/m)

Membrane resistance calculations are carried out by using a series of membrane filtration tests for pure water filtration, sludge filtration and pure water filtration after remove sludge cake. In above calculations the permeate viscosity is considered as $0.798 * 10^{-3}$ Pa.s at 30˚C.

2.3 Membrane Bioreactor (MBR)

Membrane bioreactor (MBR) process was initiated in 1967 and further modified with activated sludge storage tank and cross flow filtration mode (Smith et al., 1969). Since then MBR process modified numerous occasions. This was considered as a good alternative for the conventional activated sludge (CAS) process, but the advantages were marginalized by the cost of membranes, low cost of the treated water and membrane fouling. In the beginning, side stream filtration mode was used for MBR filtration processes. But the operation consumed large amount of energy. In 1989, Yamamoto et al. (1989) suggested for the first time in the MBR history to submerge the membranes in the activated sludge bioreactor. But currently researchers are again focusing on side stream systems due to high fouling propensity in submerged MBR systems. Side steam configurations are widely used with ceramic membrane mainly because of the resistance to chemical abrasion and flexibility in insitu cleaning (clean in place). According to the findings of Xing et al., (2001), ceramic membranes could be used effectively in removing COD and NH_3-N with removal efficiencies 95% and 96.2% respectively. But each system configurations has its advantages and disadvantage. Typical side stream and submerged MBR configurations are shown in Figure 2.4. According to the figure in cross flow mode the membrane unit keeps outside of the bioreactor and in submerged MBR the membrane places inside the bioreactor.

In general biomass washout in a MBR due to membrane filtration is negligible. This helps to maintain higher MLSS concentrations in the reactor. At the same time higher sludge retention times (SRT) can be achieved without much operational problems compared to the CAS process. Finally it is possible to achieve lower food/ Microorganism (F/M) ratio and longer SRT leads to less sludge production (Yoon[a] et al, 2004). In that sense MBR can reduce the excess sludge production thus leading to low sludge management cost.

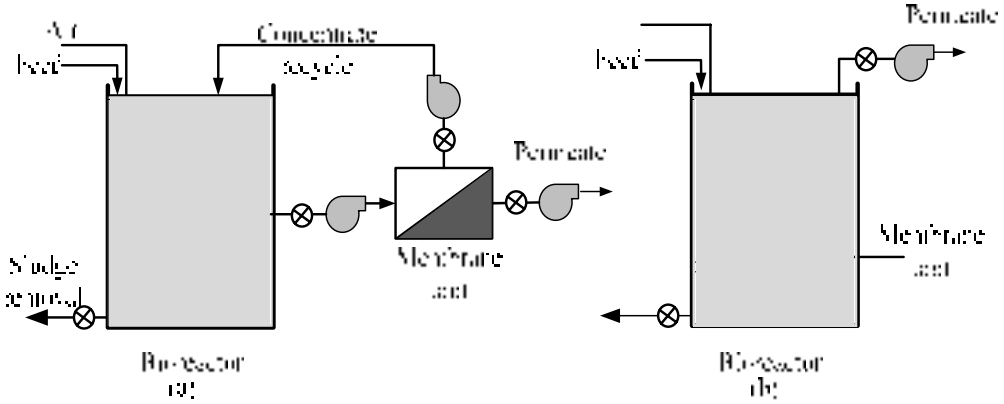

Figure 2.4 MBR configurations (a) Cross flow MBR with recirculation
(b) Submerged MBR

At present the membrane modules are operating under 25% or less permeate flux with compared to the earlier MBRs, and most of the cases the air sparging is use to control membrane fouling. Another development is the use of low solid retention times (SRT) than the early stage of MBRs. Earlier MBR systems were operated under a SRT above 100 days, but currently the SRT reduced up to 10 to 20 days. This new development leads to lower MLSS concentrations (10 to 15 mg/L) in MBRs. Less membrane fouling propensity and less chemical cleaning of membranes are some of the other advantages of the present developments.

Membrane bioreactor process can be considered as a good alternative to conventional activated sludge (CAS) process. Comparison between CAS and MBR processes is given in Table 2.2. The main problems in MBR process are membrane fouling and the high cost of membranes and related facilities. MBR process is capable of removing almost 100% of the suspended solids and more than 90% of chemical oxygen demand (COD). Finally this leads to high quality effluent. Currently, the use of MBR for nutrient removal is becoming a hot research topic. MBR has a greater nitrification potential than the CSA process, owing to comparatively longer retention time and smaller floc size. Gander et al. (2000) found, that the smaller floc size could help transferring higher oxygen in to the flocs. It was found that slow growing nitrifiers could be retained in the rectors without being washed off because of the membrane modules in the MBR (Soriano et al., 2003). In the same study it was noted that nitrification could be achieved even for low SRT and HRT values.

Currently most of the MBRs used in wastewater treatment introduce with some modifications to the conventional MBRs. Modifications can be related to reactor design or introduction of various attached growth media. The main idea of this concept is to achieve higher removal efficiencies with low operation and maintenance cost. This new type of MBR systems are called as hybrid MBR systems.

Table 2.2 Comparison of Conventional Activated Sludge (CAS) Process and Membrane Bioreactor (MBR) Process

Conventional Activated Sludge Process (CAS)	Membrane Bioreactor (MBR)
Advantages • Low energy consumption • Low operation and maintenance cost • Relatively longer operational life span	Advantages • Smaller foot print • Shorter startup time • Low operating and maintenance man power requirement • High quality effluent • No operational problems due to sludge bulking, sludge rising and *Norcardia* form • Less sludge production • Highly tolerable for shock loadings
Disadvantages • Large land requirement • Sludge bulking, sludge rising and *Norcardia* form • Cannot withstand for shock loading • Longer startup period • Low quality effluent • High operation and maintenance man power requirement • Higher sludge production	Disadvantages • Membrane fouling • Higher cost for membranes and related facilities • Shorter membrane life span • Need proper pretreatment • High energy cost

Cicek et al., (2001) found out that the nitrification retarded at 2 days of SRT condition due to the loss of nitrifying bacteria. This indicates that for slow growing nitrifying bacteria needs relatively long SRT for complete nitrification. It was observed that the organic removal in MBR was often greater than 95% disregarding the HRT value (Soriano et al., 2003). Low sludge production is one of the advantages on MBR systems. Table 2.3 provides a summary of some research findings related to sludge production in various treatment processes (Gander et al., 2000).

Table 2.3 Sludge Production of various Wastewater Treatment Processes (Adopted from: Gander et al., 2000)

Treatment process	Sludge production (kg $kgBOD^{-1}$)
Submerged MBR	0.3 – 0.2
Structured media biological aerated filter (BAF)	0.15–0.25
Trickling filter	0.3–0.5
Conventional activated sludge	0.6
Granular media BAF	0.63–1.06

2.3.1 Concepts of critical and sustainable flux

Critical flux can be defined as the flux below which a reduction of permeability with time does not occur, and higher than that fouling is taking place. There are two different types of critical flux concepts defined in previous literature; namely no fouling and little fouling occurring at sub-critical operation for the strong and weak forms (Le-Clech et al., 2006). The hysteresis technique is used to determine critical flux and it considered as one of the promising techniques to analyze critical flux (Chen et al., 1997, Ye et al., 2005).Critical flux depends on the MBR system operation parameters and sludge properties (aeration rate, floc size, cross flow etc.)

The high energy demand for the MBR operation is an inevitable drawback for future advancement of the process. Still in general understanding the energy consumption in MBR processes are higher than the CAS systems. The advantages of the MBR can be maximize by producing more permeate flux without excessive fouling. Now a days most of the large scale MBR plants are being operated in low flux ranges in order to reduce excessive membrane fouling. Economical loss due to reduced flux can be achieved by less number of chemical cleaning cycles. The flux at which there is no irreversible fouling in membranes with a smooth increase in TMP is known as sustainable flux (Ng et al., 2004). In general critical flux concept closely associates with short term experimental data where as sustainable flux can be defined for longer operational processes.

2.3.2 MBR operation modes

There are two main operation modes in MBR operation; namely constant pressure and constant flux filtration. In constant pressure filtration mode, there is a rapid flux reduction at the start of the process, after that there will be a smooth decline until it reaches to a constant value. In constant flux operation, less fouling probability was observed in previous studies. It was found that operating under constant flux, followed by constant TMP operation causes severe membrane fouling (Vyas et al., 2002). Initially in constant flux operation, it might generate large amount of particle depositions on the membrane surface, but that layer might give an advantage as a pre filter for the membrane reducing internal fouling. Operation protocols consisting intermittent filtration cycles accompanied with continuous crossflow filtration will provide less particle deposits (Le-Clech et al., 2006).

2.3.3 Effects due to hydraulic retention time (HRT) in MBR systems

Hydraulic retention time is an important parameter in MBR operations. According to the previous studies wastewater containing nitrogenous compounds needed to have higher HRT value. Most importantly correlations with HRT and other parameter should make once the MBR system reached its steady state. It was reported that, even a small variation in HRT could affect the removal efficiencies in terms of COD in treating petroleum refinery wastewater under steady state MBR (Viero and Sant'Anna, 2008). Apart from that, same authors further elaborated the strong relationship between HRT and membrane fouling also. It was found that heterogeneous nature of industrial wastewater needed high HRT value in order to obtain higher removal efficiencies. Normally steady state of a MBR system attains after two to three times SRT. But in the cases of large SRT (>50 d) values, the stabilization of volatile suspended solids (VSS) can be considered as the steady state of the system, because VSS basically represent the active microorganisms in the reactor.

2.3.4 Aerobic MBRs

MBRs can operate either aerobic conditions or anaerobic condition depending on the requirement. Most of the aerobic MBR systems can be successfully implemented for higher COD removal and complete nitrification. In general HRT and SRT can vary independently in MBRs. Due to short HRT, MBR processes can achieve higher loading rates than the other conventional methods (Gander et al., 2000). Summary of selected reported experimental details related to aerobic MBR is shown in Table 2.5.

In a study conducted by Yamamoto and Win (1991) to treat tannery wastewater which contained high amount of COD (1500-2200 mg/L) and heavy metals like chromium (19-32 mg/L). The experiment was conducted under varying SRT namely 10, 20 and 550 days and varying volumetric loading rate 3, 5, 8 and 10 kg COD/m^3.d. It was reported a removal efficiency of 93% and 95% for COD and Cr respectively. It was found that the 20 days was the best for SRT to achieve higher removal rates and it was recommended the volumetric loading to be kept below 8 kg COD/m^3.d.

SCOD removal was studied in oil wastewater by using ultrafiltration MBR (Seo et al.,1997).The experiment was conducted under varying HRT and SRT(5, 10, 20 and 30 days). It was found that the soluble COD removal efficiency was more than 90% at HRT greater than 10 days.

2.3.5 Anaerobic MBRs

Table 2.6 shows a summary of selected reported experimental details related to anaerobic MBR. Most of the studies operated under side stream configurations. The applied cross flow velocity and the TMP were in the range of 0.5 to 3 m/s and 0.5 to 2 bar (Jeison and van Lier, 2007). Vocks et al., (2005) found that the denitrification rates observed with post-denitrification without dosing of an external carbon source in an anaerobic MBR were clearly above endogenous rates. The application of membrane coupled anaerobic bioreactor is being used as an alternative process to treat industrial wastewater. Due to the slower growth rates of anaerobic culture in the biological process, it takes relatively longer HRT to prevent biomass wash out completely out of the reactor. Furthermore the settability of anaerobic biomass is low due to their diffusible and filamentous nature.

A comparison of aerobic and anaerobic MBRs (both cross flow and submerged) in terms of flux, applied pressure and energy are summarized in table 2.4 (Liao et al., 2006).

Table 2.4: Comparison of Aerobic and Anaerobic Membrane Bioreactors (Modified from Liao et al., 2006)

Parameter	Units	Aerobic MBR		Anaerobic MBR	
		Cross flow	Submerged	Cross flow	submerged
Pressure	kPa	400	20-50	150-450	15-50
Flux	L/m^2.h	50-100	20-50	10-40	15
Cross flow velocity	m/s	3-5	-	2-5	-
Energy for filtration	kWh/m^3	4-12	0.3-0.6	3-7.3	0.25-1.0

Table 2.5 Selected reported Experimental details related to Aerobic MBRs for Wastewater Treatment

Wastewater type	Volume (m^3)	HRT (h)	Final flux (L/m^2d)	COD removal (%)	MLSS (g SS/L)	Reference
Synthetic	0.007	7.8	9	>95	2.4 – 5.5	Lee et al., (2003)
Domestic	0.066	30	28	>85	-	Jefferson et al., (2001)
Oil wastewater	-	5, 10, 20, 30	-	>90	0.2	Seo et al., (1997)
Municipal	3.9	10.4 – 15.6	18 - 27	90 - 95	18 – 20	Rosenberger et al., (2002)
Municipal	1.5	15, 7.5	-	>94	3 – 4	Fan et al., (1996)

Table 2.6 Selected reported Experimental details related to Anaerobic MBRs for Wastewater Treatment (Modified from: Jeison and van Lier, 2007)

Wastewater type	Volume (m^3)	Cross flow velocity (m/s)	Final flux (L/m^2h)	Pore size	MLSS (g SS/L)	Reference
Potato starch bleaching	4	1.5 – 2.0	-	0.1 µm	100 - 150	Beaubien et al., (1996)
Palm oil mill	0.05	2.3	26 – 31	-	50 - 56	Brockmann and Seyfried, (1997)
Brewery	0.12	-	-	100 kDa	31 - 38	Fakhrulrazi, (1994)
Synthetic	0.01	0.8	20 – 40	3000 kDa	15	Harada et al., (1994)
Sewage	0.018	-	5	0.03 µm	16 – 22	Wen et al., (1999)
Acetic acid	0.01	3.5	120	0.14 µm	0.13	Elmaleh and Abdelmoumni, (1997)

2.3.6 Attached and suspended growth MBRs

Mainly there are two types of microorganisms operating in activated sludge processes; namely suspended and attached growth microorganisms. Similarly MBR also divided in to two major groups; attached and suspended growth MBRs, according to the microorganisms used in the treatment process. However, by their nature as filters, membranes are more prone to fouling as a consequence of the interactions between the membrane and the mixed liquor. In order to reduce the cake resistance in membrane modules there are several techniques currently use in MBRs. The use of various back washing protocols, operation under sustainable flux, air sparging and chemical addition can be considered as promising techniques in reducing the cake fouling. Removing the cake layer was the main objective for most of the previous studies without paying much attention to the cause for that. It was found that one of the main contributors for the cake layer formation was the suspended microorganism (Lee et al, 2001). The concept of attached growth MBR is to provide attached growth microorganisms a surface to attach by introducing a media in the bioreactor. Lee et al., (2001) compared the filterability, COD removal and nitrogen removal in suspended and attached growth systems. It was found in the study that there was no significant difference in EPS in the two systems but the fouling was seven times higher in attached growth system than the suspended growth system.

In suspended growth systems the biomass growing pattern and the utilization is described as a function of the dissolved substrate levels. Contrary in a biofilm process the substrate utilization is effectively carried out within the biofilm. The movement of substrate from bulk liquid to inside the biofilm is taking place via diffusion. A simplified diagram of a biofilm is shown in Figure 2.5. The stagnant liquid layer acts as a transition layer between the biofilm and the bulk liquid.

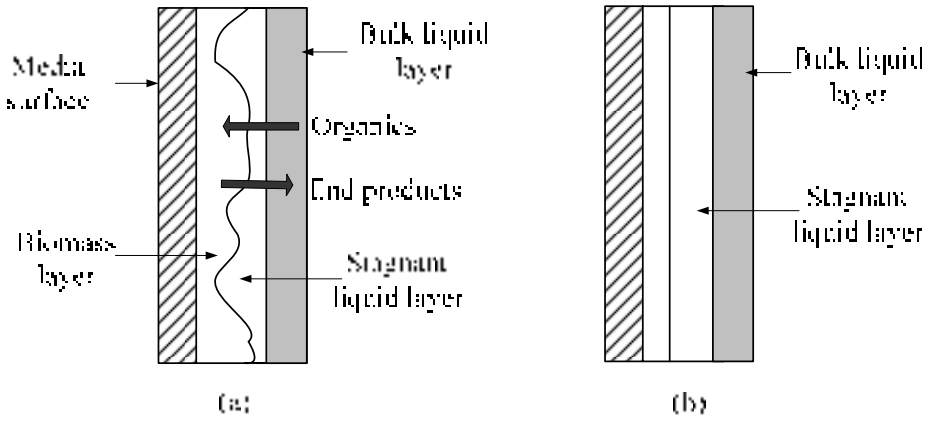

Figure 2.5 Simplified views of a biofilm: (a) Actual view (b) Idealized view (Adopted from: Metcalf and Eddy, 2004)

Attached growth MBR systems can further divide in to two categories with respect to the media movement. They are fixed bed and moving bed MBRs. There are several commercially available media types namely; Ringlase, Limpor, Sponge and Kaldnes. The large surface area is one of the important properties of a good attached growth media.

The moving bed MBRs are defined as the biomass grows on media that are continuously in moving condition with the liquid in the reactor. The moving force is generally provided by the air bubbling in aerobic systems or by mechanical mixing in anaerobic systems.

Several researchers have studied about the attached growth MBR system for wastewater treatment using different types of media, which is given in table 2.6.

Leiknes and Ødegaard, (2007) studied about a biofilm (BF) MBR process having two reactors, the moving bed biofilm reactor (MBBR) followed by a membrane reactor with submerged modules. The schematic of the BF- MBR process is shown in Figure 2.6. In that study high density polyethylene (density 0.95 g/cm^3), shaped like small cylinders were used as the media. Finally it was found that the BF-MBR could be operated under high volumetric loading (2 to 8 kg COD/m^3.d) with relatively low HRT (4 h) and higher permeate flux (50 LMH) than the conventional activated sludge MBR.

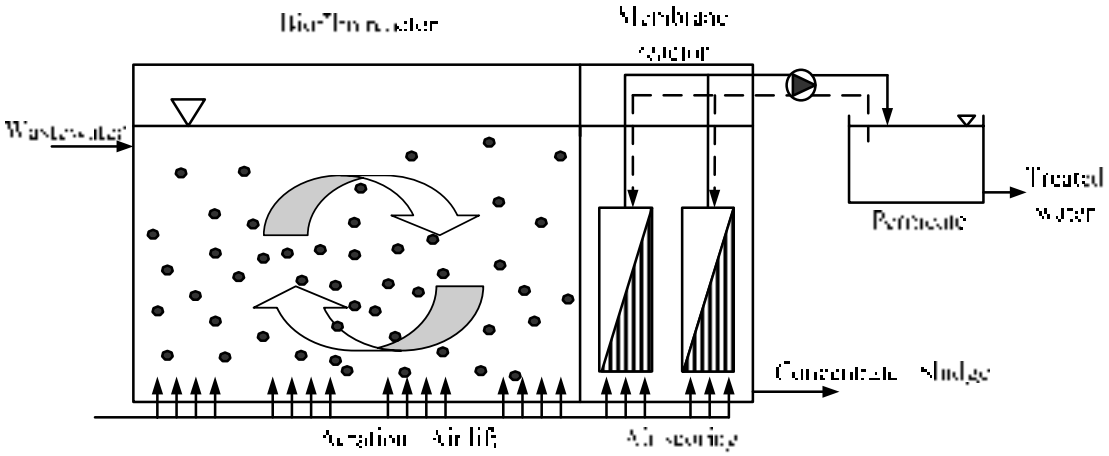

Figure 2.6 Schematic diagram of the biofilm MBR process (Adopted from: Leiknes and Ødegaard, 2007)

Lee et al., (2006) investigated in membrane coupled moving bed biofilm reactor (M-CMBBR) in order to identify the factors affecting filtration characteristics. In the study, virgin polyurethane cubes (1.3 cm) were used as the carrier media. It was found that in M-CMBBR system unlike conventional MBR, performance of the membrane was dependant on the physical parameters of the media such as kinetic energy and collision frequency. Furthermore it was concluded that the frictional forces exerted by the circulating media on the membrane unit reduces membrane fouling thus, enhances the permeability of the system.

COD removal efficiency and the performance of the biofilm reactor were studied by Tavares et at. (1994). In that case the authors used two different media types in order to create biofilm, namely; polystyrene beads and commercially available OSBG (optimum support for biological growth) media. The reactor was operated under high organic loading rates (6.9 to 24.5 kg soluble COD /m^3.d) and three different hydraulic retention times; 10, 20 and 30 min. It was found that the COD removal rate was in the range of 55 to 76% with both the media respectively. Further, the study revealed that the surface roughness of the OSBG media allowed a thin, active biofilm to grow over its surface.

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Table 2.7 Attached growth MBRs for Wastewater Treatment using different Media

Type of Wastewater	Synthetic	Sewage	Municipal	Synthetic	Synthetic	Synthetic
Type of media	Polyester-urethane Sponge, cubes(10*10*10mm)	Polyethylene glycol, Ø 5mm	Cylindrical shape polypropylene Ø 2.7mm	Virgin polyurethane cubes (1.3 cm)	Cylindrical polypropylene inner Ø 3mm Outer Ø 4mm	High density polyurethane particle size 1mm
Density (g/cm^3)	28-30 and 16-18	1.02	1.18	-	1.001	0.73
Media volume (% of the reactor volume)	10	20	42	5 and 20	24	23
HRT (h)	1.2	9	30 min	10	2	0.8 ,5
DO (mg/L)	-	2 -6	-	5	3 - 4	6
BOD loading ((kg/m^3.d)	-	1.1-2.8	-	-	-	-
COD loading (kg/m^3.d)	-	-	8.1	2.4	-	-
COD removal (%)	>97	-	>80	-	-	72 - 90
Nitrogen removal (%)	>99.5	73	-	-	-	69 – 100(NH_3 – N removal)
Reference	Ngo et al., (2007)	Mishima et al., (1996)	Tavares et al., (1994)	Lee et al., (2006)	Sombatsompop et al., (2006)	Nogueira et al., (2002)

2.3.7 Nitrogen removal in MBRs

Most of the researchers worked on aerated MBR systems achieved almost complete nitrification. But denitrification needs anaerobic or anoxic compartments before the aeration tank with circulation of mixed liqour (Gander et al., 2000). According to the findings of Genz et al., (2004) and Yoon[b] et al., (2004) simultaneous nitrification denitrification can be achieve in MBR by introducing physico-chemical treatment processes including coagulation and adsorption. In most of the previous studies it was recommended to use a separate anaerobic tank prior to the aerobic MBR, in order to remove nitrogen effectively. Ahn et al (2003) found out that by using a MBR with sequencing anoxic/ anaerobic conditions can achieve a phosphorous removal up to 93%. During another study by Zhang et al., (2006) found out that the sequencing batch membrane bioreactor can achieve approximately 90% nutrient (nitrogen and phosphorous) removal. These studies indicate the importance of operation conditions in order to reach the higher nutrient removal efficiencies.

In above mentioned hybrid MBR systems both nitrification and denitrification processes are allow to happen in a single aeration tank which is commonly known as simultaneous nitrification denitrification (SND). In conventional activated sludge processes SND can achieve in low DO concentration, by providing different mixing patterns. Aerobic and anoxic conditions will be there in the reactor depending on the distance from the mixing point. For example if the mixer is provided at half way of the aeration tank then the bottom part of the aeration tank will be under anoxic condition. But in practice operation and maintain SND in a single tank is not common in CAS processes. Two frequently used nitrogen removal methods in biological nitrogen removal are shown in Figure 2.7. The process which consists of an anoxic tank followed by an aeration tank called as preanoxic deniftrification process whereas aeration tank followed by anoxic tank is known as postanoxic denitrification process. Out of there two the most common biological nitrogen removal method is preanoxic dentrification.

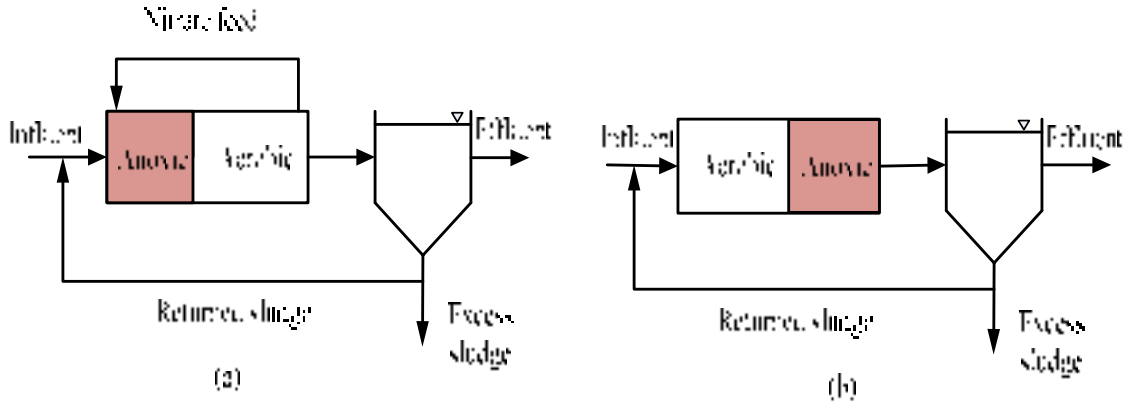


Figure 2.7 Types of denitrification configurations in CAS process; (a) substrate driven (preanoxic) process, (b) endogenous driven (post anoxic) process (Adopted from: Metcalf and Eddy, 2004)

Finding out the relationship between recirculation of mixed liquor and permeate and biological nutrient removal in MBR systems is another interesting research area. Ersu et al., (2007) investigated above topic by introducing different recirculation configurations.

In that experiment there were five configurations studied, having different recirculation rates and different aerobic, anoxic and anaerobic compartments in one reactor. It was finally concluded that out of the five configurations the one with recirculation of mixed liquor to the anaerobic compartment and permeate to the anoxic compartment was the best configuration with highest total nitrogen and total phosphorous removal. Main disadvantage of this recirculation method was the high energy consumption for the process.

Chiemchaisri et al., (1992) studied the organic stabilization and nitrogen removal in domestic wastewater by using a MBR system. It was found that when DO concentration was increased from 1.5 mg/L to 4 mg/L nitrogen removal efficiency was increased by 90%. That study was conducted under intermittent aeration.

Nah et al., (2000) investigated the carbon, nitrogen and phosphorous removal from domestic wastewater by using a MBR system. The system was operated for 150 days without cleaning and under constant suction pressure. It was observed at the end of the experiment 94% TCOD removal and 100% suspended solid removal. The total nitrogen (TN) and total phosphorous (TP) removal was reported as 83% and 55% respectively. It was found that the denitrification was the rate limiting step in the process.

According to the findings of Fan et al., (1996) it was proved that in a conventional MBR nitrification rate could reach up to 100%. But this study basically focused on low to medium strength domestic wastewater and the nitrogen concentration varied from 74 to 96 mg/L. The system was operated under four different operational conditions by varying the SRT and HRT values. It was found that the best operational conditions were SRT 10 to 20 days and HRT 10 to 7.5 h to achieve above mentioned nitrification rate.

2.3.8 Nitrogen removal in hybrid attached growth MBRs

In some research studies, successful application of attached growth media in MBRs was reported in relation with nitrogen removal. Different types of attached growth media have being used in various researches for the last few years. Out of those media types polyethylene sponge has been considered as an ideal attached growth media (Ngo et al., 2006; Psoch and Schiewer, 2006). High microbial retention ability and active participation as a mobile biomass carrier are some of the reasons for the above conclusion. It was reported by Deguchi and Kashiwaya (1994) that the nitrification denitrification rate coefficients of a sponge suspended growth MBR were 1.5 and 1.6 times, higher than CAS process. Most importantly it is necessary to maintain an anoxic zone in the reactor to achieve higher denitrification rates. In attached growth MBR systems the anoxic zone exists inside the biofilm which covers the media.

Ngo et al., (2007) studied about a new concept of sponge submerged membrane bioreactor (SSMBR) in order to achieve higher removal rates of nitrogen, phosphorous, COD and DOC under less fouling. In that study, two types of porous polyester- urethane sponge (PUS) cubes (1cm size) with two different densities were used. In that study sponge volume fraction was 10% and it was reported that more that 97% removal of both NH_4 – N and PO_4 –P. Finally it was concluded that, even without pH adjustment higher removal efficiencies in terms of COD and nitrogen, could be achieved.

2.3.9 Effects of organic loading rate (OLR) on nitrogen removal

By definition OLR means the amount BOD or COD as influent to a bioreactor per unit volume per day (Equation 2.3). Indirectly effects of OLR can be analyzed by BOD/TN (or COD/TN) ratio.

$$OLR = \frac{QS_0}{V * 10^3 \, g / kg} \qquad \text{Equation 2.3}$$

Where,

OLR = Organic loading rate (kg BOD or COD /m^3.d)
Q = Influent flow rate (m^3/d)
S_0 = Influent BOD or COD concentration (g/m^3)
V = Volume of the bioreactor (m^3)

According to the findings of Nah et al, (2000) BOD/TN ratio plays an important role on nitrogen removal. They found that if BOD/TN ratio less one then the nitrogen removal efficiency reduced to 40-60%. After doing the experiments for various BOD/TN ratios they finally concluded that for higher nitrogen removal (more that 80%) the above ratio should be greater than two. Furthermore it was reported that for low BOD/TN ratios endogenous denitrification is an important phenomenon. Endogenous denitification was assessed by batch operations by the above mentioned authors.

2.4 Membrane Fouling

2.4.1 Fouling mechanisms

As stated earlier the membrane fouling is one of the main drawbacks of MBR systems. It causes a reduction of permeate flux and increase operation and maintenance cost of the plant. There were large number of researches looked in to the problem of fouling in detail. Researchers are still studying the various aspects and trying to develop better techniques to reduce fouling.

Membrane fouling in MBRs is attributed to the physicochemical interactions between the biofluid and membrane. As soon as the membrane surface comes in to contact with the biological suspension, depositions of biosolids onto it takes place leading to flux decline. Basically, there are two types of fouling; namely reversible and irreversible fouling. Cake layer formation is known as reversible fouling, because it can be removed easily from the membrane surface by an appropriate physical cleaning. On the other hand, internal fouling caused by the adsorption of the smaller particles into the membrane pores is considered as irreversible. Irreversible fouling can generally be removed by chemical cleaning. The mechanisms of membrane fouling present in Figure 2.8. Some of the previous researchers pointed out the importance of extracellular polymeric substances (EPS) in relation to the membrane fouling.

Although it is difficult to establish a general rule about membrane fouling in MBR, the nature and the extent of the fouling are strongly influenced by three factors; namely, biomass characteristics, operating conditions and membrane characteristics. Factors effecting membrane fouling are shown in Figure 2.8.

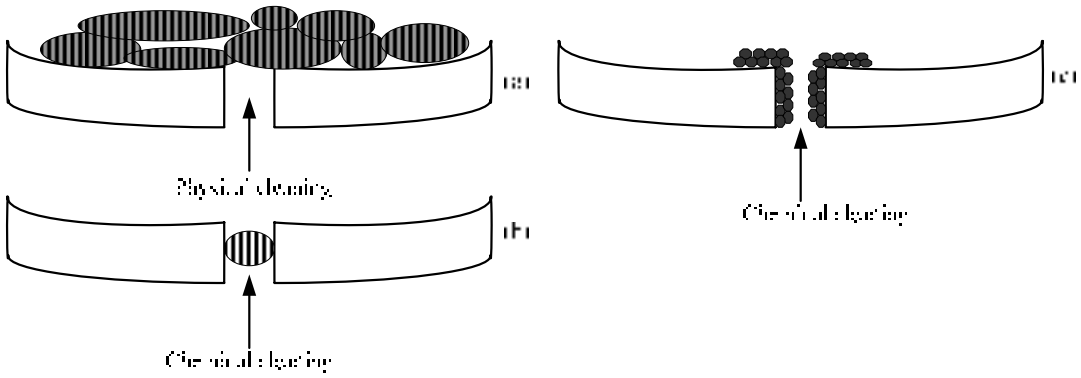


Figure 2.8 Fouling mechanisms (a) Cake layer formation; (b) Pore blocking; (c) Pore narrowing.

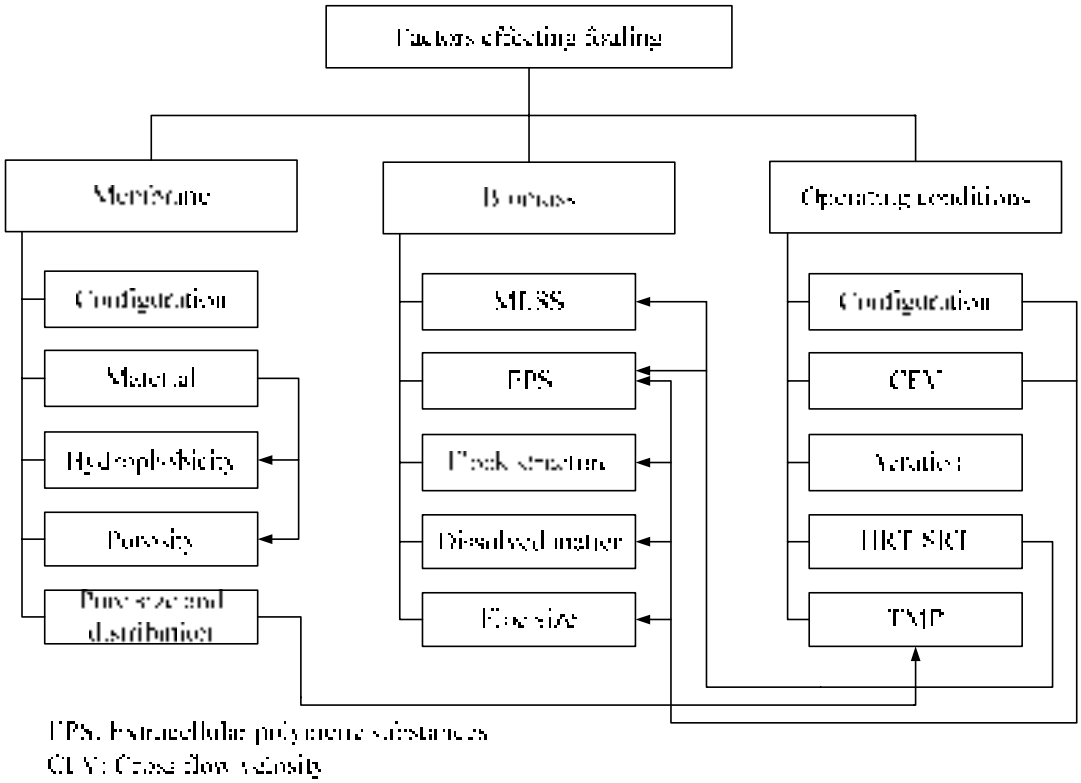


Figure 2.9 Relationship between the fouling factors in MBR
(Adopted from: Chang et al., 2002)

2.4.2 Fouling due to physical parameters of the membrane

In order to have good filtrations and less membrane fouling the physical parameters of the membrane units are playing a major role. Pore size and distribution, porosity, roughness and membrane configuration can be categorized under physical parameters. Fouling characteristics might be different from reach other depending on the pore size and the type of wastewater used. If the membrane pore size is larger than the particles in the bulk liquid

membrane pore blocking will take place. He et al., (2005) studied the effects of pore size in ultrafiltration system. They operated the anaerobic MBR under constant TMP operational mode. After an operation period of over 100 days it was found that the fouling rate as high as 94% in the largest pore size membrane. The other membranes experienced a fouling rate less than 70%. Cake layer fouling due to the operation with much smaller pore membranes is more likely to remove physical cleaning where as fouling of larger pore membranes need chemical cleaning. Fang and Shi, (2005) studied about the relationship between membrane roughness and porosity and found that membrane fouling closely related to these factors.

It was observed a general trend towards submerged MBR based experiments in recent past. Cross flow operational mode also still under consideration as a membrane configuration. The correct type of membrane should be selected depending on the configuration and the backwashing method (Cui et al., 2003).

2.4.3 Fouling due to chemical parameters of the membrane

Hydrophobicity and membrane material are grouped under chemical parameters of the membrane. In general hydrophobic membranes pose high membrane fouling potential than the hydrophilic membranes. Contrary it was observed that hydrophilicity of the membrane material could attract more foulants in the same condition (Fang and Shi, 2005). In most of the previous literature, it was noted that extracellelar polymeric substance (EPS), was the main foulant in MBR systems.

During the study of Yamato et al. (2006), it was found that polyvinylidene fluoride (PVDF) membranes could be operated longer filtrations cycles than the polyethylene (PE) membranes. Furthermore it was noted that some polymeric membrane materials posed high affinity for the foulants in MBRs causing excessive membrane fouling.

2.4.4 Fouling due to biomass characteristics

MLSS, Extracellular polymeric substances (EPS), floc structure and size and other dissolved matter are the mostly discussed fouling factors in literature. It is generally accepted that EPS and other dissolved matter causes severe fouling. But some researchers disagree with the role of EPS in membrane fouling.

Lee et al., (2001) observed that the fouling rate of the attached growth MBR was seven times higher than the suspended growth MBR. In order to explain the situation a series of analysis were done by the authors including hydraulic resistance, specific cake resistance scanning electron microscope (SEM) and atomic force microscope (AFM). Finally it was concluded that better filtration in suspended growth MBR was due to the dynamic membrane formed on the membrane surface.

According to the study conducted by Chang and Kim (2005), it was found that the cake resistance decreased with the MLSS concentration. Increase MLSS concentration increase the suspension biomass viscosity of the MBR. The effects suspension viscosity and the colloidal particles on permeability were studied by Itonaga et al. (2003). It was found that the optimum MLSS concentration for a MBR system was around 10 g/L.

2.4.5 Extracellular polymeric substances (EPS)

Activated sludge floc is a combination of microorganisms and various types of microbial products. The polymeric structure in a floc which keeps the other components in place is called as EPS. Because of the high molecular weight constituents in EPS, it was observed to be an important factor in sludge liquors (Sanin and Vesilind, 2000; Liao et al., 2001). Furthermore it was observed the presence of proteins, polysaccharides, lipids, nuclic acids and other minor constituents in EPS (Bura et al., 1998; Nielson and Jahn, 1999). EPS can be categorized in to two main groups namely; bound EPS and soluble or colloidal EPS (Nielson and Jahn, 1999). It was found that bound EPS concentrations less than 20 and higher than 80 mg EPS / a MLVSS were not effecting significantly in membrane fouling (Le Clech et al, 2006). Figure 2.10 shows the two forms of EPS in MBR systems.

Currently the relationship between EPS and fouling gained a lot of attention from MBR researchers. Chang and Lee (1998) investigated the relationship between EPS and membrane fouling by varying the operational conditions and found a linear relationship between the two parameters. The test results of various authors mainly depend on their extraction procedure. Since there is no standardized method or protocol to follow sometimes it is very difficult to compare and comment on some of the results.

Lee et al. (2001) and Sombatsompop et al. (2006) found out that there was no significant relationship between EPS concentrations (both soluble and bound forms) and the membrane fouling in attached growth systems.

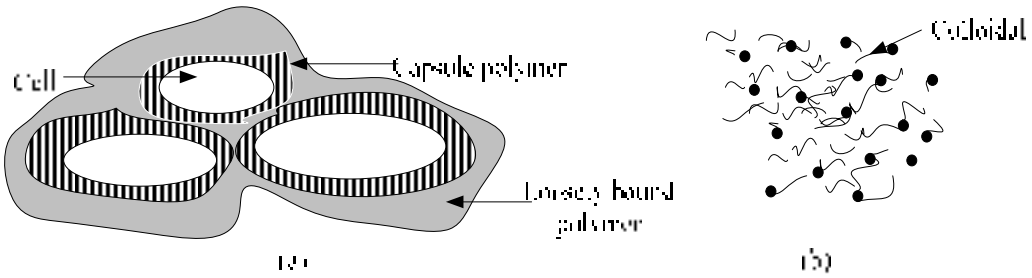


Figure 2.10 Forms of EPS (a) Bound EPS (b) Soluble EPS

2.4.6 Fouling due to operational conditions

Aeration and cross flow velocity

Since the invention of submerged MBR, air sparging has been used as a way of controlling fouling. The frictional forces between the course air bubbles and the membrane surface are known to be the reason for the above advantage. Other than fouling control aeration has other advantages such as provide oxygen to the biomass and keep biomass in suspension without settle at the bottom of the reactor. Li and Wang (2006) studied, about the flow pattern variation and introduced a mathematical model which describes the phenomenon. It was found that a high aeration rate could break the activated sludge floc structure into smaller particles leading to severe membrane fouling. Choi et al. (2005) observed a fouling reduction in membranes with increasing cross flow velocity up to 4.5 m/s. In general the cross flow velocities mostly depend on the reactors configuration and the aeration requirement and the membrane type and the pore size.

Sludge retention time (SRT)

In the earlier stage submerged MBRs operated under the SRT value of 100 days or more than that. In that case the MLSS of the reactors were very high. This ultimately led to higher membrane fouling propensities. Therefore MBR researchers currently use low SRT values such as 20 or 30 days. This current trend greatly reduced the membrane fouling and the chemical cleaning frequencies in MBRs. There are limitations of lower limit of SRT. Trussell et al. (2006) investigated the relationship between low SRT (down to two days) and fouling and found out that an increase in membrane fouling.

Mohaddam et al. (2003) studied about effects of SRT in course pore filtration of activated sludge process by varying SRT 10, 30 and 75 days respectively. It was concluded that when operated under SRT 10 and 30 d the system performance were excellent in terms of filter clogging. Furthermore the authors observed a rapid clogging in 75 d SRT and high amount of EPS in suspension.

Hydraulic retention time (HRT)

In literature there are a lot of research studies focused on the effects of HRT on membrane fouling (Seo et al., 1997; Lee et al., 2001; Rosenberger et al., 2002). The decrease of HRT means the increase in OLR (if the influent COD concentration is constant) resulting higher MLSS concentration. According to the results of several studies it is clear that the increase in HRT reduces membrane fouling.

2.5 Membrane Fouling Index (MFI)

Membrane fouling index (MFI) is uses as an indirect measurement of membrane fouling by using the cake filtration theory (Roorda and van der Graaf, 2001; Boerlage et al., 2003). The experiment is done under constant TMP (usually 1 bar) by using a dead end filtration mode. It was observed the cake compression phenomenon was responsible for the high TMP rise (Boerlage et al., 2003). The MFI can be determined from the gradient of the graph between the ratio of filtration time and the permeate volume against the volume under constant pressure. Equation 2.3 is used to plot the variation between t/V and V.

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

Where, t: filtration time (s)

ΔP: transmembrane pressure (kPa)

μ: viscosity of the permeate (Pa.s)

A: membrane surface area (m^2)

R_m: intrinsic membrane resistance (1/m)

V: Filtrate volume (mL)

α: Specific cake resistance (m/kg)

C_b: Concentration of the particles (mg/L)

The typical t/V versus V graph has three main regions, which corresponds to blocking filtration, cake filtration and cake compression (Figure 2.11). The MFI value depends on factors such as sample source, membrane characteristics and applied pressure.

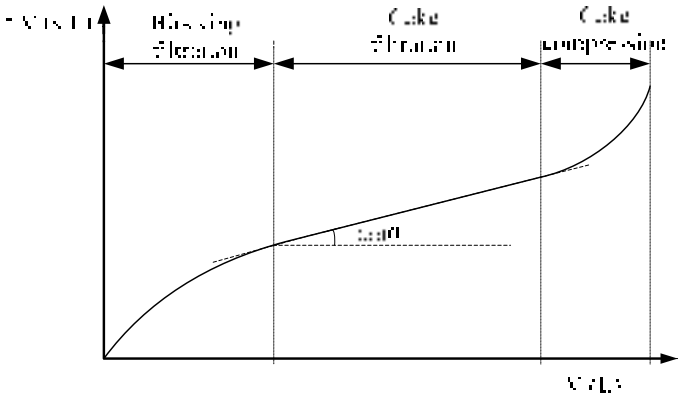


Figure 2.11 Variation of the ratio of filtration time and filtrate volume (t/V) versus filtrate volume (V)

2.5.1 Fouling and alkalinity

Ognier et al. (2002) investigated, about the effect of pH in relation with membrane fouling. In that study subcritical conditions were defined for standard pH and temperature conditions in order to compare the fouling behavior due to pH variations. It was observed that for pH values higher than the standard (critical) value there was a rapid TMP increase. Increase in TMP indirectly tells about the fouling of membrane.

Some of the latest research studies focused on the alkalinity addition as a way of reducing fouling. In this regard Kim and Jang (2006) investigated, the calcium on membrane fouling. In that study there were two submerged MBRs operated under low calcium (LC) and optimum calcium (OC) concentrations. Finally it was found out that the LC fouled 11 times faster than the OC reactor.

Chapter 3

Methodology

The main objective of this research is to compare the nitrogen removal in suspended and attached growth membrane bioreactor (MBR). Apart from the main objective, fouling characteristics of the two reactors; suspended and attached growth were compared by extracellular polymeric substances (EPS) and other biological parameters. The study mainly divided in to two stages; 1) Preliminary study 2) Laboratory scale membrane bioreactor study.

3.1 Preliminary Study

Preliminary study was mainly focused on selecting the suitable media, based on nitrogen removal to be used in MBR. Figure 3.1 shows the overall scope of the preliminary study.

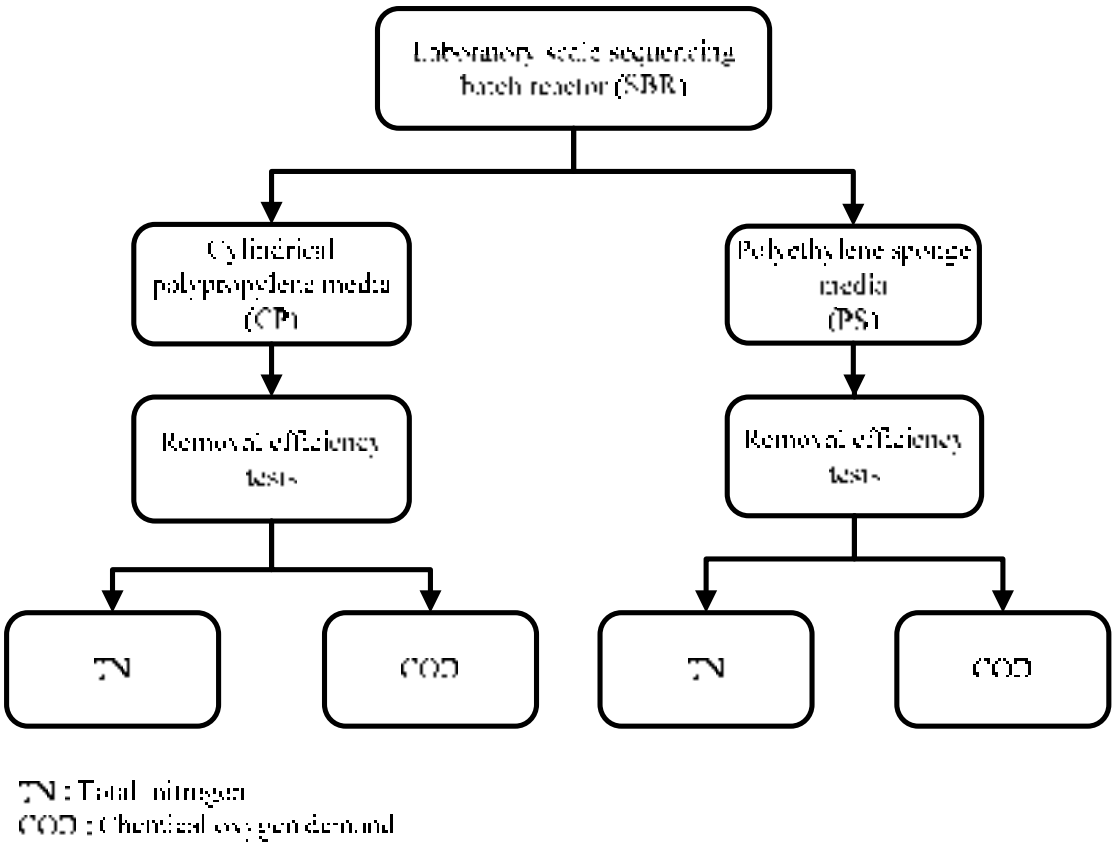


Figure 3.1 Overall scope of preliminary study

3.1.1 Selection of best media for the attached growth MBR

Media having the best removal efficiency (specially nitrogen removal) was selected and then that media was used in the attached growth MBR. Basically two types of media were considered in the study, namely; cylindrical polypropylene (CP) and polythene sponge media (PS). In this case these two types of media reported to have higher removal

efficiencies in terms of COD and TKN in previous studies (Sombatsompop, 2007). The characteristics of the two media types are given in Table 3.1.

In order to achieve the above mentioned objective, two sequencing batch reactors (SBR) having a working volume of 5L were used (Feeding: 15 min, Reacting: 11 h, Settling: 30 min, Drawing: 15 min) and the laboratory scale experimental setup is shown in Figure 3.2.

Table 3.1 Characteristics of the Media to be used in Sequencing Batch Reactor

Media	Cylindrical Polypropylene	Polyethylene Sponge
Shape	Cylindrical	Cubic
Size	Internal Diameter 3mm External Diameter 4mm Length 5mm	10mm*10mm*10 mm
External surface area (m^2/g)	$5.81* 10^{-3}$	0.02
Total media weight (g)	215.9	26.41

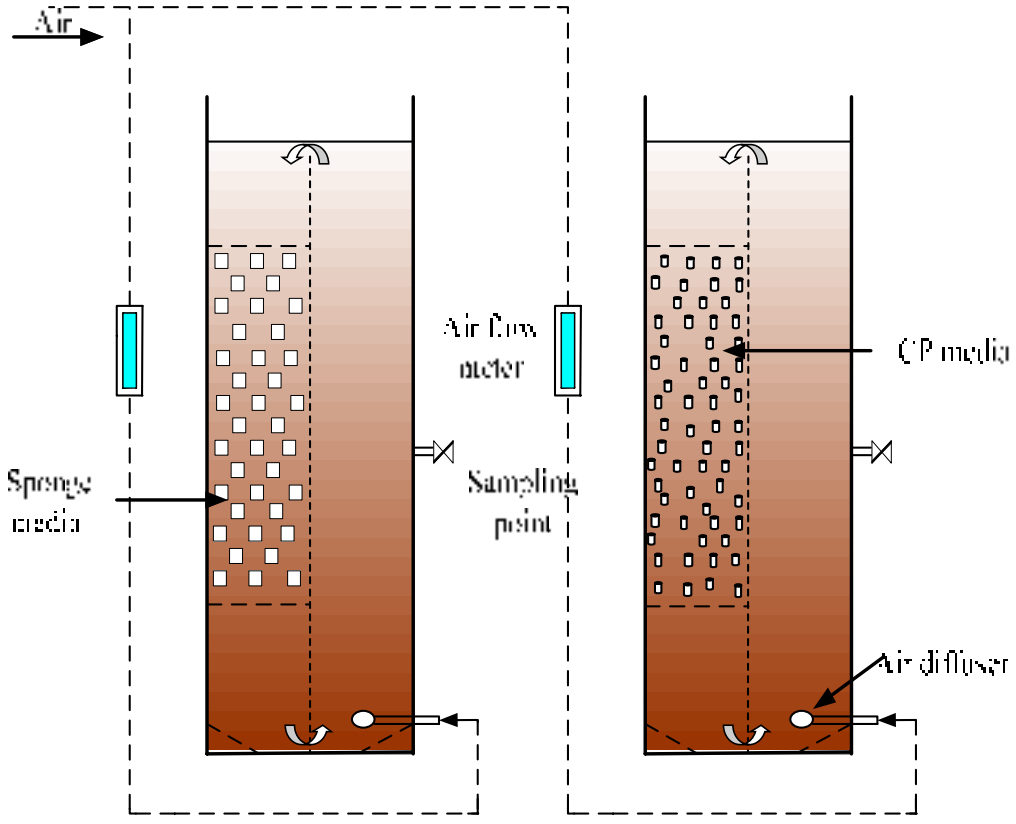


Figure 3.2 Experimental arrangement of the sequencing batch reactor (SBR)

Sequencing batch reactors were operated according to the operational conditions as shown in table 3.2. It was expected to have an air lifting flow situation inside the reactor because of the air diffusers. The volume ratios of the media to the total volume of the reactors were around 20%. The dissolved oxygen (DO) level was maintained around 2 to 3 mg/L. The intention here was to have an anoxic condition inside the reactor, so that it would enhance

the biofilm growth. DO level and pH were measured by DO meter and pH meter respectively. Removal efficiency was measured in terms of COD, TKN, TN and mixed liquor suspended solids (MLSS) was measured based on the standard methods (APHA, 1998). Attached biomass calculations were done according to the methods shown in Appendix B 1 and B 2.

Table 3.2 Operational Parameters for Batch Reactors

Parameter	Units	Value
HRT	h	24
pH	-	7 - 8
Temperature	˚C	28 ± 2
MLSS	mg/L	6000 – 8000
Organic loading	kg COD/m^3.d	2.5
DO (aeration side)	mg/L	2-3
SRT	d	20

Synthetic wastewater was used as a continuous source of biodegradable organic pollutants such as glucose, ammonium chloride, soy protein and potassium dihydrogen orthophosphate. It was selected to simulate domestic wastewater and the compositions were given in Table 3.3.

Table 3.3 Compositions of Synthetic Wastewater Used

Component	Concentration (mg/L)
Glucose	235
Soy protein	250
NH_4Cl	497
KH_2PO_4	43
$CaCl_2$	10
$MgSO_4.7H_2O$	10
$FeCl_3$	3
$NaHCO_3$	500

In this study the COD: N: P ratio was selected as 100: 30: 2 in order to measure the nitrogen removal accurately. There were two loadings; first one OLR was 1.5 kg COD/m^3.d and the second OLR was around 2.4 kg COD/m^3.d. The total nitrogen was varied from 0.45 to 0.7 kg nitrogen/m^3.d. Feeding was done twice a day. All the other operational parameters which are mentioned in Table 3.2 were the same for both reactors. The seed microorganisms for microbial growth in the reactors were obtained from an activated sludge treatment plant treating domestic wastewater. It was allowed to acclimatize in the reactor for 10 to 15 days.

3.2 Laboratory scale membrane bioreactor study

Adopting the above explained procedure polyethylene sponge media was selected for MBR studies. The laboratory experimental set up for the reactor is given in Figure 3.3. The reactor working volume was 15 liters each and there were two reactors; one for the attached growth and the other for the conventional suspended growth MBR system. The experiment was carried out for three different hydraulic retention times (HRT); 7, 10 and

13 h. The MLSS concentration was maintained between 8 to 10 g/L. Characteristics of the hollow fiber membranes used in MBRs had the properties as shown in Table 3.4 (detailed drawing attached in Appendix A Figure A 1 and A 2). The system was operated in constant flux mode. The membrane units were connected to suction pumps (MasterFlex pump, Cole-Parmer) for continuous permeate suction. They were operated intermittently with a cycle of 10 minutes suction and 2 minutes off. A manometer was connected to the permeate line in order to measure transmembrane pressure (TMP).

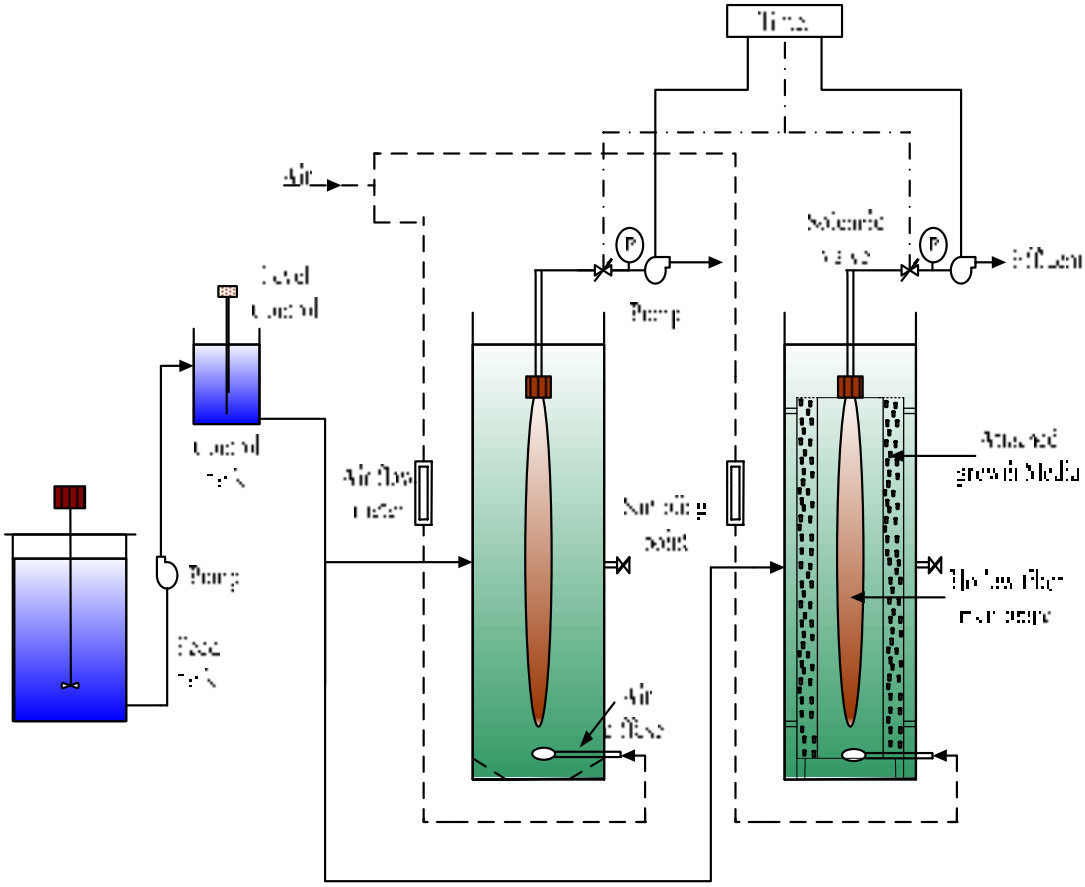


Figure 3.3 Laboratory scale experimental setup for membrane bioreactor (MBR) system.

Table 3.4 Membrane Characteristics

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

In the laboratory scale MBR, the suspended and attached growth MBRs were operated in parallel. The effects of varying HRT on removal efficiency, fouling mechanisms, EPS production, sludge characteristics and microscopic observations were carried out. The attached growth MBR comprised of inner and outer cylinders which was made out of

polyethylene nets. Media was inside theses two cylinders. Net cylinders were selected in order to provide more space for biomass circulation. Figure 3.4 shows the photos of the attach growth media cylinders top view and elevation view after packing the sponge media. The attached growth reactor was designed to have air lift condition. Therefore at the bottom of the reactor there was a 2 cm gap between the bottom of the reactor and the bottom of the media cylinder.

a) Inner and outer net cylinders

b) Top view of the two cylinders

c) After packing sponge media

Figure 3.4 Photos of the two cylinders, elevation top view and after packing media.

Overall laboratory scale MBR experimental work plan is shown in Figure 3.5. In this case MBR was operated under three different HRT values; 10, 7 and 13 h. The MLSS concentration was maintained between 8 and 10 g/L during the operation. For each experimental run analysis for removal rates in terms of TN and COD, EPS, MFI and microscopic observations were performed in order to achieve the final conclusions.

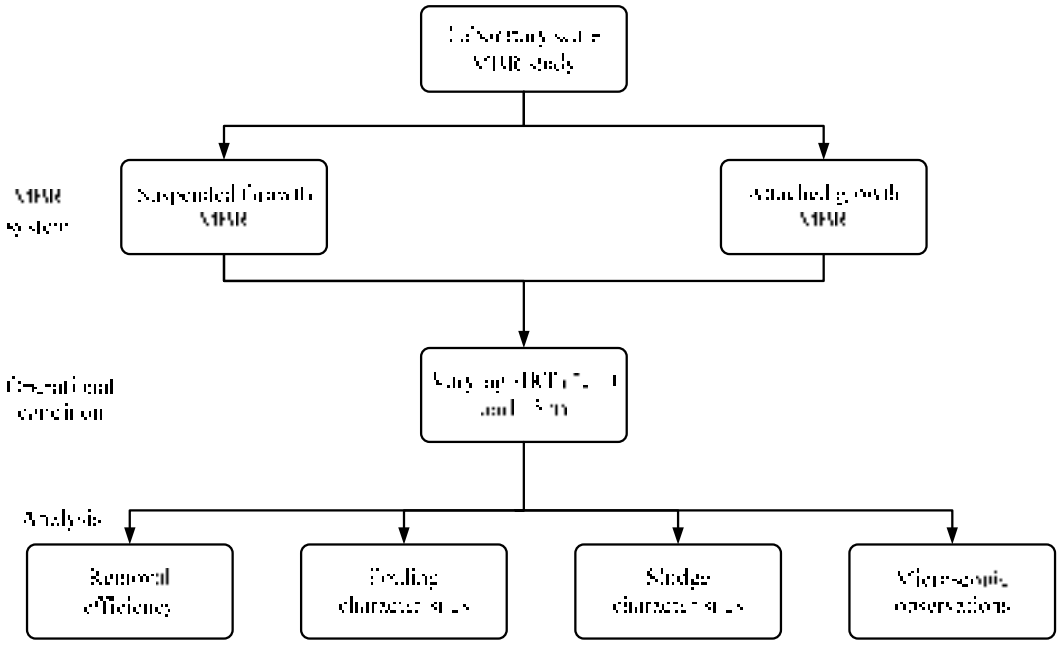


Figure 3.5 Experimental work plan for MBR study.

The variables and constants used in both SBR and MBR analysis are given in Table 3.5. The variable for the MBR study was the HRT value and it was varied in three different values as mention in the Table 3.5. Organic loading and nitrogen loading rates were operated as constants for all the HRT values. Therefore the COD and nitrogen concentration were varying depending on the HRT value.

Table 3.5 Variables and Constants in the Study

<table>
<tr><td colspan="4">Phase I: SBR operation to select suitable media for the MBR</td></tr>
<tr><td colspan="4">Phase II: MBR operation
MLSS concentration will be maintained between 8 to 10 g/L during the operation</td></tr>
<tr><td>Variable</td><td>Value</td><td>Constants</td><td>Analysis</td></tr>
<tr><td rowspan="3">HRT (h)</td><td>7</td><td rowspan="3">SRT: 30 d,
Temperature: 28 ± 2 ˚C,
Organic loading rate:
2.1 - 2.4 kg COD/m^3.d
Nitrogen loading rate:
0.4 kg N /m^3.d</td><td rowspan="3">Removal efficiency in terms of TN and COD
Fouling and
Sludge characteristics
Microscopic observations</td></tr>
<tr><td>10</td></tr>
<tr><td>13</td></tr>
</table>

Synthetic wastewater

For MBR analysis synthetic wastewater characteristics were used as shown in Table 3.6 and the trace nutrients used in feeding the systems were listed in Table 3.7. Feeding was carried out twice a day and the feed volume varied according to the HRT and the permeate flow rate.

Table 3.6 Synthetic Wastewater Composition for Membrane Bioreactor Analysis

Component	Concentration in g/10 L stock solution
Dextrose ($C_6H_{12}O_6$. H_2O)	516
$(NH_4)_2SO_4$	471
KH_2PO_4	43
$CaCl_2$	10
$MgSO_4$.7 H_2O	10
$FeCl_3$.6 H_2O	10
$NaHCO_3$	900

Table 3.7 Trace Nutrient Concentrations

Component	Concentration in mg/ 6L stock solution
H_3BO_3	900
$CoCl_2$. 6 H_2O	900
$CuSO_4$. 5 H_2O	180
$MnCl_2$.2 H_2O	720
$Na_2Mo_4O_{24}$. 2 H_2O	360
$ZnSO_4$. 7 H_2O	720
KI	180

3.3 Analytical methods

Analytical tests for removal efficiencies of COD, TKN, NH_3 N, NO_2^- and NO_3^- were done according to the standard method (APHA, 1998). Other analytical tests were done as describe follows. The entire analytical test and the methods are tabulated in Table 3.8.

Specific cake resistance (α)

The specific cake resistance, α, was determined by the plot of time to volume ratio versus volume of filtrate. The linear portion of this plot was used to calculate α (m/kg) value. The following steps were followed to determine α, using Amicon Model 8400 with a working capacity of 400 mL. Figure 3.6 shows the experimental setup to determine specific cake resistance.

The procedure for the specific cake resistance is given in Figure 3.7. Instrument set up was directly connected to a computer and the input data was saved in it. Equation 3.1 was used for the calculations.

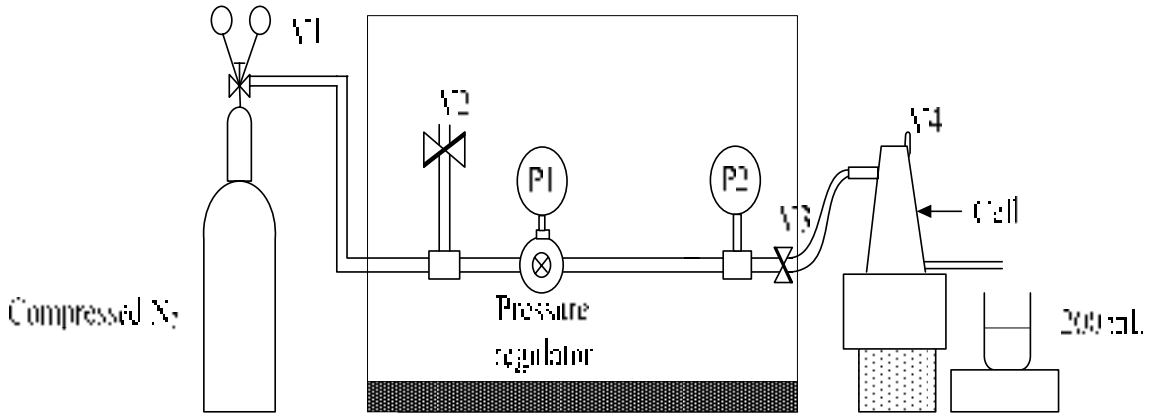


Figure 3.6 Specific cake resistance experimental setup.

Table 3.8 Analytical Parameters and Testing Methods

Parameter	Analytical method	Equipment	Applicable accuracy and range	Source
DO	DO meter	DO meter	0.1 mg/L range 2-3 mg/L	
pH	pH meter	pH meter	0.1 and 6 - 8	
COD	Closed reflex	Titration	0.1 mg/L	APHA *et al*., (1998)
TKN	Semi-Micro-Kjedahl	Titration	0.1 mg/L	APHA *et al*., (1998)
NH_3-N	Distillation	Titration	0.1 mg/L	APHA *et al*., (1998)
NO_2-N	Colorimetric	Spectrophotometer (Hitachi U-2001)	0.1 mg/L	APHA *et al*., (1998)
NO_3-N	Colorimetric	Spectrophotometer (Hitachi U-2001)	0.1 mg/L	APHA *et al*., (1998)
MLSS	Dry at 103˚C and 105˚C	Filter / Owen	100 mg/L	APHA *et al*., (1998)
MLVSS	Dry at 550˚C	Furnace	100 mg/L	APHA *et al*., (1998)
EPS	CER method	Centrifuge	0.1 mg/L	Frolund *et al*., (1996)
Carbohydrate	Phenolic-sulfuric acid	Spectrophotometer (Hitachi U-2001)	0.1 mg/L	Dubois *et al*.,(1956)
Protein	Lowry	Spectrophotometer (Hitachi U-2001)	0.1 mg/L	Lowry *et al*., (1951)
CST	Capillary time	CST appratus	0.1 s	APHA *et al*., (1998)
Specific cake resistance	Dead end filtration	Filter holder (Amicon)		Boerlage *et al*.,(2003)
TOC	TOC Analyzer	TOC Analyzer (Shimadsu)	0.01 mg/L	
Sludge morphology	Microscopic observation	Microscope		Jenkins *et al*., (1993)
SOUR	Standard method	Respirometer	0.1 mg/L	APHA *et al*., (1998)
Particle size distribution	Laser light scattering	Malvern Mastersizer/S (Malvern, UK.)		

Note: For COD, high concentration of NO_2^- and Cl^- will have interference

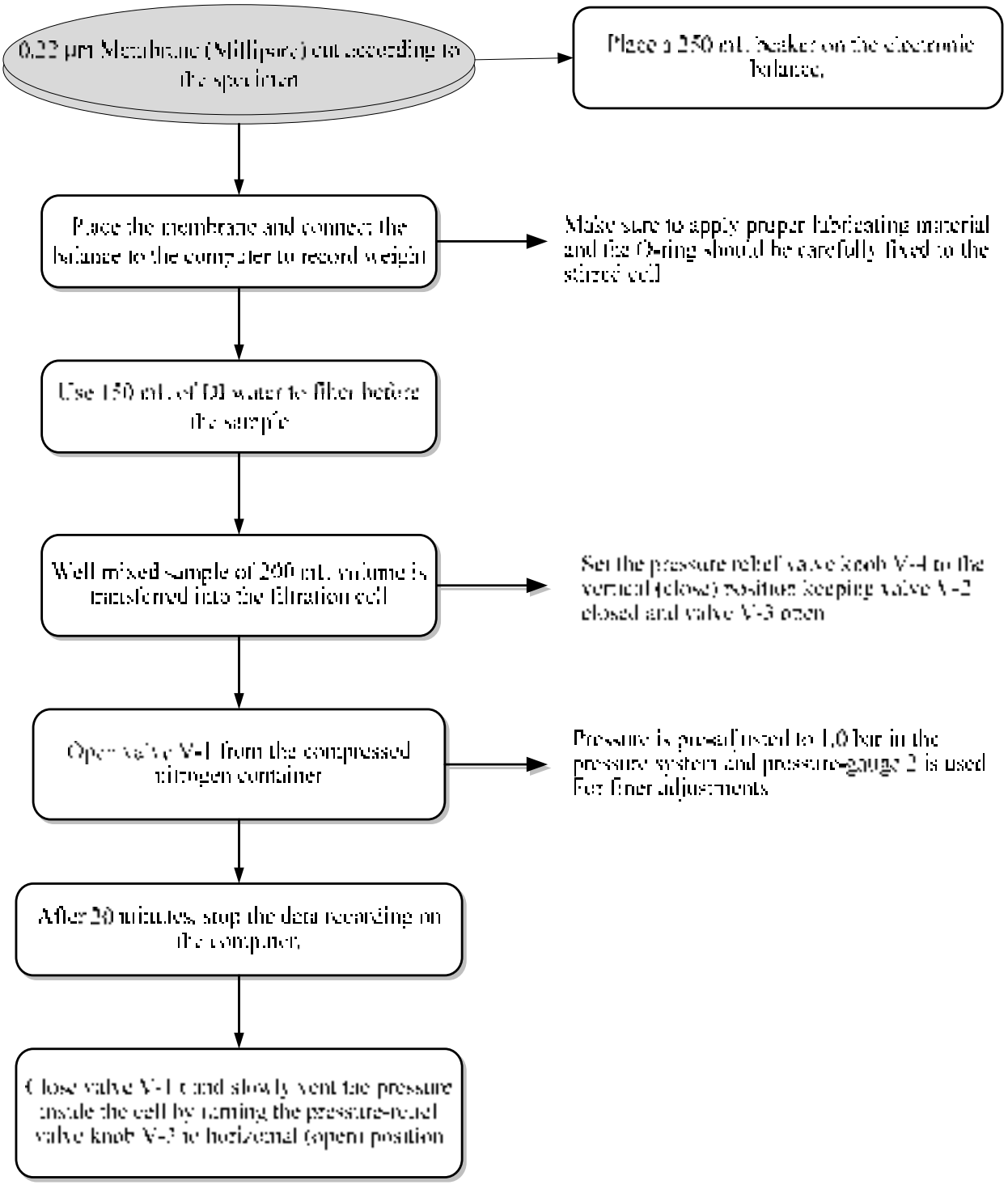


Figure 3.7 Protocol for specific cake resistance measurement.

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

Equation 3.1

Where t = filtration time (s)
V = filtrate volume (mL)
μ = viscosity (Pa.s)
R_m = membrane resistance (1/m)
ΔP = transmembrane pressure (kPa)
α = specific resistance of the cake deposited (m/kg),
C_b = concentration of the particles (mg/L)
A = membrane surface area (m^2).

Particle size distribution

The particle size distribution was determined by using a Malvern Mastersizer/S (Malvern, UK.). For analysis fresh sludge was collected directly from the reactors.

Capillary suction time (CST)

Capillary suction time was carried out to check and compare the dewaterability of the activated sludge. Triton CST apparatus (Type 165, UK) was used to perform the test. The test procedure was in accordance with the APHA method 2710G (APHA, 1998).

Exracellular polymeric substance (EPS)

EPS calculations were carried out according to the cation exchange resin (CER) method. For EPS extraction the commercial grade of CER resin in the sodium form was used. Table 3.9 presents the specifications of the resin used in the experiments.

Table 3.9 Cation Exchange Resin Specifications

Product	DOWEX HCR-S/S
Type	Strong acid cation (Na^+ form)
Matrix	Styrene-DVB gel
Functional group	Sulphonic acid
Bead size distribution range	0.3-1.2 mm (50-16 mesh)
Water content	48-52 %
Maximum operating temperature	120^oC
pH range	0-14

CER was stirred for 20 min after adding 100 mL of the extraction buffer solution. It is always better to clean the resin before adding the extracted samples for EPS determination. The CER buffer solution consists of the following constituents and respective concentrations as shown in Table 3.10.

Table 3.10 Cation Exchange Resin Buffer Solution Constituents

Chemical name	Concentration	Amount in 1 L of DI water
Na_3PO_4	2 mM	164*2/1000 = 0.328 g
NaH_2PO_4	4 mM	120*4/1000 = 0.48 g
NaCl	9 mM	58.5*9/1000 = 0.5265 g
KCl	1 mM	74.6*1/1000 = 0.0746 g

The CER extraction procedure will be followed as describes in Figure 3.8.

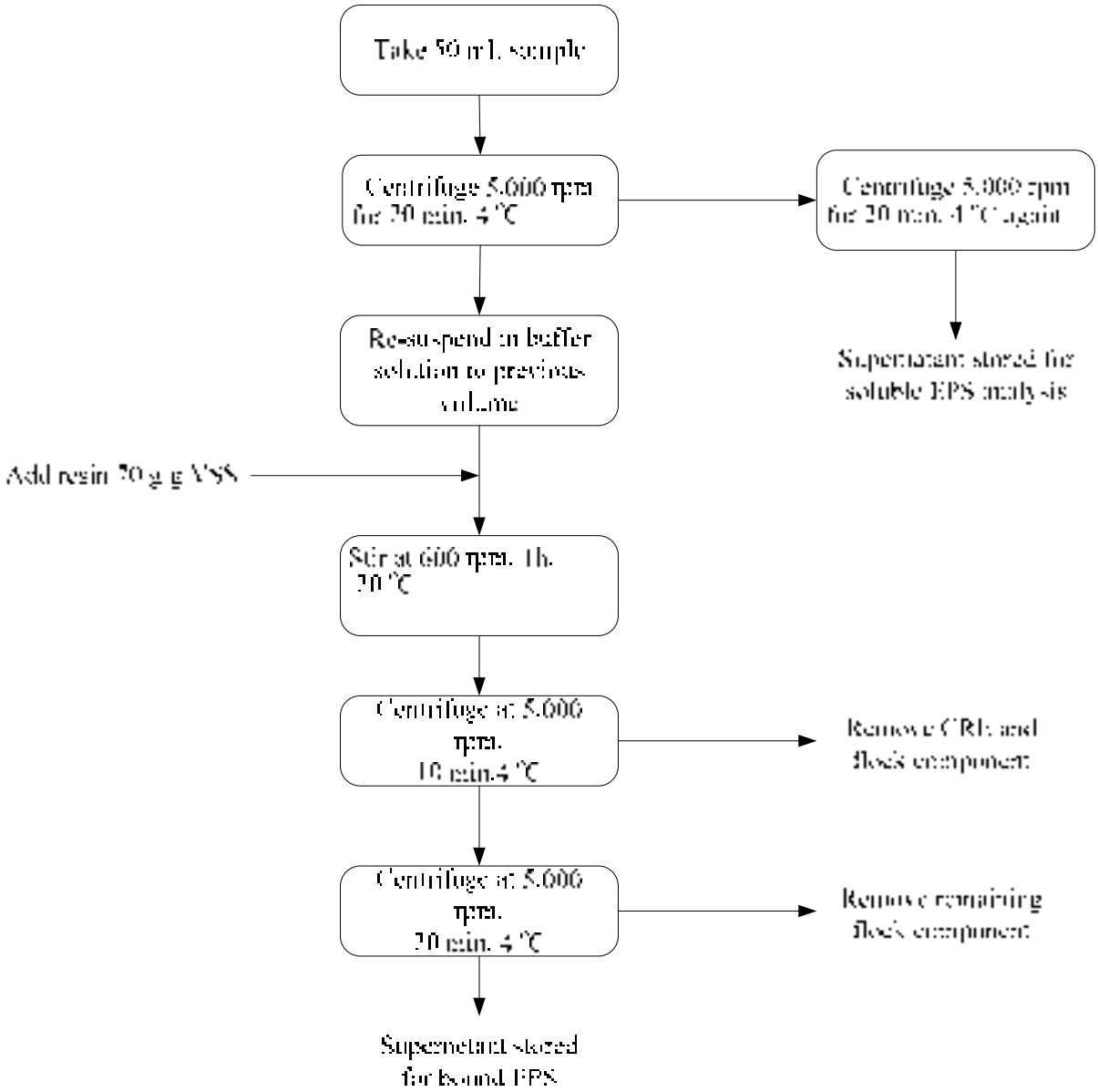


Figure 3.8 Procedure for Cation exchange resin (CER) extraction method.

3.4 Membrane cleaning

One of the main disadvantages of MBR is membrane fouling due to the formation of cake layer. In order to reinstate the performance of the membrane modules in the MBR it is necessary to carry out membrane cleaning.

Membrane cleaning was carried out once the TMP reached to a maximum value of 30 kPa. Then the fouled membrane was taken out of the system carefully in to a separate water bath and the total resistance was measured (R_t). After that the membrane was cleaned by tap water and then it was dipped in a deionized (DI) water and measure the membrane resistance ($R_c + R_f$). After that the membrane was dipped in a chemical cleaning solution for another 6 hrs. The chemical cleaning solution contained NaOCl 10 % and NaOH 4%. Then the membrane was washed with tap and followed by the DI water to make sure that the solution is removed from the membrane. Then the clean membrane resistance was measured (R_m).

In order to increase the efficiency of the cleaning process chemical recirculation was done with both acid and base cleaning solutions. For the acid cleaning it was recommended in the operational manual (Mitsubishi Rayon) to use HCl 1.8 % to 3.6% solutions. In this research it was used 1.8% HCl solution. The setup for the recirculation is given in Figure 3.9. Instead of soaking in a chemical solution the recirculation of chemical was effective and needed less time duration. Normally acid and base chemical solutions were recirculated for a 2 h period and in between the membrane was cleaned by DI water. It is very important to clean the membrane module after using each of the chemical. Otherwise there is a possibility of serious damages to the membrane. It is recommended to use tap water to rinse the membrane and in this study DI water was recirculated for 2 h in between each chemical cleaning process.

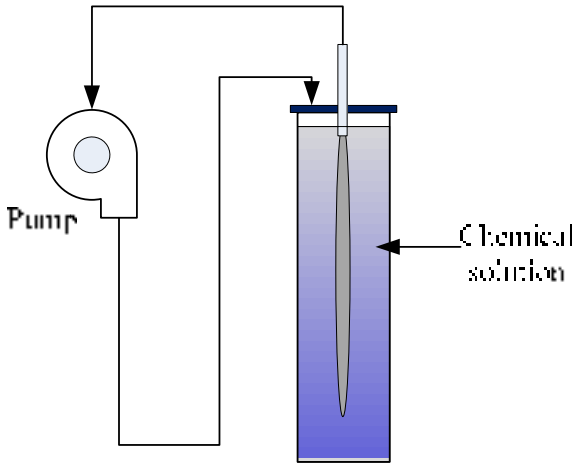


Figure 3.9 Membrane cleaning by chemical solution recirculation.

3.5 Membrane resistance measurement

The membrane resistance will be calculated by using the following two equations.

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

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

Where, J is the permeate flux, μ is the viscosity, R_m is the intrinsic membrane resistance, ΔP is the transmembrane pressure, R_t is the total resistance, R_c is the cake resistance formed by the cake layer, R_f is the fouling resistance due to solute adsorption. For pure water R_m will be calculated from Equation 3.2 and once the membrane is fully clogged the R_t will be calculated. Then after cleaning carefully $R_m + R_f$ will be calculated. After substituting the equation 3.3 the cake resistance can be calculated. The protocol for membrane cleaning is shown in Figure 3.10.

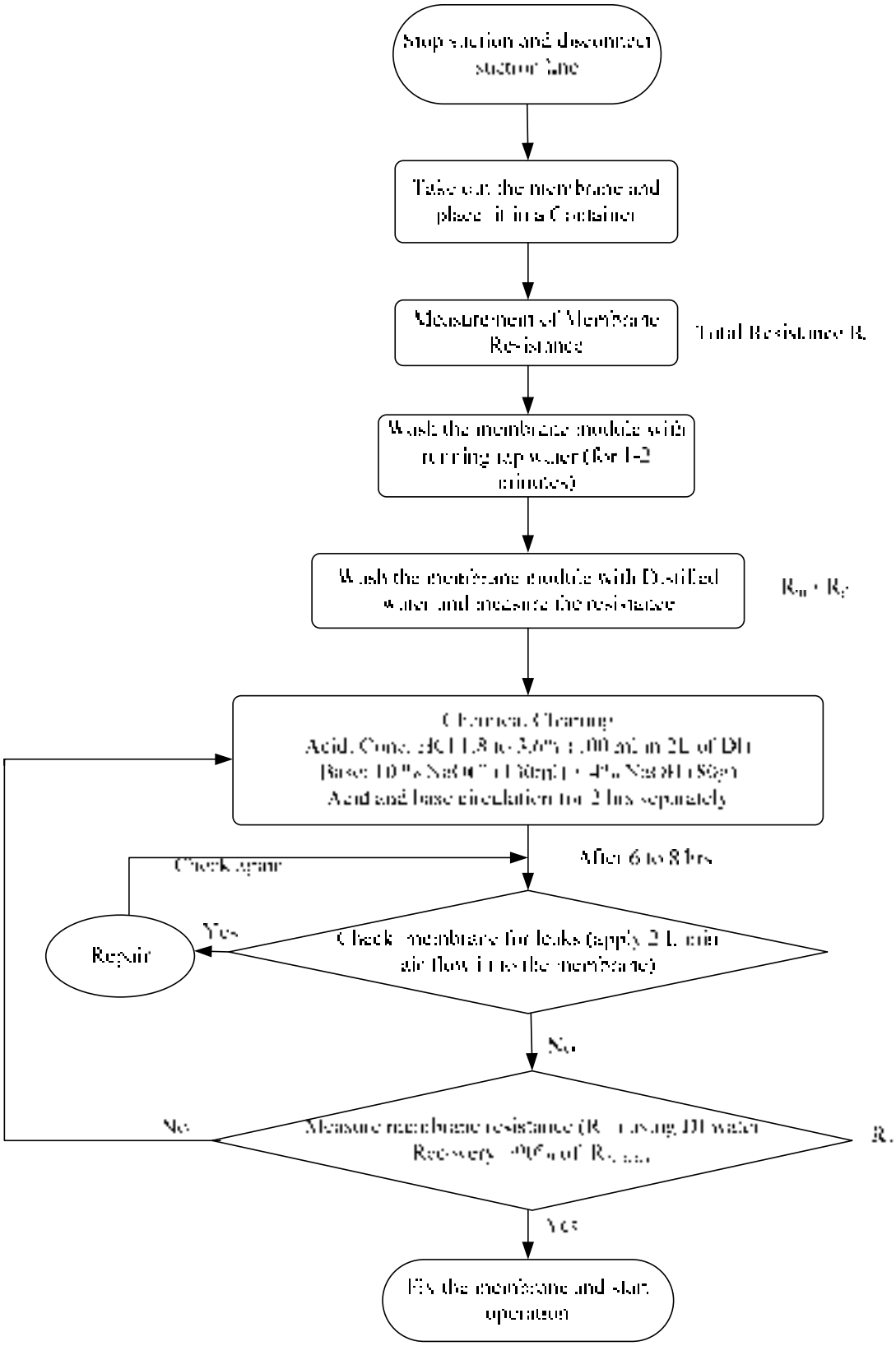


Figure 3.10 Membrane cleaning and resistance calculation procedure.

Chapter 4

Results and Discussions

Findings of this thesis research work are divided into two main categories; results of phase I and results for phase II. Phase I of the study focused on selection of the appropriate media type out of the two selected media types. There were two sequencing batch reactors operated for a period of nearly three months under ambient conditions. The media selection was based on COD and TN removal efficiencies of the two reactors. Apart from that, there was another sponge media SBR operated with a different configuration. The objective of the third reactor was to select the suitable configuration for MBR study. The first part of this chapter presents the results of the above mentioned objectives.

The latter part of the chapter presents the results related to the other two objectives, considering the analytical data obtained during the second phase of the study.

4.1 Selecting an Appropriate Media

Final decision of the suitable media type for the MBR study was made by considering the removal efficiencies in terms of COD and TN of the two reactors; reactor 1 (R1) with cylindrical polypropylene (CP) media and reactor 2 (R2) with polyethylene porous sponge media (PS).

4.1.1 Startup of the reactors

The two reactors were acclimatized for a period of 20 days during which the DO level (Appendix C table C 8) and the pH were measured. The media volume ratios were around 20% from the total volume of the reactors for both R1 and R2. HRT for the two reactors was maintained as 24 h. After operating the two reactors R1 and R2 for 24 days the MLSS concentration was observed as 4.97 and 5.55 g/L respectively. The method adapted to measure MLSS of the media is described in appendix B Figure B 1 and B 2. During the startup of the SBR system the organic loading rate was around 1.2 kg COD/m^3.d. MLSS was controlled between 6 to 8 g/L by wasting the excess sludge. Excess sludge wastage of the reactors were stated once the MLSS reached 8 g/L in R2 and maintained sludge retention time as 20 days. pH of the reactors were maintained between 7.3 and 8.3 (Appendix C table C 6 and C 7)

4.1.2 MLSS and DO variations

Figure 4.1 shows the MLSS concentration variation throughout the operational period of the SBR. According to that from day 20 to day 40 there is a clear increase of biomass in suspension in R2; the sponge media reactor. This period there was no excess sludge removal. In the same period R1 containing CP media showed a low growth rate of suspended biomass. In day 43 the excess sludge withdrawal started and it was observed a reduction in mixed liquor suspended solids in R2. Attached biomass to the sponge and CP media remained unchanged at 15.2 g/L and 5 g/L respectively. After 20 days of operation suspended biomass in R1 became black color (anaerobic condition). Photos of the SBR system after 10 days and 20 days operation are presented in Figure 4.2. Furthermore it was observed a media settlement in the media compartment of the reactor. In order to move the media bed intermittent aeration was introduced just below the perforated plate in both the

reactors. The DO levels of the two reactors were maintained above 2.5 mg/L in the media side of the reactors. MLSS concentration of both R1 and R2 reached to a steady state after day 52 of the operation. Final MLSS concentrations were maintained between 6 and 8 g/L for both the reactors (Appendix C table C 1).

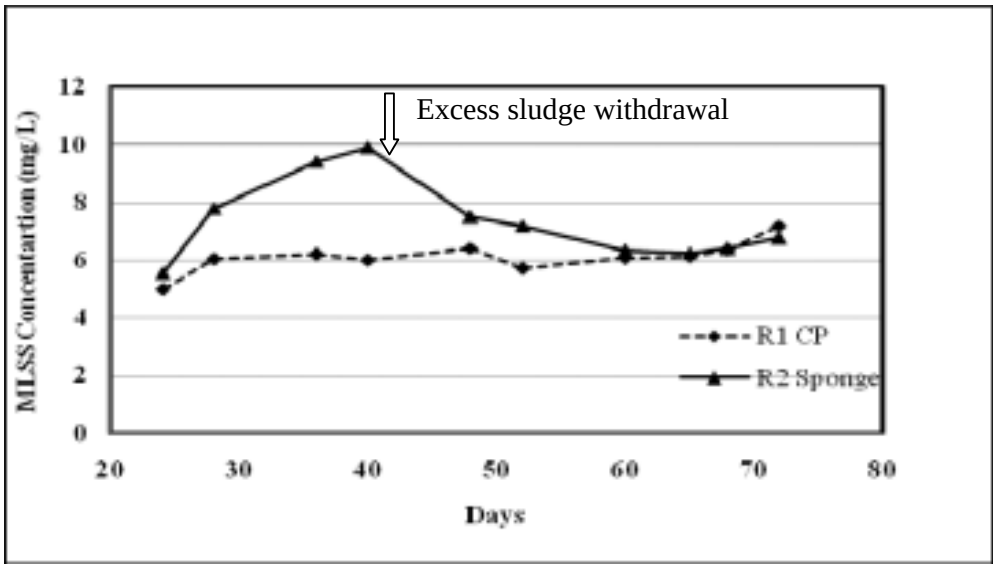
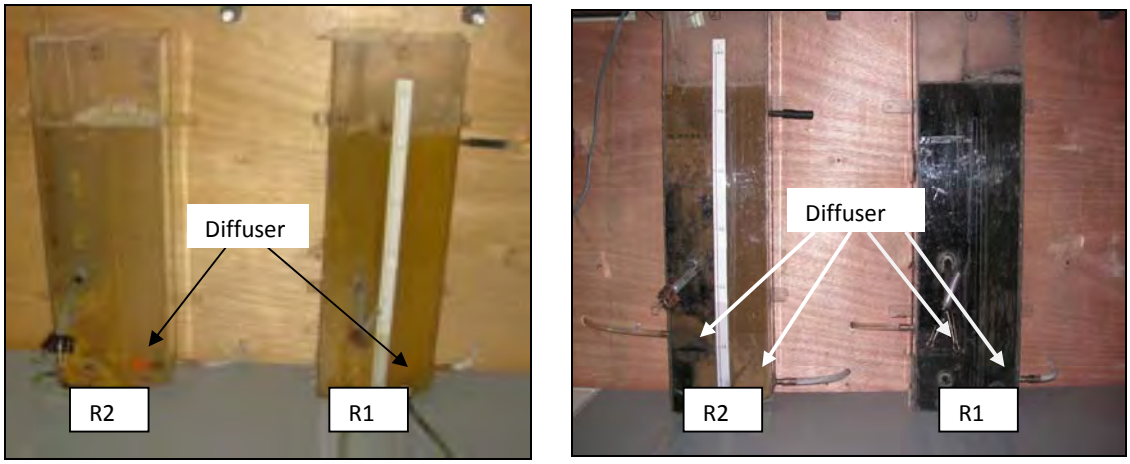


Figure 4.1 MLSS variation in R1 and R2 through out the operation.



(a) (b)

Figure 4.2 SBR (a) after 10 days (b) after 25 days of operation.

Variation of DO throughout a 12 h period of operation presents in Figure 4.3. According to that R1 aeration side and media side DO concentrations were varied between 3.5 and 4.5 mg/L (Appendix C Table C 5) and the sharp drop was observed due to the feeding of new batch of synthetic wastewater. In R2 the DO concentrations were varied between 2.3 and 4.2 mg/L during its normal operation despite the drastic reduction at the feeding time. It was observed a gradual increase of DO in R2 both aerated and media sides but in R1 the variations were more or less constant. Few hours after feeding, it was observed a biomass settlement in the media side of R1 and this might be the reason for the constant DO profile in R1. On the other hand in R2 no biomass settlement was observed.

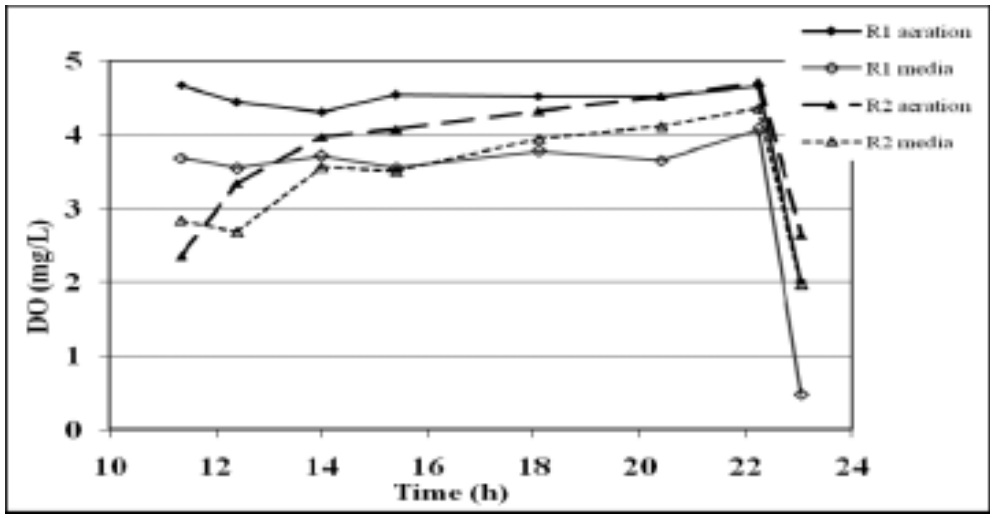


Figure 4.3 Dissovled oxigen variation throughout a 12 h period for both R1 and R2.

4.1.3 COD removal of the SBR

Figure 4.4 shows the variation of influent and effluent COD for both R1 and R2. From day 1 to day 36 the system was operated under the first loading i.e. OLR 1.4 kg COD/m^3.d. The COD concentration was maintained between 1100 to 1300 mg/L. During the second loading the OLR was maintained between 2.2 to 2.4 kg COD/m^3.d and the respective COD concentration was in the range of 1800 to 2100 mg/L. Effluent COD in R1 was varied between 80 and 270 mg/L during the first loading and for the sponge reactor (R2) it was varied between 30 and 180 mg/L. Towards the end of the second loading the effluent COD concentration was observed to be varying around 130 mg/L for R1 and 50 mg/L for R2 (Appendix C Table C 2).

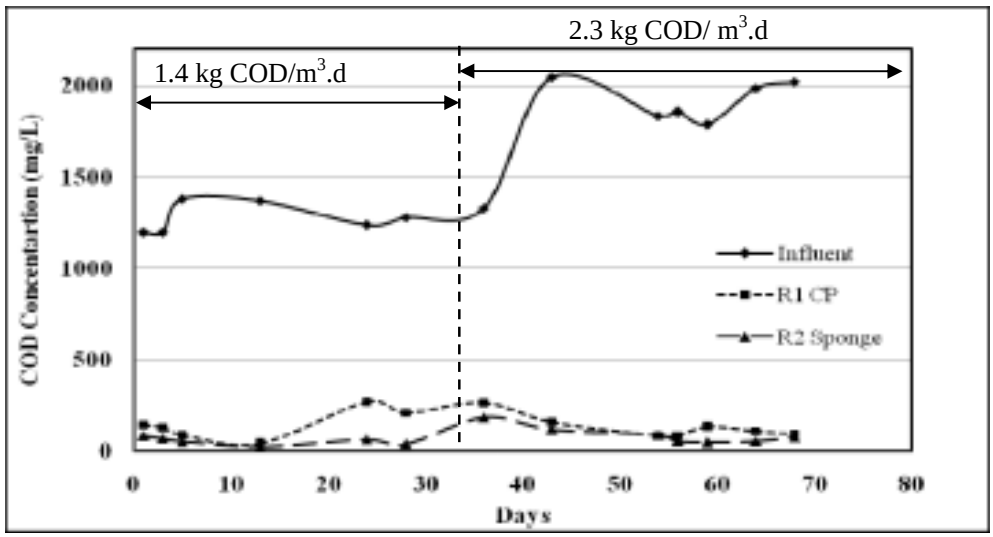


Figure 4.4 COD concentartion in Influent and Effluent of R1 and R2.

COD removal efficiencies in R1 and R2, presents in figure 4.5. It was observed a drop of removal efficiency to a value of 78% between day 12 and 23 in R1. Furthermore a media settlement was observed in R1 with in the same period and the biomass in the reactor became black. In order to achieve higher removal efficiencies there is a necessity of

substrate diffusion from bulk liquid into the biofilms over the media (Chae et al., 2007; Metcalf and Eddy, 2004). Therefore the reason for the reduction in above mentioned period might be due to less biomass diffusion into the biofilms in R1. To overcome the above mentioned operational problem, additional air diffusers were installed in each reactor at the bottom of the media compartment. Finally it was observed a fairly stable COD removal of about 95% and 97% for R1 and R2 respectively.

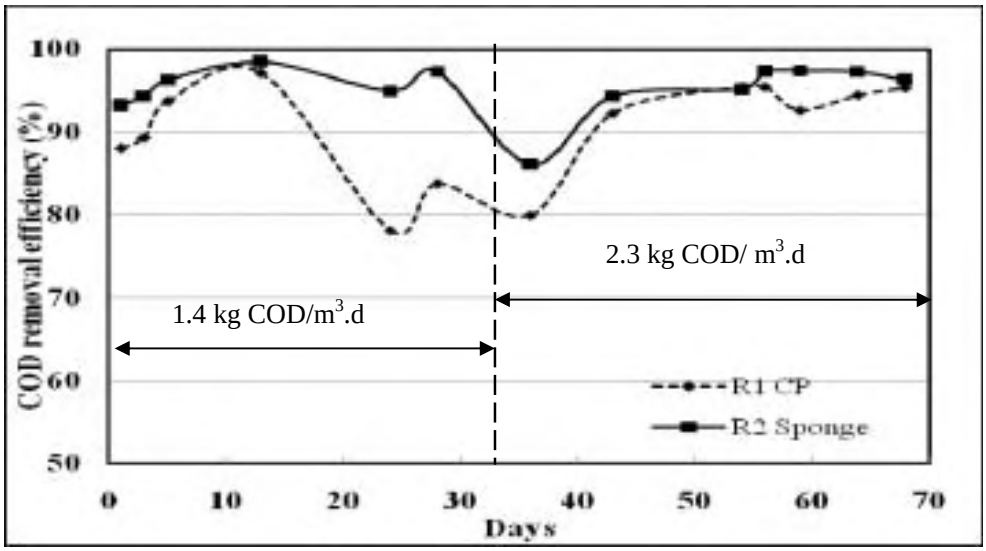


Figure 4.5 COD removal efficinecies of R1 and R2.

4.1.4 TN removal in SBR

TN removal was one of the key parameters used in the phase I analysis. Figure 4.6 shows the TN concentrations in influent and the effluent of R1 and R2. At the beginning of the operation the nitrogen concentration was around 260 mg/L and then it was gradually increased to 630 mg/L (Appendix C Table C 4 and C 5). According to the Figure 4.6, R2 (sponge media) contained less effluent TN concentration than R1 in all the time. This means Sponge media had been able to remove more TN than CP media. The removal efficiency of TN presents in Figure 4.7. At the beginning the TN removal rate in R2 was around 82% and with time it decreased to 70% at the end of the analysis. On the other hand in R1 TN removal efficiency increased from 25% to 50% at the end. The decrease in R2 (Sponge) may be due to the less biomass diffusion into the sponge media. This can be further discussed with the biofilm growing pattern of the sponge media. During the startup period in R2 the sponge media were clean without any biomass on them. Later with time the porous cavities inside the sponge media started filling up with biomass. Furthermore it was observed an increase in MLSS (in suspension) in R2 during the same period (Figure 4.1). This high biomass might have blocked the circulation paths between media resulting less fresh food diffusion into the biofilm. This would have finally led to a reduction in denitrification rate of the reactor. Figure 4.8 shows some of the photos of the media surfaces with biofilms. The media samples were taken at day 62 of the SBR operation. It was observed a biofilm thickness up to 5 mm over the sponge media during the analysis.

Biofilm thickness is an important factor deciding the performance of the media. Chae et al., (2007) observed a rapid ammonia ion concentration decreased in a biofilm up to a depth of 2 mm. The authors further observed micro channels inside the biofilm to diffuse

the bulk liquid in to the biofilm. Once these channels blocked, the amount of diffusion would be less resulting a reduction of removal efficiencies in terms of COD and nitrogen.

For R1 initially there was no biofilm over the media surface and unlike sponge media CP was not porous. Therefore the only place that the biofilm can create was the outer surface of the media (Figure 4.8 e and f). Therefore it would have been taken more time than Sponge media to deniftrification to take place. The observed biofilm thickness for CP media was around 0.4 to 0.8 mm. Furthermore it was observed CP media settlement and packing in the media side of the reactor after few days of operation. Due to the media settlement in the reactor the media side became completely black creating an anoxic/anaerobic zone. At the end of the operation a stable TN removal rate (50%) was observed in R1 (Figure 4.7).

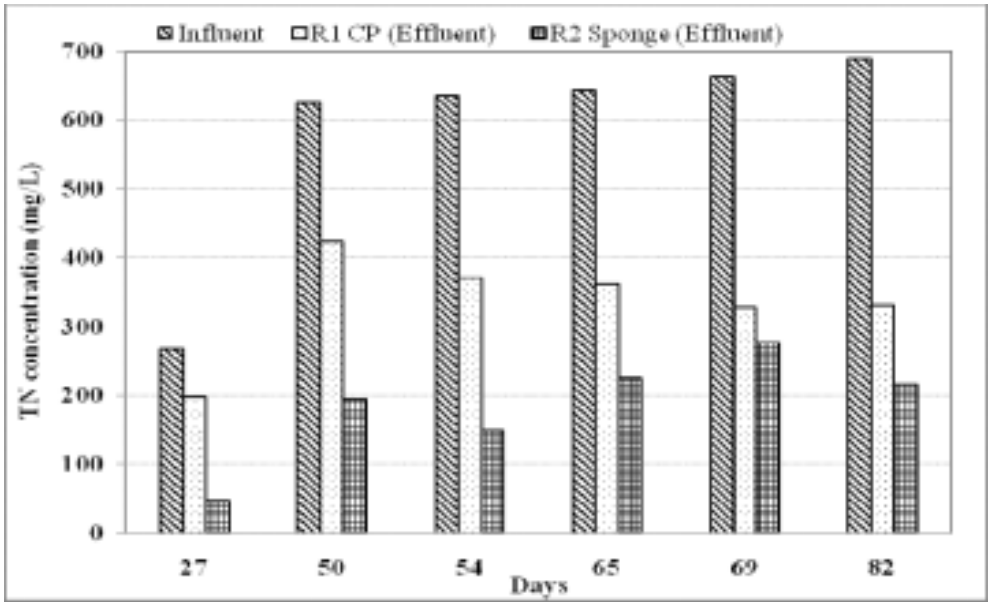


Figure 4.6 TN concentrations in influent and effluent of R1 and R2.

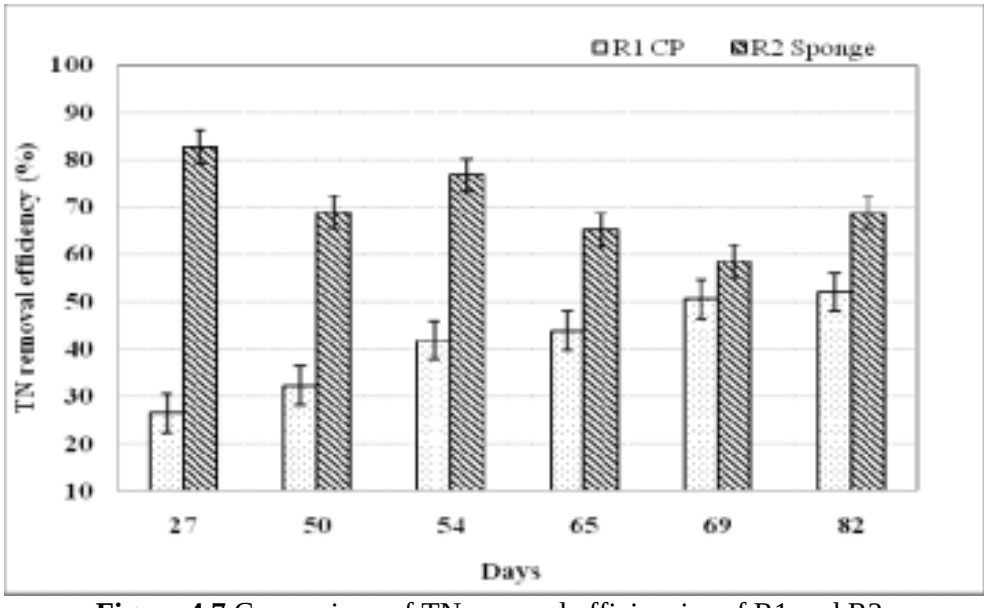


Figure 4.7 Comparison of TN removal efficiencies of R1 and R2.

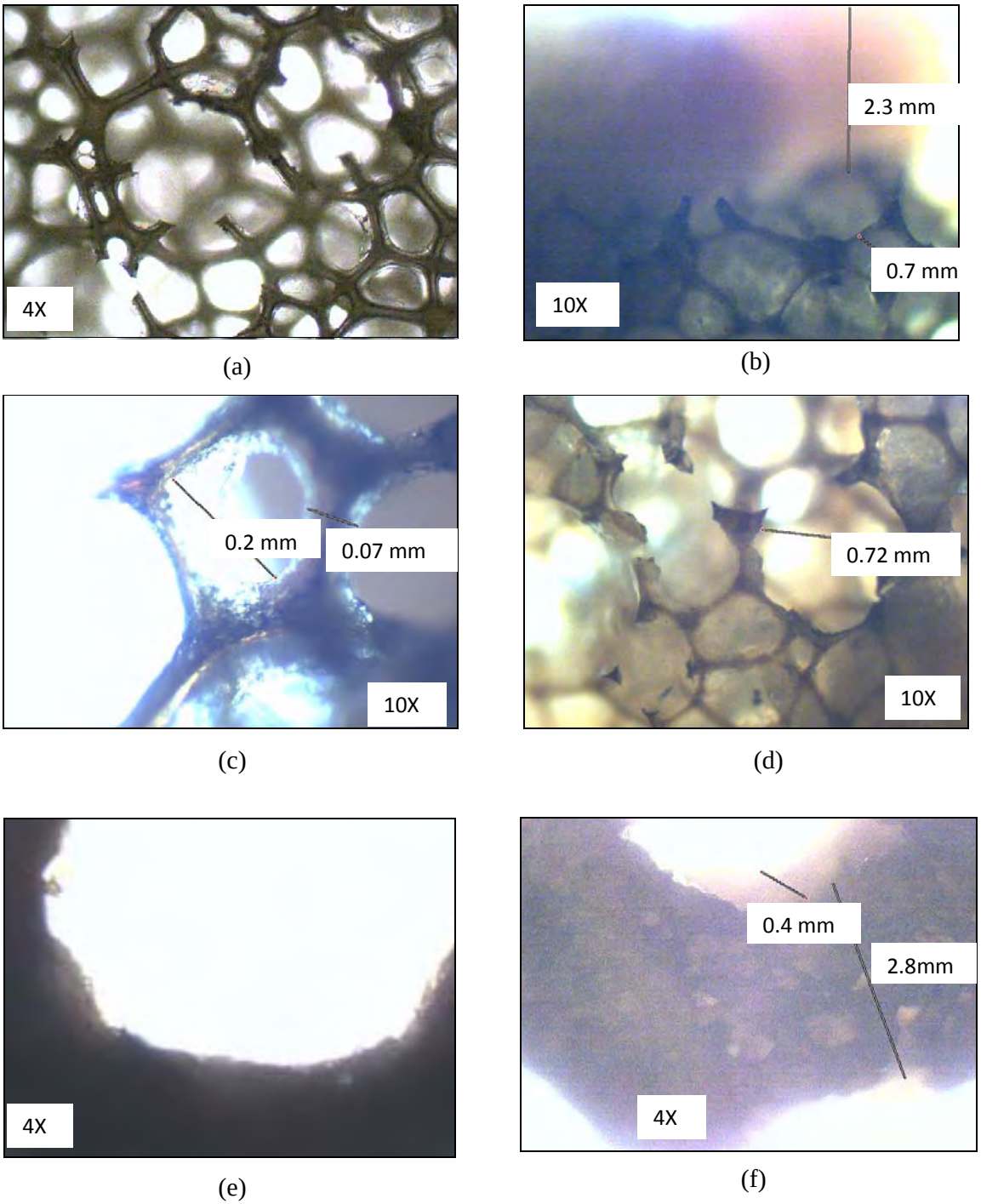


Figure 4.8 Photos of media (a) Virgin Sponge (b), (c) and (d) Sponge with biofilm, (e) Virgin CP and (f) CP with biofilm.

According to the photos in Figure 4.8 biofilm growth can be seen all over the sponge media including inside the pores but, on the other hand in R1 biofilm covers the outer surface and the thickness is around 0.4 mm. In Figure 4.8 (e) and (f) shows the cross sectional views of the CP media.

4.1.5 Media selection

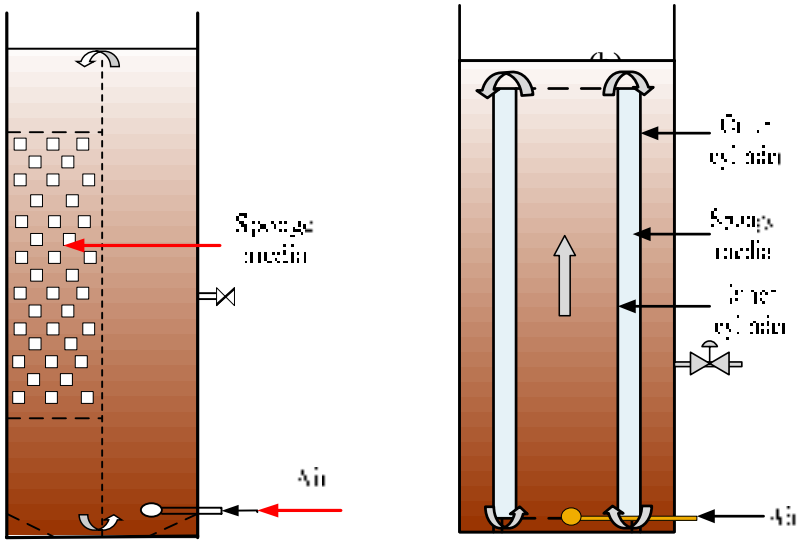
As described in the earlier sections media selection was carried out by comparing the COD and TN removal efficiencies of R1 (CP) and R2 (Sponge) and the operational feasibility. According to a previous study conducted by Sombatsompop (2007) the TKN removal of CP and Sponge media types were found to be 86 and 83% respectively. In that case the author used a moving bed sequencing batch reactor and the initial nitrogen concentration was around 30 mg/L. There was no biofilm formation on media surfaces due to the media movement and agitation. It was assumed denitrification to be zero in that study. But in the present study media was in a confined compartment where there was less DO (around 3 mg/L) and less movement and the total nitrogen in influent was around 650 mg/L. Therefore it was observed simultaneous nitrification and denitrification in both the reactors.

According to the findings of this study COD removal efficiency of the two reactors were around 95% and this agreed with the findings of Ngo et al. (2008) and Sombatsompop (2007). Leiknes and Odegaard (2007) found out that the COD removal rate for a biofilm membrane bioreactor (BF-MBR) was around 85%. During their pilot scale study combined sewerage wastewater used as the influent.

In summary, TN removal efficiency was higher in R2 (sponge media) than R1. In percentages, it was around 70% in R2 and 50% in R1. After considering the removal efficiencies in terms of COD and total nitrogen, it was decided to use sponge media for the MBR study as the attached growth media.

4.1.6 Selection of a suitable configuration for the MBR analysis

Apart from the two media reactors; R1 and R2, there was another sequencing batch reactor with a circular (R3) configuration operated in order to find out the suitable configuration for the MBR. Figure 4.9 presents the two different configurations used in the analysis.



(a) (b)

Figure 4.9 Comparison of the two different configurations; (a) Rectangular, (b) Circular.

The main differences of the two configurations were the flow pattern and the size of the membrane chamber. Operational parameters of the new R3 circular reactor were similar to the R2 (Sponge rectangular). DO and the pH variations were monitored daily (Appendix C Table C7 and C8).Removal efficiency of the reactor was analyzed in terms of COD and TN. The volume ratio of sponge media in R3 was selected as 20% of the total reactor volume. Finally the removal rates of R3 were compared with R2.

Figure 4.10 presents the COD concentrations and the removal efficiency of R3. During the study period the COD removal rate in R3 (Circular) was varied between 95% and 97%. Finally, it was found that there was no significant difference between the two configurations in terms of COD removal (Appendix C Table C 2)

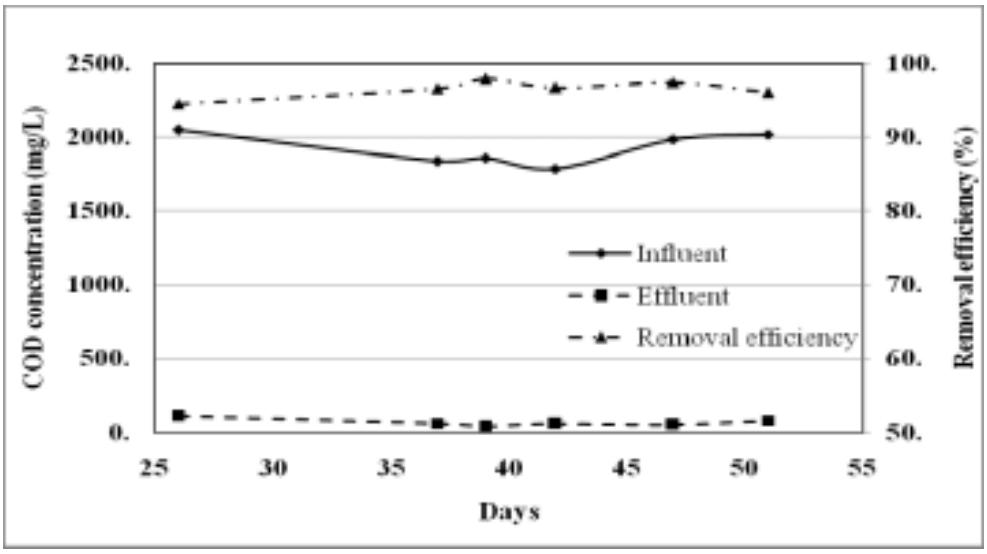


Figure 4.10 COD concentrations in influent, effluent and removal efficiency.

Apart from COD removal rate the other deciding factor was the comparison of TN removal rate between the two configurations. At the end of phase I it was found that the TN removal of R3 (Circular) reactor was around 10% higher than the R2 rectangular configuration (Appendix C Table C 9). Furthermore, R3 (Circular) configuration demonstrated a far better hydrodynamic condition without sludge settlement at the bottom of the reactor. Therefore the circular configuration was selected as the suitable configuration for phase II (for MBR) of the study.

4.2 Performance of MBR

Phase II of the study mainly focused on the performance of the membrane bioreactor in terms of COD and TN removal rates and the fouling behavior. There were two MBRs; R1 conventional and R2 attached growth. R1 was operated as a completely mixed suspended growth MBR while R2 was operated as an attached growth MBR. The porous sponge media was selected as the attached growth media based on the previous results. The removal efficiencies and the fouling propensities were compared between the two reactors in order to conclude the better performing system. The MBRs were operated in three different HRT values namely; 7, 10 and 13 h while keeping OLR and NLR constant. SRT was maintained at 30 days for the whole study period. The COD: N: P ratio was selected as 100:20:2 for the MBR analysis.

4.2.1 Effects of hydraulic retention time on MBR performance

In this study the system was operated for three different HRT values (Table 3.5). The COD and nitrogen concentrations were varied in order to keep OLR and NLR constant throughout the experiment. Table 4.1 presents a summary of number of days operated the systems under each HRT and the net permeate flux in each reactor.

Table 4.1 Summary of number of days Operated each Reactor under three HRTs and Permeate Flux

		Permeate flow rate (mL/min)	Net permeate Flux ($L/m^2.h$)	R1 Conventional (d)	R2 Attached growth (d)
HRT (h)	7	43	5.10	40	40
	10	30	3.57	90	90
	13	23	1.15	30	30

pH of the two reactors were maintained between 7.3 and 8.2 for all HRT values. It was observed a pH drop due to the nitrification process in R1 (conventional) and the pH adjustments were done externally adding $NaHCO_3$ (Appendix D Table D 16). DO level of the reactors were maintained between 4.5 and 6.0 mg/L in R1 and between 2.0 and 4.0 mg/L in bulk liquid in R2. There was a limitation in air flow rate of the two reactors due to the change in configuration. Hence it was used two different air flow rates in order to maintain more or less same air flow rate per unit cross section in the two rectors. It was observed an air flow rate per unit cross section as 190 $L/min.m^2$ and 200 $L/min.m^2$ for R1 and R2 respectively.

A. MLSS and MLVSS variation

MLSS and MLVSS of the reactors were measured according to the standard method. Biomass attached to the sponge media was measured according to the protocols given in Appendix B, Figure 1 and 2. Table 4.2 presents the summary of MLSS and MLSS/MLVSS ratio for all the HRT values. It was observed a variation of MLSS (in suspension) between 7 and 10 g/L for both conventional and attached growth reactors Attached biomass concentration in R2 was observed to be between 18 and 20 g/L. No significant MLSS variation was observed in R1 and R2 during the three different HRTs. Constant OLR and the continuous sludge wastage might be the reason for the above observation. F/M ratio was maintained around 0.25 g COD/g VSS. d for all HRTs. For both R1 conventional and R2 attached growth reactors MLSS/ MLVSS ratio was observed close to 0.9. In other words the non biodegradable portion of the biomass was very low in both the reactors (Appendix D Table D 1 to D 6).

Table 4.2 MLSS and MLSS/MLVSS ratio Variation with HRT

HRT	MLSS (mg/L) (MLSS/MLVSS) ratio	
	R1 Conventional	R2 Sponge
7	8530 (0.91)	9000 (0.90)
10	10160 (0.89)	9720 (0.89)
13	9730 (0.91)	7250 (0.88)

B. COD removal

Table 4.3 presents a summary of influent and effluent COD in each reactor and the removal efficiencies related to different HRTs. In this study dextrose ($C_6H_{12}O_6.H_2O$) was used as the carbon source. The study was conducted under a OLR between 2.2 and 2.4 kg COD /m^3.d and it was kept constant for all HRTs. Based on analysis data it can be observed that there was no significant variation of COD between different HRTs. It can be seen that the COD removal efficiency in R2 sponge reactor was above 98% for all the HRTs. The removal efficiencies for R1 conventional reactor was above 97% despite the fact that higher concentrations of COD in 13 h HRT. Other than the removal rates the effluent quality of both R1 and R2 were excellent. Similar observations were made by Ngo et al. (2007) and Sombatsompop (2007) but the influent COD concentrations of their studies were around 230 mg/L and 520 mg/L respectively, whereas in current study influent COD concentrations were between 650 to 1200 mg/L for HRT 7 h to 13 h. Complete COD concentration data Table presents in appendix D Table D7 to D9.

Table 4.3 COD Variation and Removal Efficiency with HRT

HRT (h)	7		10		13	
	R1	R2	R1	R2	R1	R2
Influent (mg/L)	643		906		1198	
Effluent (mg/L)	19	9	24	16	25	14
Removal efficiency (%)	97	99	97	98	98	99

Note: Current research was conducted under OLR between 2.2 and 2.4 kg COD/m^3.

C. Nitrogen removal efficiencies and mechanisms

Nitrogen removal in biological systems can be mainly based on assimilation of nitrogen in to cell biomass and nitrification-denitrification process. While assimilation was the major mechanism of TN removal in conventional MBR, it was expected that the simultaneous nitrification-denitrifiaction (SND) would be the dominating TN removal process in attached growth MBR system.

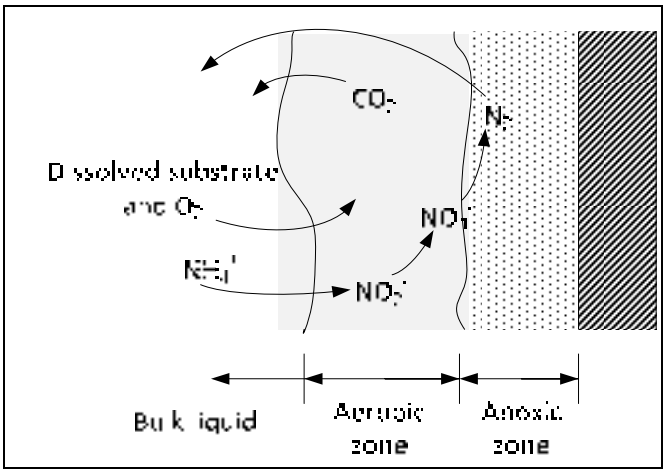


Figure 4.11 Anoxic and aerobic zones in a biofilm (Modified from Metcalf and Eddy, 2004).

Furthermore it was expected denitrification to take place in the biofilm over the surface and the inner pores of the sponge media under anoxic condition (Appendix D Table D 10 to D 15). Figure 4.11 presents the anoxic and aerobic zones of a biofilm and the possible transformations inside each zone.

Figure 4.12 presents the influent and effluent TN concentrations of R1 (conventional) and R2 (sponge) reactors for the three HRT values. The influent TN was varied from 130 mg/L to 240 mg/L for HRT 7 h to 13 h respectively (Figure 4.12 and Figure 4.13). It was observed that the effluent TN concentrations were in the range of 100 mg/L to 150 mg/L for R1 and 100 mg/L in R2 for HRT 7 h and 13 h. The lowest effluent TN concentration 11.7 mg/L was recorded on 56th day in R2 (sponge) during HRT 10 h.

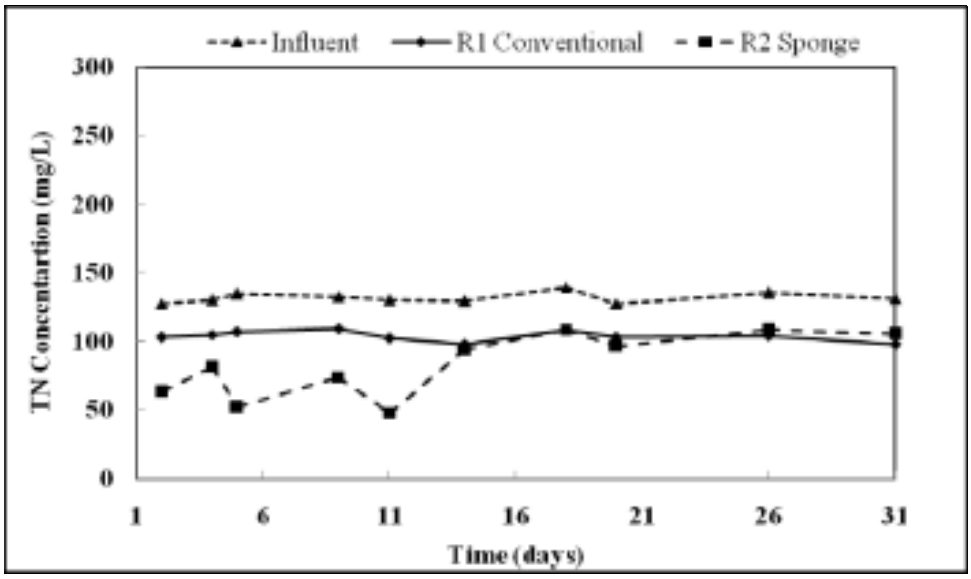


Figure 4.12 Influent and effluent TN variations in R1 and R2 for HRT 7 h .

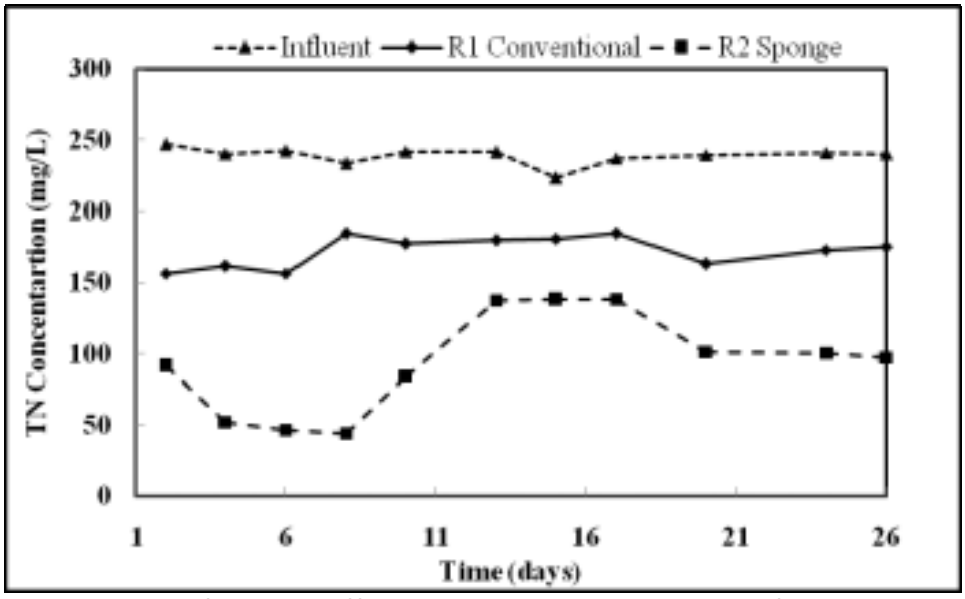


Figure 4.13 Influent and effluent TN variations in R1 and R2 for HRT 13 h.

There was a reactor modification in R2 between day 23 and day 43 when the system was operated during 10 h HRT. Moreover, it was observed relatively high TN concentration in effluent in R2 during that period. Initially the modifications were carried out for R2 in order to reach high TN removal by letting the media out of the internal media cylinder. After the modifications the thick biofilms over sponge media were reduced giving rise to increase MLSS in suspension. Contrary after the modifications the TN removal was decreased mainly because of the change in DO level (by having an inner media cylinder it was easy to create an anoxic zone in previous configuration). Hence reactor R2 (sponge) was brought back to its previous configuration which was there before the modifications. It can be clearly seen by Figure 4.14 the effluent TN concentration was reduced and finally it reached to a minimum value towards the end of the cycle.

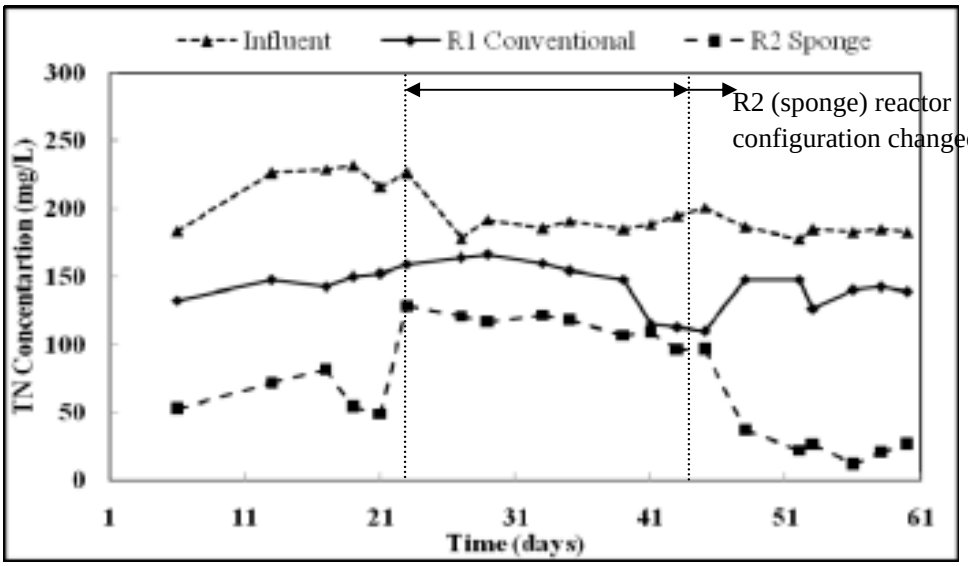
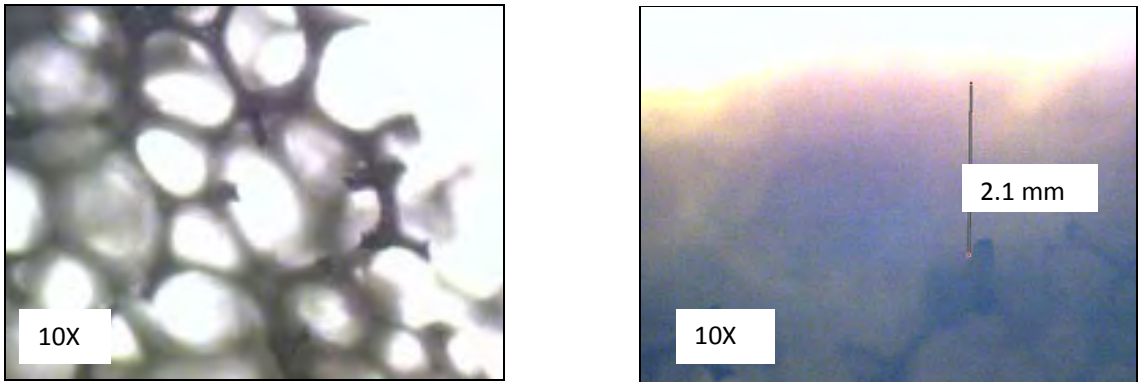


Figure 4.14 Influent and effluent TN variations in R1 and R2 for HRT 10 h.

During the same time period air diffuser of R1 was changed because of biomass clogging. It can be seen from Figure 4.14 there was an increase in effluent TN concentration in R1 after the modification.

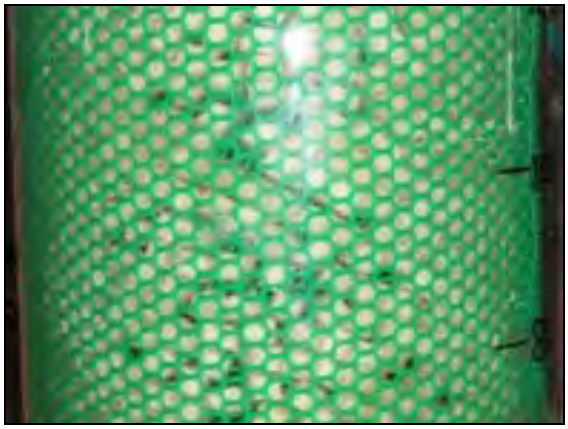


(a) (b)

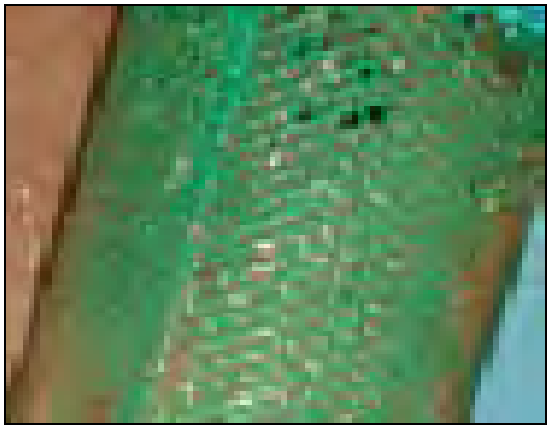
Figure 4.15 (a) Sponge media surface after the modifications, (b) Biofilm on sponge media surface before modifications.

Figure 4.15 presents some photos of the sponge media before and after the reactor modifications. It was observed less biofilm on media after the modification. Hence the denitrification was reduced due to the less biofilm thickness and the high DO concentration in the media zone.

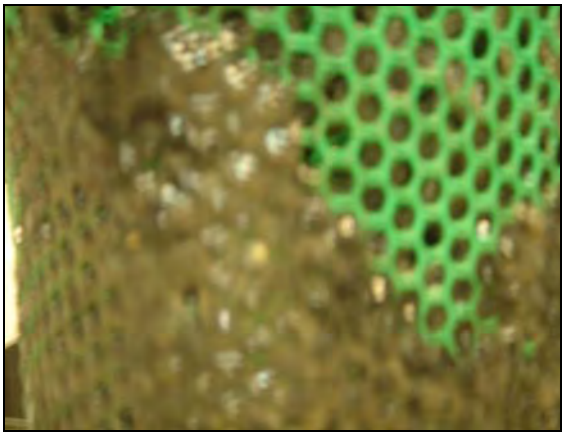
Apart from the biofilm over the media surface it was observed a thick biomass layer over the media cylinder inside R2. Figure 4.16 presents some of the photos of the media cylinder inside R2 during various stages of operation. It can be seen from the photos the increase of the biofilm thickness with the different HRT values.



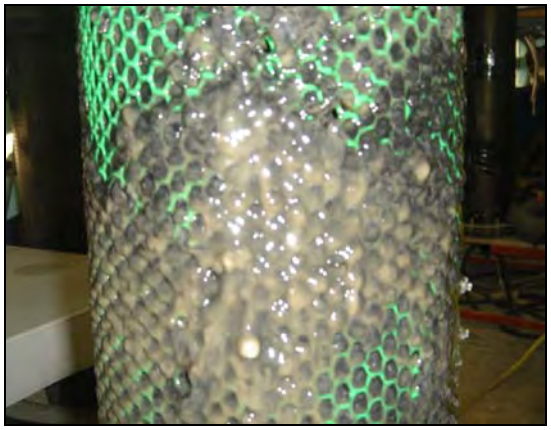
(a) Initial



(b) After 10 h HRT



(c) After 7 h HRT



(d) After 13 h HRT

Figure 4.16 Biofilm cover over the surface of the inner media cylinder; (a) initial stage, (b) After 10 h HRT operation, (c) After 13 h HRT operation, (d) after 13 h HRT operation

After the operation under 10 h HRT it was observed a thin layer of biofilm over the inner cylinder and it was progressively increased during 7 h and 13 h HRTs. Finally it was observed a black biomass layer over the media cylinder (Figure 4.16 d). It can be seen that the thick biofilm over the media rectors might have prevented substrate diffusion from the bulk liquid into the sponge media.

Figure 4.17 presents the TN removal efficiency of R1 and R2. It was interesting to observe the highest TN removal in R2 at HRT10 h. It can be clearly seen that the TN removal in the conventional reactor (R1) was between 22% and 27%. In other words TN removal was not influenced much by the HRT in conventional reactor. This is mainly because the system was specifically design as a completely mixed suspended growth system in order to achieve high nitrification. Furthermore in R1, most of the observed TN removal was due to bio assimilation. Total nitrogen requirement for bio assimilation was calculated according to Equation 4.1 for both R1 and R2.

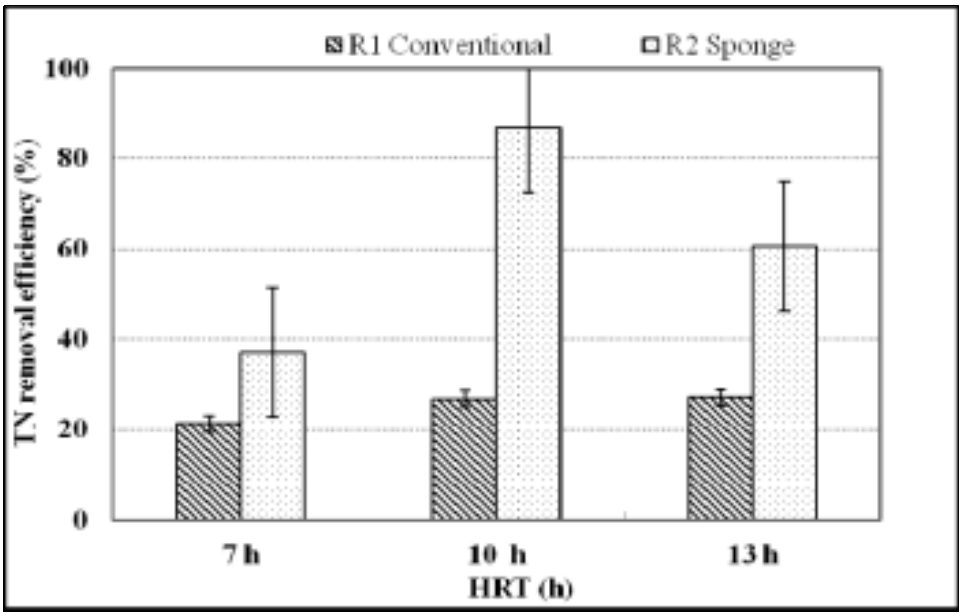


Figure 4.17 TN removal efficiency of R1 and R2 for the 7 h, 10 h and 13 h HRT.

$$TN_{assimilation} = \frac{COD_{influent} - COD_{effluent}}{30} \qquad \text{Equation 4.1}$$

Note: In this case COD: N: P ratio for biomass synthesis is taken as 150: 5: 1
Sources: Choi et al. (2008), Chiu et al, (2007), He et al, (2006)

On the other hand the TN removal in R2 was reached its maximum value of 86%, when the system was operating under 10 h HRT. One of the reasons for the high removal rate was due to the perfect biomass diffusion into the biofilms of the sponge media. Furthermore, change in configuration was reduced the thick biomass layer over the media to a thinner biofilm. Once it was packed again into the original configuration the substrate diffusivity increased because of the less biofilm thickness.

Table 4.4 Summary of Average Influent and Effluent Nitrogen Species under all HRTs in R1 (Conventional) and R2 (Sponge) Reactors

Nitrogen specie	HRT (h) (influent TN mg/L)					
	7 (131.7)		10 (196.5)		13 (238.7)	
	R1	R2	R1	R2	R1	R2
NH_3-N	2.5	82.5	5.2	10.3	1.9	3.8
NO_3^- N	99.4	0.6	132.6	8.4	168.4	50.9
NO_2^- N	2.0	0.0	5.2	5.5	1.7	39.0
TN	103.9	83.1	143.0	24.2	172.0	93.7

Table 4.4 presents the variation of nitrogen species with HRT in R1 and R2. It can be clearly seen that nitrification was effectively taking place in the conventional reactor (R1). It was further observed that NH_3-N and NO_2^-N concentrations were less than 6 mg/L in R1. On the other hand in sponge media reactor (R2) the highest simultaneous nitrification and denitrification was taking place only under 10 h HRT. In that case concentrations of all the other nitrogen species were below 10 mg/L. It was further observed a high NH_3-N concentration under 7 h HRT and high nitrate and nitrite concentration under 13 h HRT in R2. Mass transfer limitations and NH3-N inhibition might have affected the nitrification process in R2 under 7 h HRT. For SND process the nitrification can be retarded by low DO level and the denitrificaton process can be low due to less substrate diffusion in to the biofilm (Metcalf and Eddy, 2004). Hence in this case there could be a possibility of less DO in the bulk liquid than the requirement. For example 2 to 3 mg/L DO concentration in bulk liquid is considered to be sufficient for most of the aerobic suspended growth processes but this low DO level can be insufficient for attached growth processes (Metcalf and Eddy, 2004). Moreover, it was observed high nitrate and nitrite concentrations (around 50 mg/L and 39 mg/L) in R2 under 13 h HRT. Under 13 h HRT the presence of ammonia was observed to be low compared to HRT 7 h.

The increase in HRT from 7 to 13 h might have increased the ammonia to nitrite conversion but the complete nitrification might have inhibited due to less DO. Furthermore it was reported that the nitrification rates were related not only to the DO level but also to the bulk liquid BOD concentration (Stenstrom and Song, 1991). Same authors found that higher oxygen uptake rate for higher influent soluble BOD and low nitrification for the same bulk DO level. They explained above scenario as a depletion of aerobic zone in activated sludge flocs.

The behavior of the sponge media needs to investigate further in order to discuss more about the removal efficiencies under HRT 7 h and 13 h. Due to the time constrains the study was limited to one and half months for each HRT. Moreover, the most of the previous researchers used a moving bed attached growth system rather than fixed media beds. Therefore it was difficult to find experimental data to compare the results of current study with the previous studies.

The main advantage of having aerobic or anoxic zones in one reactors is to achive both nitrification and denitrification which is known as simultaneous nitrificaion and denitrification (SND) in the same reactor. Figure 4.18 presents the variation SND rate in R1 and R2 for all HRT values. It can be seen from the above figure SND rate was much

higher in R2 than R1 in all the HRT values. Specially under 10 h HRT R2 showed a seven times higher SND rate compared to R1.

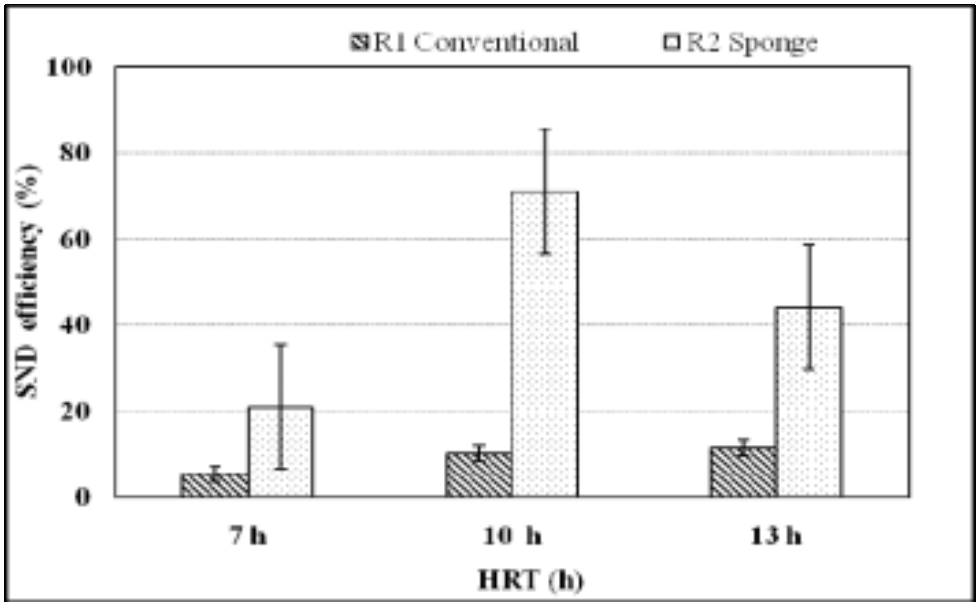


Figure 4.18 Simultanious nitrification and denitrification with varying HRT in R1 and R2.

It was observed a slight increase in SND efficiency when HRT increased from 7 h to 13 h in R1(conventional). In this case, the COD concentartion of the bulk liquid was increased with HRT because the OLR was kept constant. This might have improved the diffusivity of the substrate in to the flocs resulting high SND in conventional reactor. On the other hand SND showed a rapid increase between 7 h and 10 h HRT in R2 and it decreased in 13 h HRT. The thickness of the biofilm and the biomass packing inside the media reactor might have reduced the SND apart from the factors discussed earlier in section 4.2.1 C for low TN removal rate.

Nitrogen removal mechanism used in this study presents in figure 4.19.

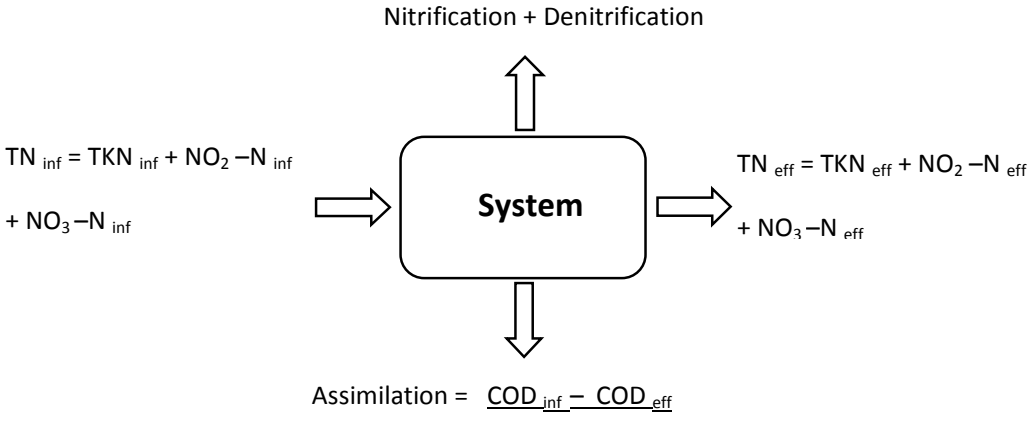


Figure 4.19 Nitrogen removal mechanism used in this study.

According to the above figure the following equation can be derived for TN removal, SND and nitrification process.

$$TN_{removal} = (TKN_{inf} + NO_2\text{–}N_{inf} + NO_3\text{–}N_{inf}) - (TKN_{eff} + NO_2\text{–}N_{eff} + NO_3\text{–}N_{eff}) \quad \text{Equation 4.2}$$

$$SND = TN_{inf} - TN_{eff} - \text{Assimilation} \quad \text{Equation 4.3}$$

$$\text{Nitrification} = (NO_2\text{–}N_{eff} + NO_3\text{–}N_{eff}) - (NO_2\text{–}N_{inf} + NO_3\text{–}N_{inf}) \quad \text{Equation 4.4}$$

TN removal calculations were carried out according to Equation 4.2. Similarly Equations 4.3 and 4.4 were applied in the calculations of SND and nitrification respectively.

Table 4.5 and Table 4.6 present the summary of nitrogen mass balance calculations according to the previously mentioned equations (Equation 4.2, Equation 4.3 and Equation 4.4) for R1 and R2. Table 4.7 shows a comparison of the TN removal efficiencies and other operational parameters of CAS and the conventional and attached growth MBR (Demoulin et al. 1997).

Table 4.5 Summary of Nitrogen Balance Calculation for R1 (Conventional)

HRT (h)	TN_{inf} (mg/L)	TN_{eff} (mg/L)	TN removal (%)	Assimilation (mg/L)	SND (mg/L)	Nitrification (%)
7	131.7	103.9	21.2	20.8	7.1	77.0
10	196.5	143.0	26.7	29.4	24.9	70.3
13	238.7	172.0	27.8	39.2	27.5	71.3

Table 4.6 Summary of Nitrogen Balance Calculation for R2 (Sponge)

HRT (h)	TN_{inf} (mg/L)	TN_{eff} (mg/L)	TN removal (%)	Assimilation (mg/L)	SND (mg/L)	Nitrification (%)
7	131.7	83.1	37.0	21.2	27.5	0.5
10	196.5	24.2	86.8	29.6	130.2	7.1
13	238.7	93.7	60.6	39.5	105.5	37.7

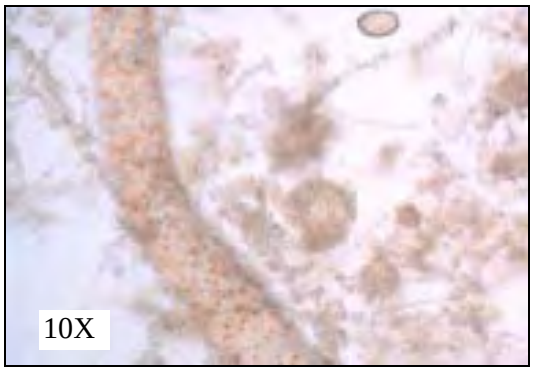
Table 4.7 Comparison of TN removal in Conventional Activated Sludge (CAS) process, Conventional (R1) MBR and Attached growth (R2) MBR

Parameter	Conventional Activated Sludge Process* (CAS)	Conventional MBR (At 10 h HRT)	Attached growth MBR (At 10 h HRT)
SRT (d)	10	30	30
Influent TN (mg/L)	60	196	196
Effluent TN (mg/L)	19	143	24
TN removal efficiency (%)	67	27	87
F/M (g COD/ g VSS.d)	0.11	0.28	0.28

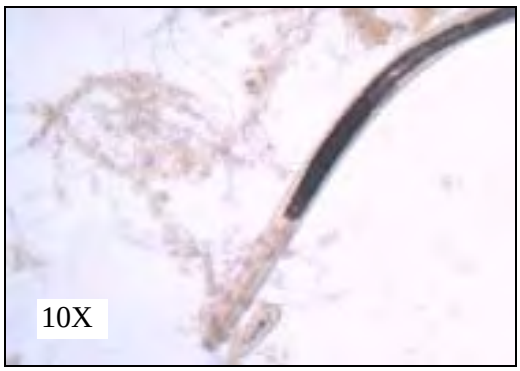
Note (*): CAS process uses two tanks configuration with secondary clarifier
(Modified from : Demoulin et al., 1997)

4.2.2 Microbial observations

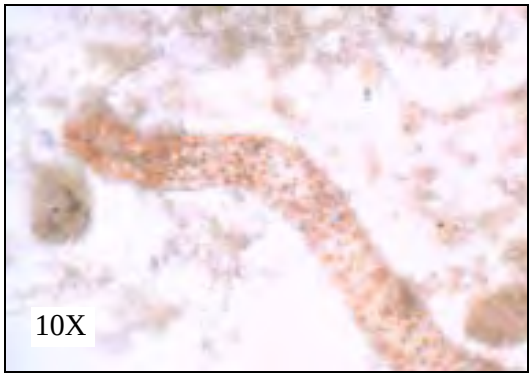
Figure 4.20 presents some of the photos of the sludge particle observations in R1 and R2 reactors. It was observed Rotifers, Filamentous microorganisms dominance in R2 while Rotifers and some other invertebrates (*Aeoloosma hemprichii sp*) were common in R1(Fan et at. 2006). Fan et al (2006) noted that the presence of the above mentioned microbial species, were evidence of good sludge settlability. The Filamentous microorganisms and the presence of Ameba mostly observed under low DO level caused poor sludge settling characteristics. Poor sludge dewaterability of R2 sludge was observed during the CST measurements also.



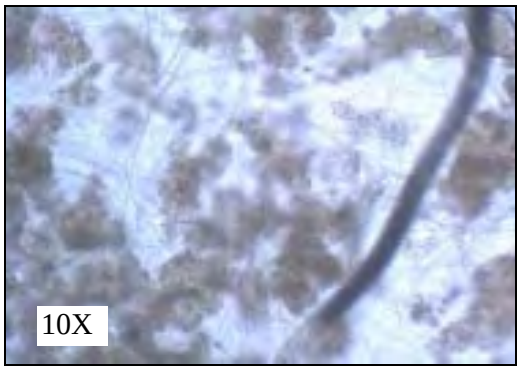
(a) R1 (Sludge flocs)



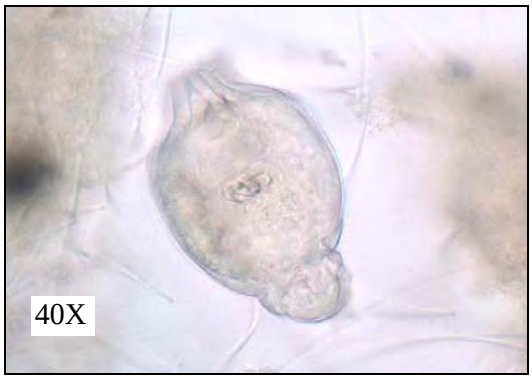
(b) R1



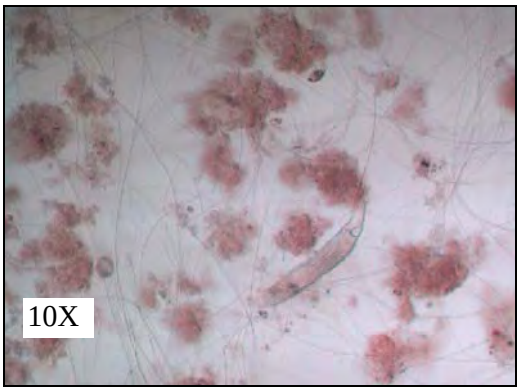
(c) R1 (Aeolosoma hemprichii sp)



(d) R2 (Sludge flocs)



(e) R2 (Rotifer)



(f) R2 (Rotifer and Ameba)

Figure 4.20 Sludge observation in R1 (Conventional) and R2 (Sponge) rectors.

4.3 Fouling Behavior of the MBR

Fouling behavior of the MBR system was analyzed according to the observed variations of TMP, EPS, particle size distribution (PSD), modified fouling index (MFI) and alkalinity of the reactors.

4.3.1 TMP profiles for the three HRT values

Figure 4.21 presents the TMP variation of R1 and R2 for HRT 10 h. The maximum suction pressure for the membranes in the system was selected as 30 kPa. Once TMP reached its maximum value the operation was stopped and membrane was cleaned according to the membrane cleaning protocol. Both MBRs were operated more than 70 days before the membranes were fouled under HRT 10 h. It was observed R1 (conventional) MBR was fouled after 71 days of operation and the R2 (sponge) MBR was fouled after 74 days. Moreover the sudden TMP increase before fouling, known as "TMP Jump" was observed between 69 and 71 days for R1 and between 67 and 74 days for R2. Cho and Fane (2002) found, that the above phenomenon was due to the increase in critical flux as a result of progressive pore blocking with EPS.

Figure 4.22 and Figure 4.23 present the TMP variation of R1 and R2 with time for 7 h and 13 h HRT respectively. It was observed opposite fouling trend under 7 h HRT compared to 10 h. It was observed that R2 (sponge) was fouled 12 days earlier than R1 (conventional) MBR. It was reported an indirect relationship between HRT and fouling propensity (Visvanathan et al, 1997). The authors noted a reduced fouling at longer HRTs. Longer HRT provides less nutrients supply for biomass. This leads to a low biomass growth (low MLSS concentration).

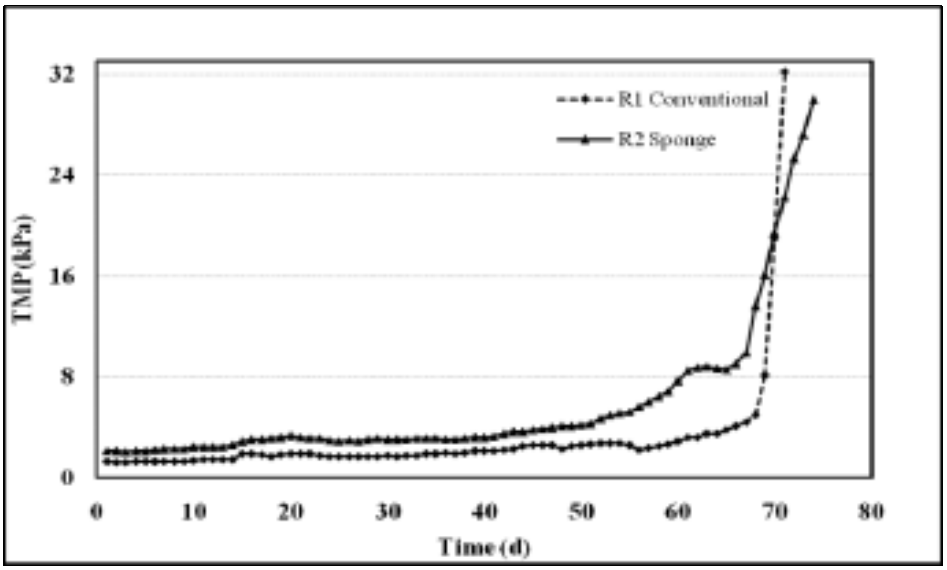


Figure 4.21 TMP variation with time for 10 h HRT.

Results of HRT 7 h were in agreement with the above findings. Lee et al. (2001), found that the attach growth system TMP increment was seven times higher than that of suspended growth systems. In their study the MLSS concentration of the suspended biomass was around 100 mg/L and attached biomass concentration was 2,000 mg/L. But the current study was conducted under 8,000 to 10,000 mg/L suspended MLSS

concentration and a similar amount of attached biomass. That might be the reason for the observed 1.5 times increase in fouling propensity between attached and suspended growth systems under the operation of 7 h HRT. According to the authors the dynamic membrane formed on the surface of the membrane effectively reduced the membrane fouling in suspended growth system (Appendix D Table D 16 to D 18).

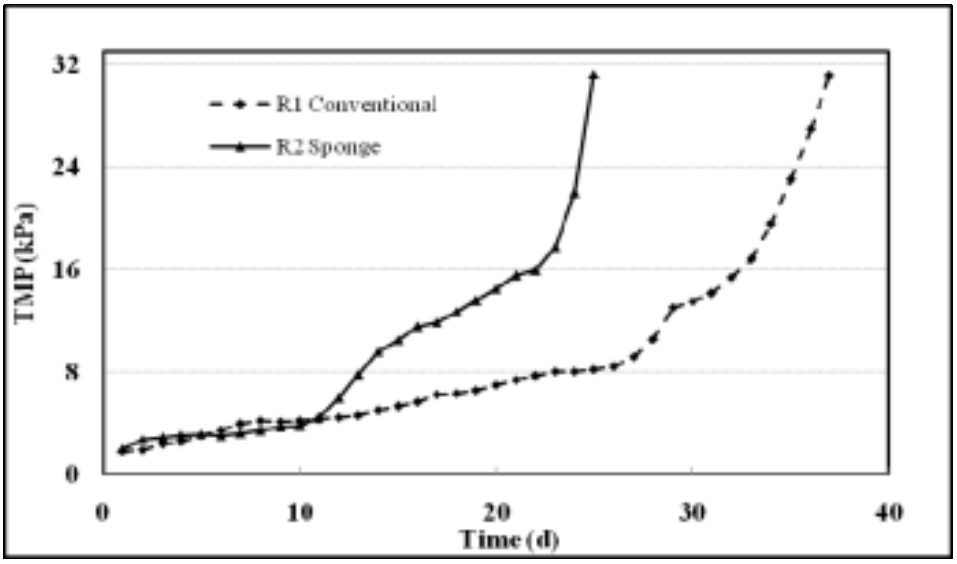


Figure 4.22 TMP variation with time for 7 h HRT.

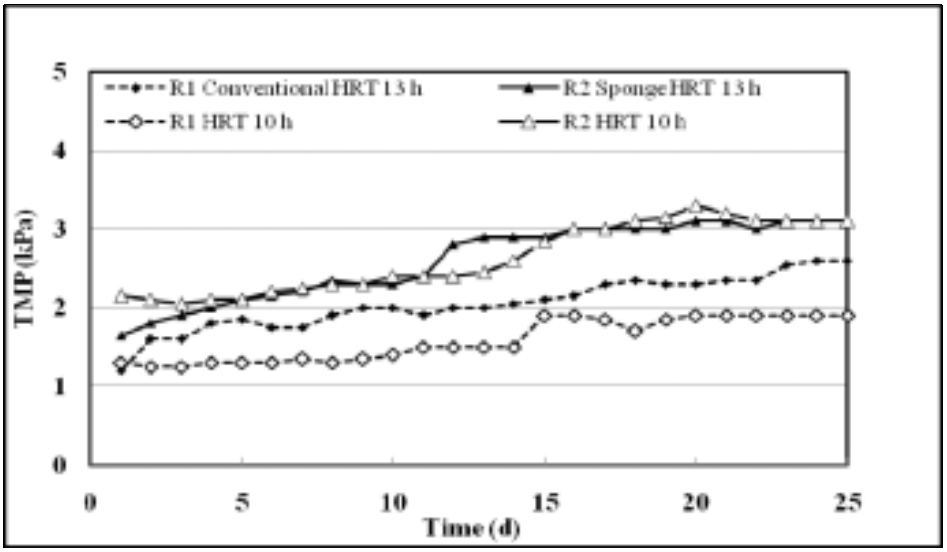


Figure 4.23 Comparison of TMP variation with time for 13 h and 10 h HRT for R1 and R2.

The systems were not operated until the membranes foul under 13 h HRT due to the time constraints. Hence operation of R1 and R2 were stopped after 25 days of operation under HRT 13 h. The fouling rates for R1 (Conventional) and R2 (sponge) were found to be 0.056 and 0.058 kPa/d respectively. It was observed a relatively similar TMP variation during 25 days of operation. Furthermore the TMP profiles under 13 h HRT were

compared with 10 h HRT and it was observed a relatively similar TMP increase pattern. Therefore it can be concluded that the system could be operated more than 70 days.

4.3.2 Membrane resistance

Table 4.8 Membrane Resistance Values for HRT 7, 10, and 13 h for R1 and R2

Reactor	HRT (h)	R_t (* 10^{12} 1/m)	R_c (* 10^{12} 1/m)	R_f (* 10^{12} 1/m)	R_m (* 10^{12} 1/m)	R_c/R_t
R1	7	5.52	4.84	0.19	0.49	0.88
	10	6.29	4.74	1.16	0.39	0.75
	13	N/A			0.23	
R2	7	4.74	4.12	0.23	0.38	0.87
	10	10.74	9.64	0.58	0.51	0.90
	13	N/A			0.36	

Note: R_t: Total membrane resistance; R_c: cake fouling resistance; R_f: irreversible fouling; R_m: membrane resistance.

Table 4.8 presents the membrane resistance values for the three HRTs. It was observed the total resistance ($R_t = R_c + R_f + R_m$) was higher in R2 under 10 h HRT compared to R1. Furthermore it was observed a larger percentage of R_t was cake resistant (R_c). Irreversible fouling (R_f) of R1 was observed to be double compared to R2. Irreversible fouling occurs due to the internal pore blocking. That means the rapid fouling of R1 was due to the internal pore blocking.

Similarly under the HRT 7 h, irreversible fouling was higher in R2 than R1. It was observed rapid fouling in R2 even though the cake fouling (R_c) was slightly lower than R1. It can be seen from this results the fouling in the current study was in relation with the internal pore blocking mechanism. That means fouling of R1 and R2 mostly depended on the particle size of the biomass which was in suspension.

4.3.3 Capillary suction time (CST) and Particle size distribution (PSD)

Figure 4.24 shows the variation of CST in R1 and R2 with HRT. CST normally measures the dewaterability of activated sludge. Higher the CST value means lower the dewaterability. It was observed relatively constant variation of CST for R1 (conventional) reactor. However the CST variation was not consistence in R2 for the three HRT values. It was observed a highest CST value of 40 s in R2 under the operation of 7 h HRT. Similarly average CST reached to a value of 27 s during the operation of 13 h HRT. The increase in CST might be due to the finer biomass flocs in R2. Interestingly under HRT 10 h operation it was observed a fairly similar CST values for both R1 and R2. Moreover it was observed a highest TN removal under HRT 10 h (section 4.2.1 C). It was further noticed that the fouling behavior of R1 and R2 correctly correlated with the CST variations. That means the fouling phenomenon closely related to the particle size of the biomass. Increase in percentage of fine particles in R2 might have increased the CST value. Similarly membrane fouling might have rapid due to the pore blockings with finer particles (submicron range).

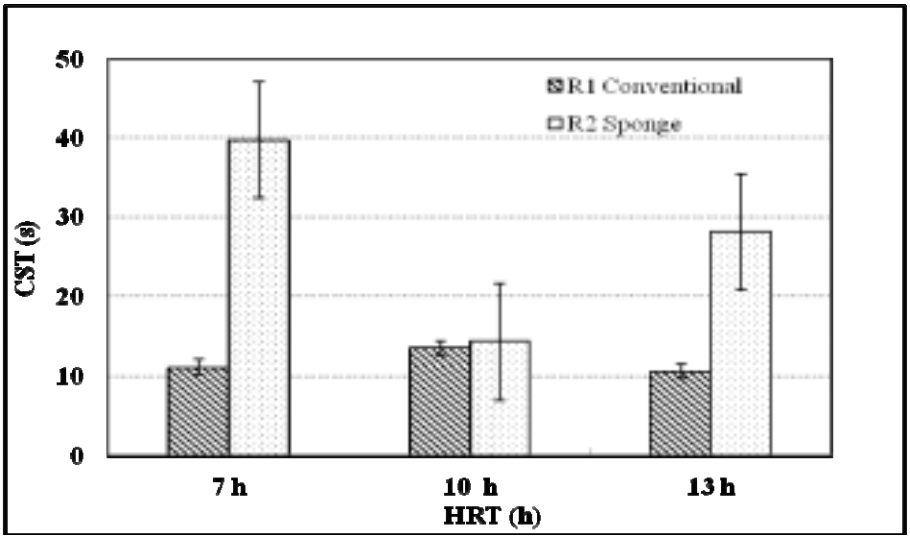


Figure 4.24 Capilary suction time (CST) varation of R1 and R2 with three HRT values

Figure 4.25 presents the particle size distribution against percentage intensity for the two reactors R1 and R2. The mean particle diameters for R1 and R2 were 230 µm and 190 µm respectively (Appendix D table D 21 and table D 22).

It can be clearly seen that the percentage intensity of the particle size of R2 was two times larger than R1. That means R2 comprised of large percentage of smaller particles than R1. This might be the reason for rapid fouling in R2 for HRT 7 h and 13 h. In the current study, HRT operational sequence was selected as 10 h HRT first and followed by 7 h and 13 h HRTs.

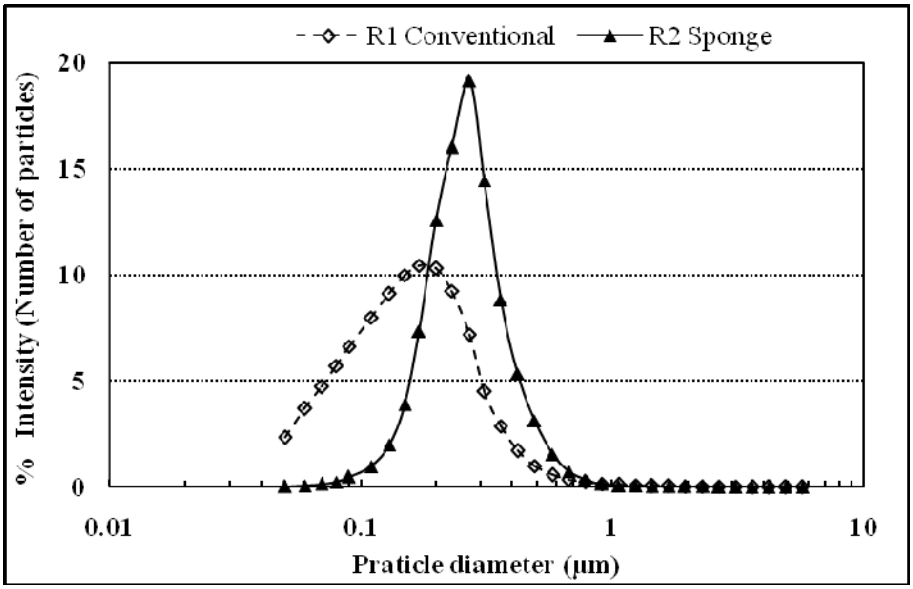


Figure 4.25 Particle size distrbution for R1 and R2

Leiknes and Ødegaard (2007) found, that fouling due to submicron particles was the domination fouling mechanism in biofilm reactors. During that study the authors varied the OLR with HRT (varied between 2.3 kgCOD/m3.d and 7.8 kg COD/m3.d). The authors

further concluded that fouling rate was low when the system was operated under low OLR. In the current study OLR was a constant during all HRTs.

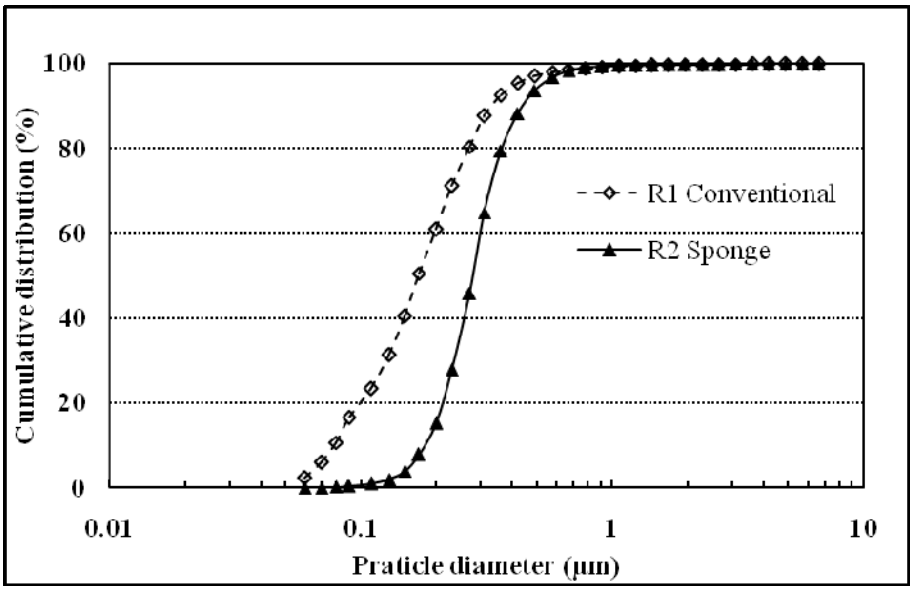


Figure 4.26 Cummulative particle size distrbution for R1 and R2

Figure 4.26 presents the cumulative particle size distribution for R1 and R2. It was observed a fairly narrow and steep distribution for R2 compared to R1. Hence fouling of membrane might be mainly due to pore narrowing rather than cake fouling in R2. In R1 it was observed an elongated distribution with bigger particle sizes than R2. There for particle size diameters and the percentage intensities could be used to substantiate the previously explained fouling behavior of the two reactors (Appendix D Table D 20 and D 21).

4.3.4 Effects of EPS and MFI on fouling

According to most of the previous literature EPS, mainly consists of polysaccharides and proteins known to be the primary cause for membrane fouling in MBRs. Table 4.9 presents a summary of polysaccharide and protein concentrations in R1 and R2 for different HRT values. It was observed that the concentrations of bound and soluble polysaccharides in R1 and R2 were in the same order of magnitude. But the observed values for R1 were higher than that of R2. In the case of soluble protein concentrations, it was observed slightly higher concentrations in R2 than R1. Lee et al. (2001) and Sombatsompop et al. (2006) observed the same phenomenon.

Lee at al. (2001) used the fixed attached growth system while Sombatsompop et al. (2006) used attached growth system with moving media. Finally the authors concluded that there was no direct relationship with EPS and membrane fouling for their work. It was interesting to note that there was not much influence from EPS to membrane fouling in current study also. It was observed that particle size and the distribution might have influenced more in membrane fouling than the EPS according to the finding of the current study (Appendix D Table D 19). Standard curves used in the calculations are shown in Appendix E Table E 6 and E7 and the Figures E 6 and E 7.

Table 4.9 Variation of Concentrations of Polysaccharides and Proteins in R1 and R2 with three HRT values

HRT (h)	Polysaccharides				Proteins			
	Bound (mg)/g VSS		Soluble (mg/L)		Bound (mg)/g VSS		Soluble (mg/L)	
	R1	R2	R1	R2	R1	R2	R1	R2
7	10.00	6.08	7.41	4.57	9.20	5.73	1.91	3.30
10	7.55	4.50	11.96	9.82	26.38	15.97	4.48	3.01
13	7.34	6.25	10.22	5.82	5.01	7.39	1.74	2.74

Figures 4.27 to 4.29 present the filtration curve time/volume (t/V) versus volume (V) curves for all the HRT values. The filtration was carried out under one bar constant pressure in dead end filtration mode. The slopes of each straight line in the figures indicate the MFI value. It can be clearly seen that the MFI value for R2 (Sponge) reactor was higher than the respective value of R1 (Conventional).

The results of MFI were in agreement with the fouling behavior of the MBR system. It was observed a rapid fouling propensity in attached growth system (R2) compared to the conventional system for most of the fouling cycles under different HRTs. It was further noted that under HRT 10 h, membrane fouling occurred more or less at the same time in the two systems. Moreover fouling behavior observed in current study was in agreement with the work of Lee et al. (2001). The authors found that the attached growth system fouled rapidly compared to the suspended growth system. Contrary the results of the current study contradict with the findings of Sombatsompop et al. (2006). Configuration used in this study was a fixed bed attached growth system whereas in the previous study it was used a moving bed system. The collision between the membrane and the moving media, mitigate the fouling (by removing the cake layer) and enhance the filterability (Lee et al., 2006). In the current study sponge media was not allowed to agitate with the membrane. Hence the fouling reduction due to the effect of agitation was not taken place in the current study.

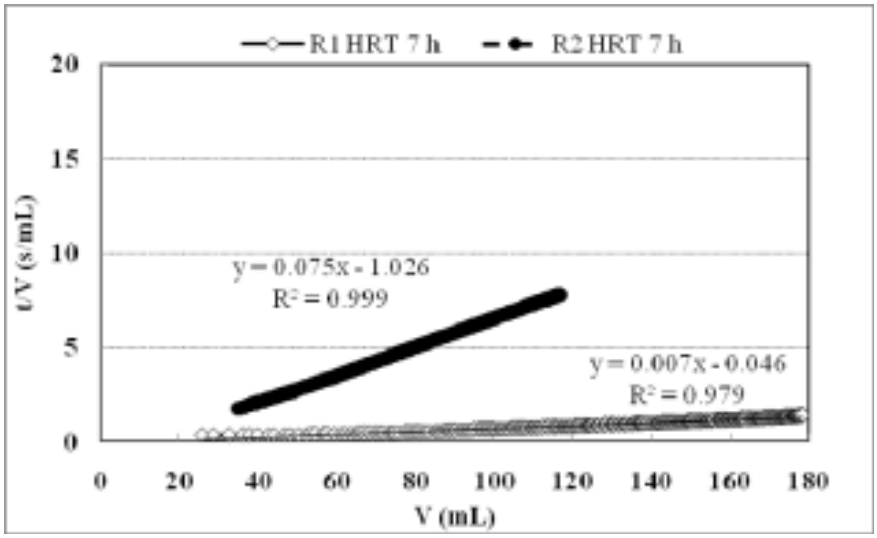


Figure 4.27 Filtration curve t/V versus V measured for HRT 7 h for R1 and R2

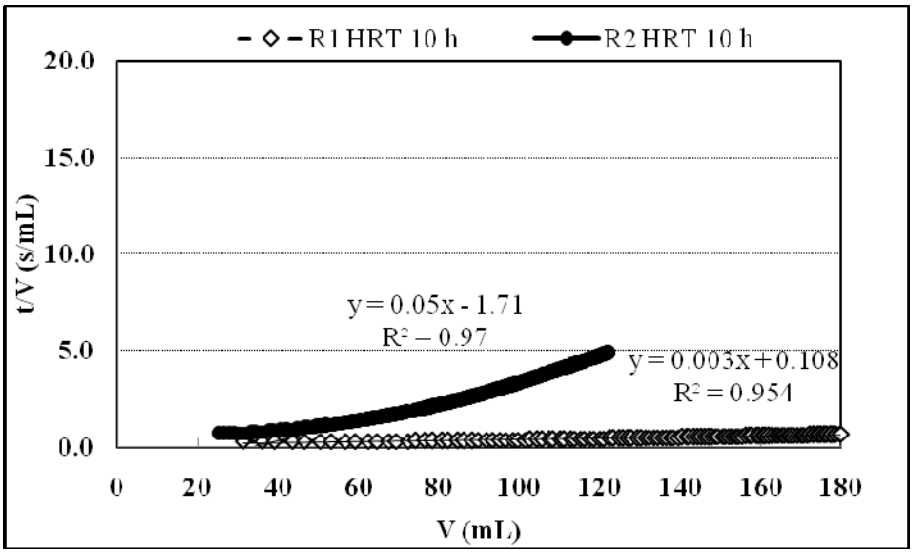


Figure 4.28 Filtration curve t/V versus V measured for HRT 10 h for R1 and R2

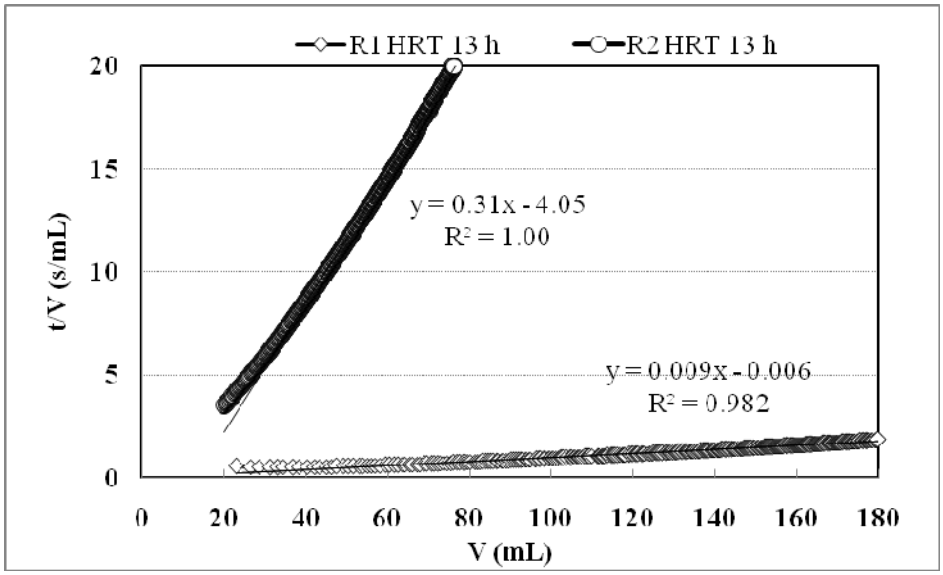


Figure 4.29 Filtration curve t/V versus V measured for HRT 13 h for R1 and R2

It was observed tremendous increase in MFI in R2 (Sponge) reactor when HRT changes from 10 h to 13 h. On the other hand the increment for R1 conventional was observed to be low. In other words activated sludge properties in the conventional reactor deteriorate in a much lower rate than in attached growth (sponge) system.

In summary, it can be seen from above observations, the fouling behavior of the attached growth system can partially described by the MFI, CST and the particle size distribution curves. It might be useful to explore the microbiological aspects of the biomass (in suspension and attached) in R2 for a better understanding about the fouling characteristics in this particular configuration of attached growth MBR.

Chapter 5

Conclusions and Recommendations

The current study mainly focused on nitrogen removal efficiency and the fouling behavior in conventional and attached growth MBR systems. The study consisted of two phases; namely phase I (SBR analysis) and phase II (MBR analysis). During phase I of the study, a suitable media type was selected out of the two media types; cylindrical polypropylene (CP) and polyethylene sponge. The appropriate media selected from phase I was used in phase II as the media for the attached growth MBR. In order to compare the removal efficiencies and the fouling characteristics a conventional activated sludge MBR was operated.

Most important part of the study was phase II which focused on nitrogen removal and the fouling characteristics of the two MBR systems. In this case three different HRTs were used to characterize the two systems while keeping the OLR, NLR and SRT constant. Following conclusions were made according to the results and findings of the study.

5.1 Conclusions

Following conclusions were made upon the completion of phase I analysis.

- It was observed under SBR analysis there was no significant difference in COD removal between the two media types (more than 95% COD removal efficiency was achieved in both media reactors.
- TN removal efficiency was observed around 70% in sponge media and for the CP media TN removal was in the range of 25 to 50%.
- Finally, polyethylene sponge media was found to be more appropriate than cylindrical polypropylene media to be used in fixed bed MBR configuration.
- The circular configuration with inner media cylinder was selected as the MBR configuration due to higher TN removal rate (between 73% and 79%) and better hydrodynamic performances (no biomass settlement, uniform biomass circulation and relatively more area for the membrane)

Following conclusions could be drawn from phase II experimental results.

- It was observed that there was no significant different in MLSS under the operation of three different HRT values. In this case it should be noted that the OLR was kept as a constant throughout the study.
- No significant difference in COD removal rate was observed during the MBR analysis for both conventional and attached growth (sponge media) MBR systems. Furthermore it was observed a slightly higher COD removal rate for attached growth MBR (98%) than the conventional MBR (97%). In general the COD removal was not affected by the HRT variation during the study period.
- It was noted that the dominant TN removal mechanisms in the conventional MBR was assimilation (TN removal 22 to 27%). On the other hand mainly SND was responsible for the TN removal in attached growth MBR apart from assimilation.

- It was found that the TN removal in attached growth system was around 86% under the operation of 10 h HRT. Furthermore it was observed a TN removal of 40 and 60% in sponge reactor during the operation of 7 h and 13 h HRTs respectively.

- Similarly it was observed a highest SND rate (around 70%) under 10 h HRT and SND rates for HRT 7 h and 13 h were observed as 20% and 42% respectively in the sponge reactor.

- It was observed during the study that there was a relationship between the biofilm thickness over the sponge media as well as the cover of the inner media cylinder and the TN removal rate. Higher removal rate was observed with less biofilm thickness (around 2 mm) over media during 10 h HRT. One of the limitations in biofilm process is less substrate diffusion into the biofilm. This diffusion takes place through micro channels in the biofilm. If the biofilm is too thick then there is a chance of blocking those micro channels. This leads to a less substrate diffusion resulting less removal efficiencies. The other limitation is the DO level of the bulk liquid. To achieve maximum SND the biofilm should have an aerobic zone and anoxic zone with less DO.

- Furthermore sponge media and conventional reactors were reported 74 and 71 days respectively under 10 h HRT before the fouling of the membranes. Attached growth system showed 1.5 times greater fouling propensity than the conventional reactor under the operation of 7 h HRT. Fouling rates for attached growth and conventional reactors were found to be 0.058 and 0.056 kPa/d respectively.

- It was noted that there was no significant variation in EPS production in the two systems during the three HRT values.

- It was further observed that the attached growth configuration might have influenced in changing the microbial structure rather than the particle size and the hydrodynamic flow pattern of the system.

5.2 Recommendations for Further Research

Following recommendations can be made in order to achieve higher TN removal rates.

- Microbiological changes in terms species and quantity should be investigated with varying HRT in order to obtain a clear idea about the fouling behavior of the attached growth system by using microbiological investigation techniques (FISH or PCR).

- It was proved from this study that SND could be achieved in a single reactor configuration. However there are limitations in current system due to the fixed bed configuration. These limitations include periodic biofilm removal from the outer net of the media cylinder and the biomass removal from the media reactor. These system limitations might affect adversely in the industrial scale applications. Therefore it is recommended to investigate the attached growth system with moving media (fluidized bed).

Figure 5.1 presents the proposed configuration for the media reactor. In this case the sponge media size can be increased (1.5 cm *1.5 cm * 1.5 cm cubes) in order to increase anoxic zone of the media.

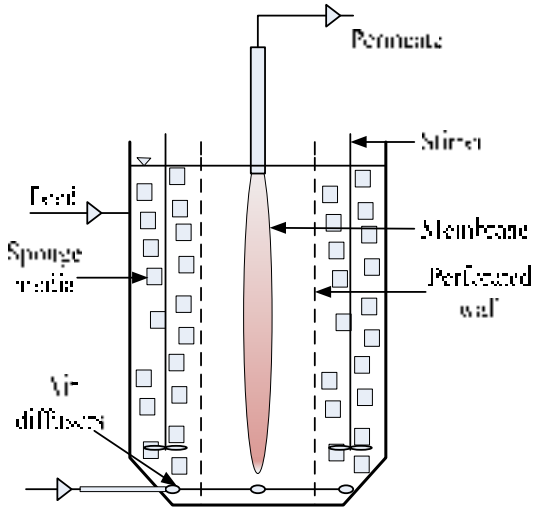


Figure 5.1 Proposed attached growth MBR configuration

In this case the sponge media can be kept in fluidized condition by supplying air flow through air diffusers. Media chamber and the membrane can be separated by a perforated wall and the DO concentration can be controlled by the air flow controlling on the media side.

- It is interesting to investigate moving media attached growth system with low dissolve oxygen level in order to maintain the anoxic condition inside the sponge media. In this case higher biofilm thicknesses can be eliminated. The results can be compared with the current study.

- It can be further investigated the system by varying HRT and keeping the COD and nitrogen concentrations constant (allowing OLR and NLR to vary accordingly). In this case the MLSS will vary according to the loading rate and the TN removal can be investigated.

- Attached growth system can be investigated under an intermittent aeration (for example 3 h aeration 1h without aeration) condition. Intermittent aeration will provide the oxic/ anoxic combination in the reactor in order to maximize the removal efficiencies.

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Appendix A

MBR design details

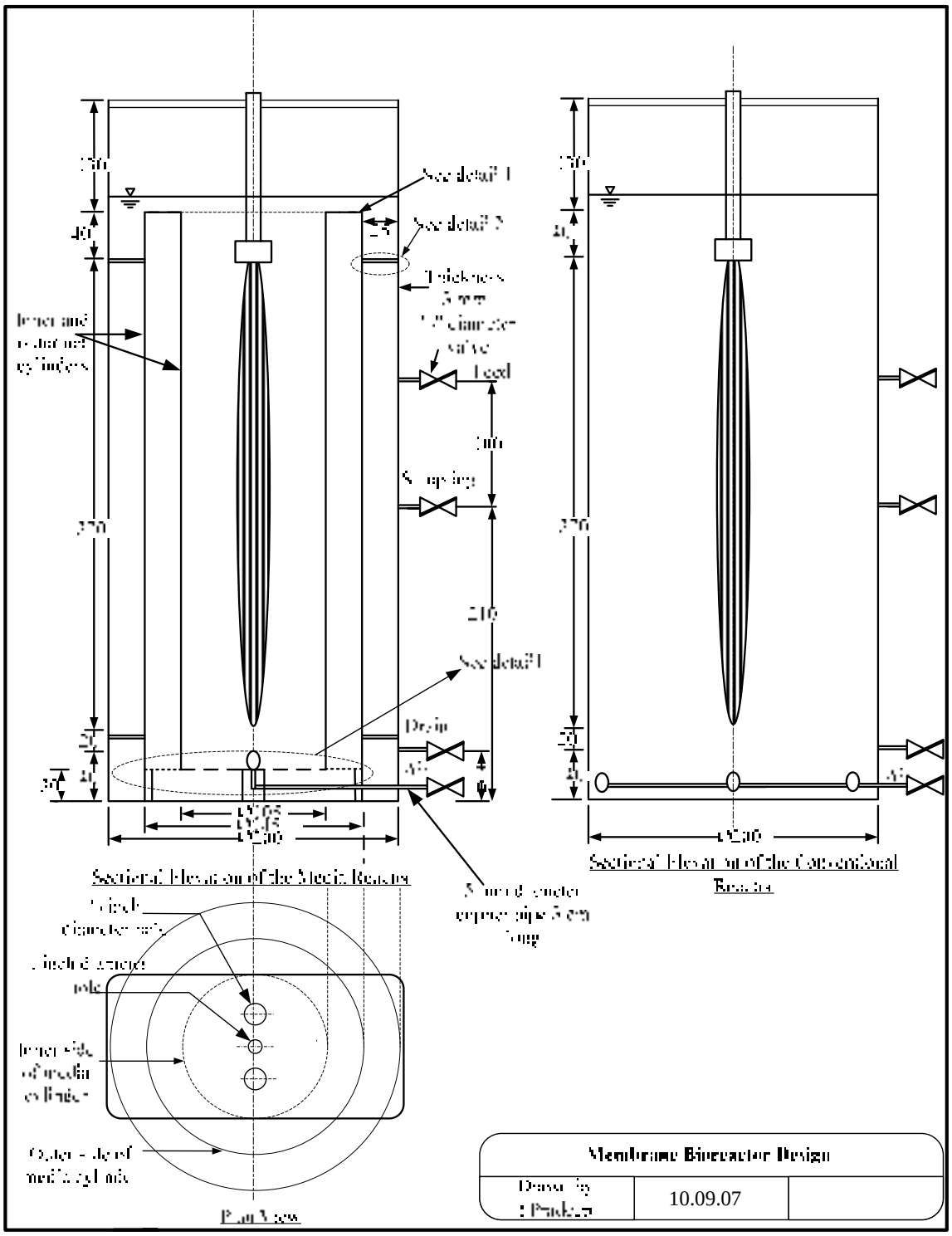

Figure A.1 Detailed design of media and conventional membrane bioreactors

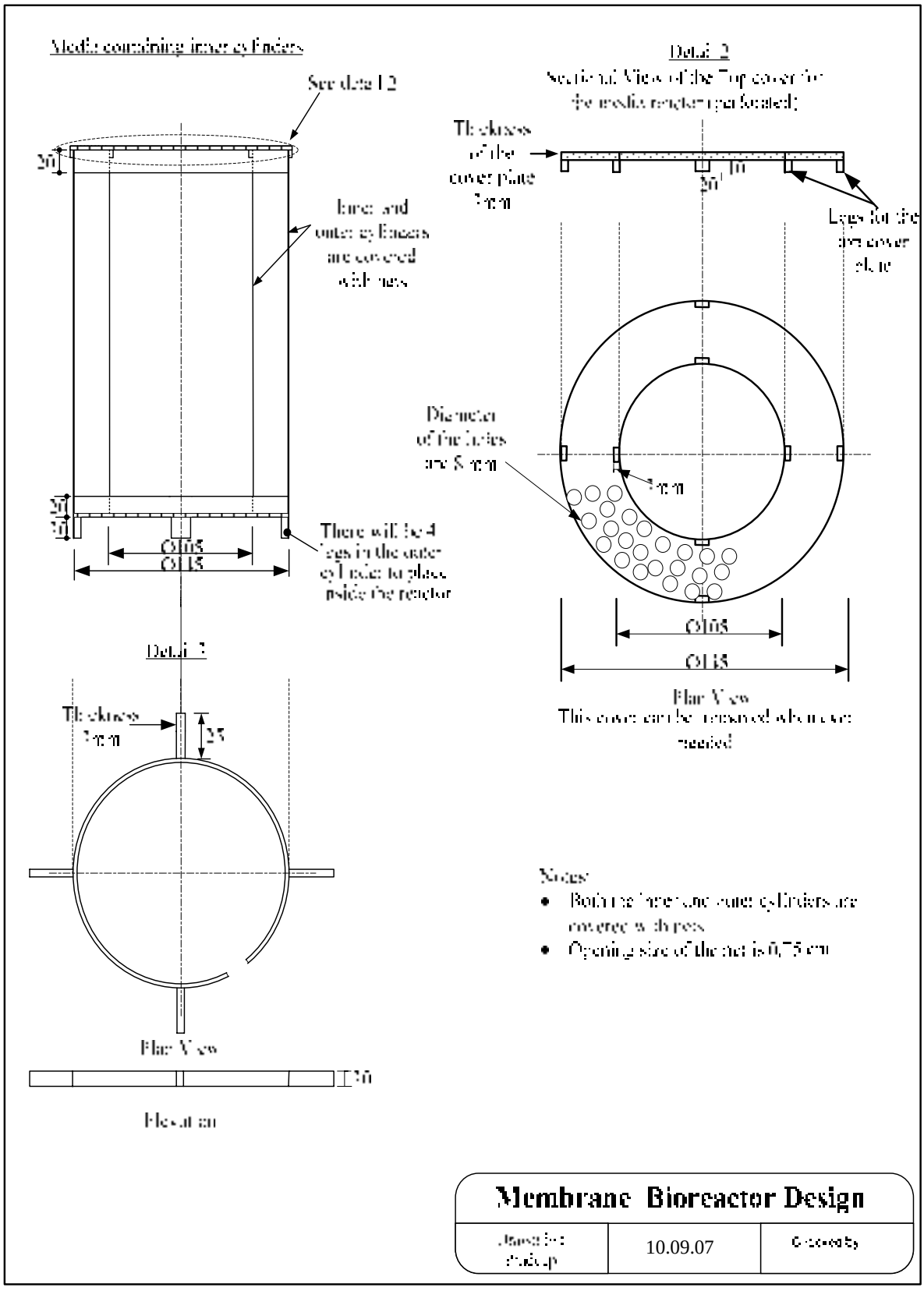

Figure A.2 Inner and outer net cylinders and supporting details of the MBR

Appendix B

Protocols for MLSS Calculation of attached growth media

1. Biomass calculation for Sponge media

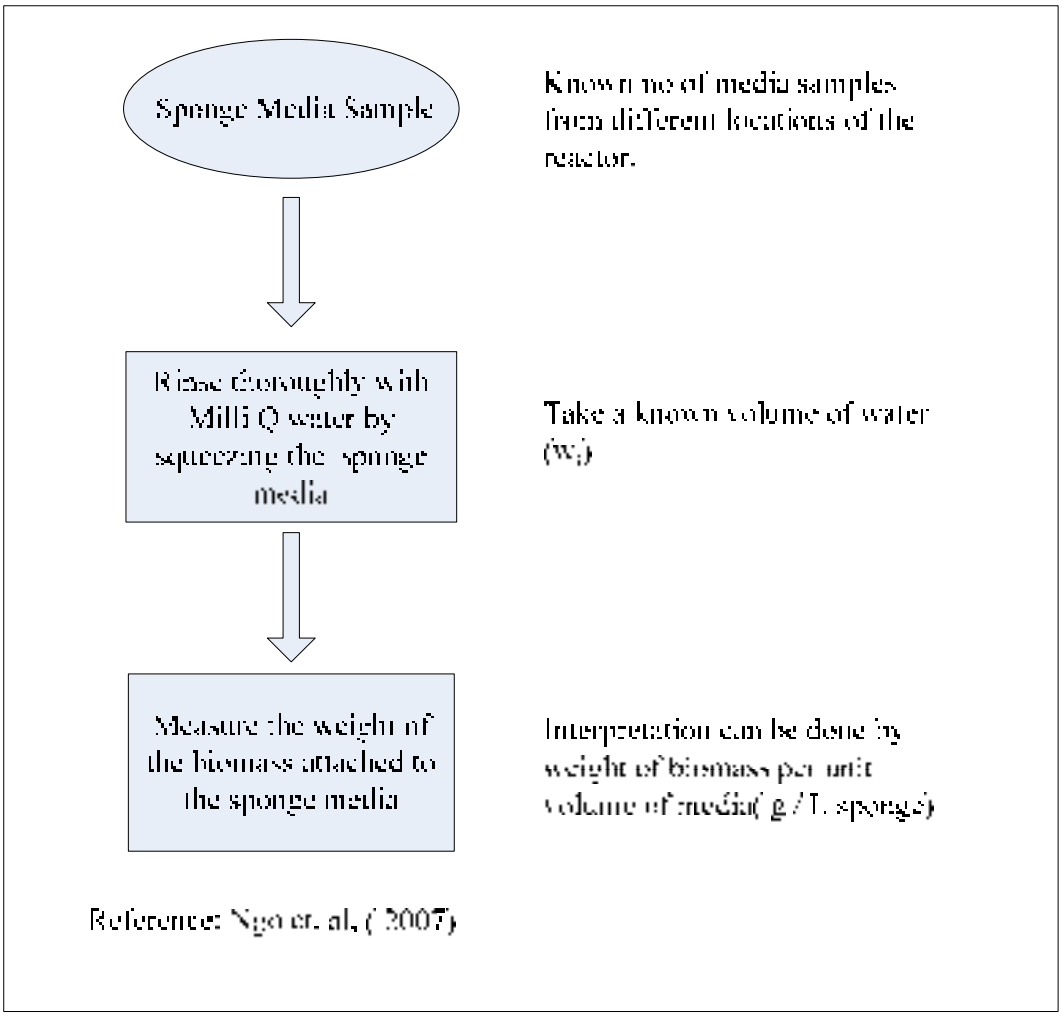

Figure B 1 Flow diagram for biomass calculation for Sponge media

2. Biomass calculation for Cylindrical Polypropylene (CP) media

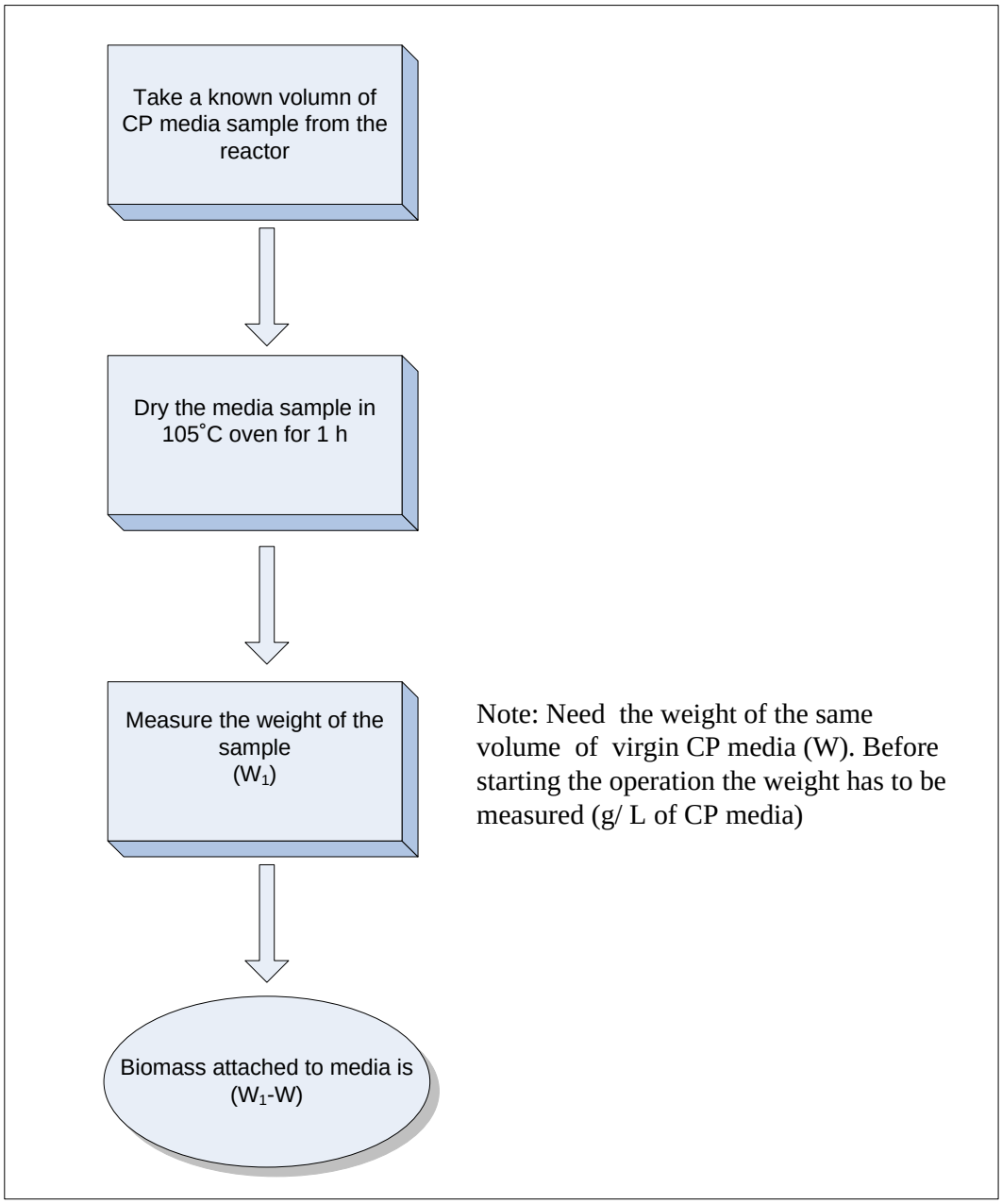

Figure B 2 Biomass calculation for Cylindrical Polypropylene media

Appendix C

MLSS, COD, TN, pH and DO data for SBR analysis

Table C 1. MLSS concentration of R1 CP and R2 Sponge media reactors

Date	Day	R1 CP reactor (g/L)	R2 Sponge reactor (g/L)
29.07.07	24	4.97	5.55
02.08.07	28	6.03	7.80
10.08.07	36	6.20	9.42
14.08.07	40	6.00	9.90
22.08.07	48	6.42	7.50
26.08.07	52	5.70	7.19
03.09.07	60	6.07	6.32
08.09.07	65	6.11	6.23
16.09.07	68	6.35	6.40
22.09.07	72	7.18	6.76

Table C 2. COD variations in R1, R2 and R3 (Sponge circular)

Date	Day	Influent (mg/L)	R1 (mg/L) CP	R2 (mg/L) Sponge	COD Removal Efficiency R1	COD Removal Efficiency R2	R3 (mg/L) Sponge Circular	COD Removal Efficiency R3
04.07.07	1	1200.0	144.0	82.0	88.0	93.2		
06.07.07	3	1200.0	128.0	68.0	89.3	94.3		
08.07.07	5	1380.0	87.1	51.5	93.7	96.3		
16.07.07	13	1370.0	39.5	21.4	97.1	98.4		
27.07.07	24	1237.6	270.4	62.8	78.2	94.9		
31.07.07	28	1280.0	208.2	34.7	83.7	97.3	63.7	95.0
08.08.07	36	1330.0	265.9	184.6	80.0	86.1	100.2	92.5
15.08.07	43	2047.4	158.7	116.6	92.2	94.3	112.8	94.5
26.08.07	54	1835.4	84.7	88.3	95.4	95.2	63.5	96.5
28.08.07	56	1857.1	84.4	51.6	95.5	97.2	38.9	97.9
31.08.07	59	1786.9	131.4	46.3	92.6	97.4	58.9	96.7
05.09.07	64	1984.9	109.5	53.3	94.5	97.3	51.9	97.4
09.09.07	68	2020.1	94.8	75.6	95.3	96.3	80.8	96.0

Table C 3. Nitrogen species of R1 (CP) and removal efficiencies

Day	TN in (mg/L)	TN out (mg/L)	NH3-N (mg/L)	NO3- N (mg/L)	NO2-N (mg/L)	TKN removal	TN removal rate (%)	Assimilation (mg/L)	SND (mg/L)	SND %
27	267.4	196.7	194.6	0.0	0.0	27.2	26.4	35.7	35.0	13.1
50	625.3	423.5	400.4	0.0	9.6	36.0	32.3	55.2	146.6	23.4
54	636.0	370.4	324.8	0.0	32.7	48.9	41.8	59.0	206.6	32.5
65	642.8	361.5	296.8	0.0	58.2	53.8	43.8	62.5	218.8	34.0
69	663.3	328.7	291.2	0.0	26.0	56.1	50.4	44.7	289.9	43.7
82	688.8	330.3	313.6	0.0	13.7	54.5	52.0	51.3	307.2	44.6

Table C 4. Nitrogen species of R2 (Sponge) and removal efficiencies

Day	TN in (mg/L)	TN out (mg/L)	NH3-N (mg/L)	NO3- N (mg/L)	NO2-N (mg/L)	TKN removal	TN removal rate (%)	Assimilation (mg/L)	SND (mg/L)	SND %
27	267.4	46.2	15.4	12.4	17.9	94.2	82.7	41.5	179.7	67.2
50	625.3	194.4	103.6	46.0	37.6	83.4	68.9	58.0	372.9	59.6
54	636.0	148.0	120.4	9.4	22.7	81.1	76.7	60.2	427.8	67.3
65	642.8	224.4	148.4	2.5	80.9	76.9	65.1	64.4	354.0	55.1
69	663.3	275.8	222.6	0.9	41.9	66.4	58.4	45.1	342.4	51.6
82	688.8	215.2	194.6	0.0	11.2	71.7	68.8	52.3	421.3	61.2

Table C 9 Nitrogen species of R3 (Sponge circular) and removal efficiencies

Day	TN in (mg/L)	TN out (mg/L)	NH3-N (mg/L)	NO3- N (mg/L)	NO2-N (mg/L)	TKN removal	TN removal rate (%)	Assimilation (mg/L)	SND (mg/L)	SND %
11	267.4	116.4	25.2	70.5	19.8	90.6	56.5	40.5	110.5	41.3
34	625.3	133.2	84.0	11.7	34.3	86.6	78.7	58.0	434.1	69.4
38	636.0	142.4	100.8	5.4	40.4	84.2	77.6	60.2	433.4	68.1
49	642.8	174.3	130.2	0.0	49.0	79.7	72.9	64.4	404.1	62.9
53	663.3	197.7	170.8	0.0	19.3	74.2	70.2	45.1	420.5	63.4
66	688.8	192.4	158.8	0.5	34.2	76.9	72.1	52.3	444.1	64.5

Table C 5. DO variation for 12 h on 27.07.07 for R1 and R2

	DO (mg/L)				
Time(h)	R1 Aeration	R1 Media	R2 Aeration	R2 Media	R3
11.34	4.67	3.68	2.35	2.83	2.40
12.40	4.44	3.55	3.34	2.68	2.28
14.00	4.31	3.71	3.97	3.56	2.60
15.40	4.54	3.55	4.07	3.50	3.08
18.10	4.52	3.78	4.32	3.94	3.90
20.40	4.52	3.65	4.52	4.11	4.30
22.24	4.66	4.07	4.71	4.36	4.42
23.04	2.01	0.48	2.64	1.97	2.24

Table C 6. pH data for reactors R1 (CP) and R2 (Sponge) for SBR analysis

Date	Time	R1	R2	Date	Time	R1	R2
02.07.07	15:00	8.58	8.65	08.07.07	22:50	8.02	7.77
	21:00	7.47	8.07	09.07.07	23:30	7.91	7.42
03.07.07	11:30	7.85	8.27	10.07.07	11:10	7.92	7.24
	12:30	8.30	8.15		22:45	8.01	7.20
	13:30	8.76	8.50	11.07.07	12:10	8.03	7.28
	14:30	8.80	8.44		23:00	8.03	7.24
	16:10	8.78	8.43	12.07.07	11:00	8.00	7.32
	17:30	7.52	7.35		23:10	7.99	7.32
	20:10	8.05	7.90	13.07.07	10:35	8.05	7.30
	21:30	8.74	8.58		22:45	8.31	6.37
	22:15	8.15	8.02		23:10	7.66	6.95
04.07.07	12:15	8.04	8.14	14.07.07	10:45	7.98	7.35
	23:45	7.97	7.59		22:50	8.10	7.16
05.07.07	12:15	7.96	7.74	15.07.07	11:10	8.12	5.94
	16:00	8.64	8.51		11:20	7.76	7.05
06.07.07	11:30	8.01	7.76	16.07.07	11:15	7.76	7.11
	23:00	8.56	8.76		22:50	7.41	7.12
	23:15	7.89	7.85	17.07.07	10:50	7.62	7.20
07.07.07	11:30	7.99	8.10		23:00	7.76	7.32
	22:10	8.13	8.45	18.07.07	11:30	7.49	7.16
	23:00	7.60	7.97		23:10	7.71	7.27
	23:15	7.56	7.75	19.07.07	10:45	7.80	7.32
08.07.07	11:15	7.76	8.03				

Table C 7. pH data for reactors R1 (CP), R2 (Sponge) and R3 (Sponge circular) for SBR analysis

Date	Time	R1	R2	R3
19.07.07	23:10	7.87	7.52	6.89
20.07.07	11:15	7.54	7.19	6.82
	23:00	7.86	7.45	7.12
21.07.07	11:10	7.70	7.37	6.97
	22:40	7.73	7.36	6.99
22.07.07	11:15	7.78	7.38	6.93
	23:10	7.55	7.28	7.11
23.07.07	12:00	8.16	7.93	7.47
	22:10	7.67	7.38	7.12
24.07.07	10:45	7.65	7.16	6.92
	22:50	7.83	7.10	6.91
25.07.07	22:00	7.79	7.23	6.96
26.07.07	12:00	8.00	7.44	7.06
	22:20	7.80	7.31	7.00
27.07.07	11:40	8.17	7.72	7.28
	12:40	8.36	7.71	7.13
	14:10	8.29	7.67	6.74
	15:40	8.38	7.58	6.30
	18:10	8.43	7.28	5.90
	20:40	8.43	6.71	5.73
	22:24	8.35	6.58	5.74
	23:04	8.20	7.79	7.29
28.07.07	11:45	8.06	7.74	7.16
	22:55	8.52	6.49	5.92
	23:00	8.15	7.74	7.15
29.07.07	11:20	8.07	7.72	7.19
	22:50	8.03	7.51	6.99
30.07.07	11:22	7.88	7.46	7.00
	22:55	7.78	7.30	6.99
31.07.07	12:10	7.93	7.51	7.18
	22:35	8.05	7.73	7.22
01.08.07	11:45	8.16	7.62	7.08
	23:50	7.90	7.59	7.19
02.08.07	11:45	7.91	7.63	7.06
	22:22	7.71	7.46	7.11
03.08.07	11:25	7.82	7.63	7.19
	22.05	7.62	7.44	7.09

Table C 7. pH data for reactors R1 (CP), R2 (Sponge) and R3 (Sponge circular) for SBR analysis (Cont.)

Date	Time	R1	R2	R3
04.08.07	11:35	7.98	7.96	7.26
	23:10	7.93	7.82	7.20
05.08.07	11:50	7.80	7.84	7.14
	23:00	7.73	7.63	7.07
06.08.07	11:30	7.83	7.87	7.17
07.08.07	12:00	7.91	7.77	7.14
	23:20	7.89	7.53	7.23
08.08.07	12:10	7.87	7.78	7.30
	23:25	8.05	7.54	7.44
09.08.07	11:40	8.05	7.80	7.64
	23:45	7.98	7.83	7.69
10.08.07	11:43	8.03	7.73	7.71
	22:55	7.41	6.00	7.25
	23:30	7.88	7.70	7.65
11.08.07	11:20	7.88	7.57	7.53
	23:40	7.86	7.66	7.61
12.08.07	11:55	8.02	7.82	7.68
	22:10	7.91	7.59	7.53
13.08.07	11:20	7.89	7.59	7.48
	23:21	7.84	7.49	7.51
14.08.07	12:50	7.66	7.28	7.31
	22:35	8.33	5.92	7.97
	23:08	7.85	7.35	7.49
15.08.07	11:00	8.01	7.60	7.63
	22:50	7.94	5.55	7.90
	23:10	7.76	7.45	7.47
16.08.07	11:50	7.78	7.47	7.56
	22:45	7.65	5.87	7.49
	23:10	7.72	7.32	7.49
17.08.07	11:20	7.92	7.74	7.60
	23:10	7.98	7.58	7.61
18.08.07	11:20	7.64	7.54	7.49
	23:10	7.68	7.54	7.61
19.08.07	11:05	7.76	7.36	7.46
	22:40	7.62	5.76	6.73
	23:10	7.52	7.19	7.21

Table C 7. pH data for reactors R1 (CP), R2 (Sponge) and R3 (Sponge circular) for SBR analysis (Cont.)

Date	Time	R1	R2	R3
20.08.07	11:20	7.84	7.21	7.28
	23:30	7.71	7.19	7.13
21.08.07	14:30	7.98	7.45	7.25
	0:20	7.88	7.35	7.41
22.08.07	12:10	7.78	7.34	7.42
	23:10	8.22	5.78	7.21
	23:50	7.85	7.31	7.23
23.08.07	11:30	7.96	7.60	7.61
	23:35	7.92	7.33	7.37
24.08.07	11:45	7.88	7.44	7.39
	23:50	8.00	7.50	7.36
25.08.07	12:05	8.00	7.50	7.31
	23:55	8.07	7.51	7.38
26.08.07	11:50	7.99	7.39	7.20
	13:20	8.24	7.62	7.81
	14:20	8.35	7.48	7.83
	15:20	8.37	7.20	7.74
	16:20	8.39	6.69	7.67
	18:10	8.38	5.87	7.42
	20:10	8.47	5.81	6.84
		8.44	5.77	5.74
	23.55	8.01	7.47	7.35
27.08.07	12.30	8.15	7.49	7.27
	23.50	7.96	7.54	7.22
28.08.07	12.10	7.91	7.57	7.22
	23.20	7.91	7.68	7.45
29.08.07	12.30	8.01	7.76	7.55
	0.30	8.20	7.81	7.66
30.08.07	12.20	8.21	7.68	7.41
	0.34	8.28	7.67	7.48
31.08.07	12.05	8.28	7.84	7.69
	0.30	8.32	7.69	7.62
01.09.07	11.30	7.98	7.59	7.62
	0.20	8.03	7.60	7.52
02.09.07	11.20	7.86	7.59	7.49
	23.50	7.78	7.59	7.40

Table C 7. pH data for reactors R1 (CP), R2 (Sponge) and R3 (Sponge circular) for SBR analysis (Cont.)

Date	Time	R1	R2	R3
03.09.07	0.40	7.64	7.72	7.47
04.09.07	12.10	7.67	7.66	7.56
	0.30	7.81	7.67	7.48
05.09.07	12.00	7.86	7.70	7.55
	0.20	7.96	7.64	7.55
06.09.07	12.26	7.97	7.77	7.71
	13.57	8.45	7.80	7.98
	14.50	8.42	7.61	7.92
	15.50	8.44	7.27	7.86
	16.50	8.45	6.68	7.84
	23.20	8.03	7.66	7.49
07.09.07	12.18	7.93	7.86	7.68
	13.18	8.29	7.87	8.03
	14.18	8.27	7.53	7.87
	15.18	8.30	7.25	7.97
	16.18	8.17	6.46	7.94
	17.18	8.12	7.39	7.93
	18.20	7.83	7.19	7.66
	19.20	7.75	7.21	7.59
	20.20	7.67	6.52	7.49
	21.20	7.42	6.19	7.26
	0.20	6.47	6.12	6.20
	1.20	7.50	7.63	7.46
08.09.07	13.15	7.63	7.98	7.60
	14.05	7.73	7.81	7.86
	1.20	7.47	7.73	7.55
09.09.07	12.30	7.52	7.74	7.51
	23.30	7.57	7.74	7.63
10.09.07	12.20	7.57	7.69	7.73
	0.10	7.60	7.80	7.71
11.09.07	12.20	7.61	7.73	7.78
	0.20	7.84	7.92	7.73
12.09.07	11.35	7.89	7.97	7.86
	0.20	7.56	7.79	7.72

Table C 7. pH data for reactors R1 (CP), R2 (Sponge) and R3 (Sponge circular) for SBR analysis (Cont.)

Date	Time	R1	R2	R3
	1.02	8.51	8.45	8.52
13.09.07	10.57	6.50	6.25	7.08
	12.03	7.70	7.76	7.82
	12.36	8.02	8.08	8.10
	13.32	8.06	8.18	8.12
	14.45	8.06	8.14	8.18
	17.10	7.70	7.30	8.03
	20.45	7.20	6.50	7.70
	22.07	7.20	6.45	7.52
	23.34	8.03	7.96	7.82
14.09.07	14.10	8.02	8.07	8.04
	20.54	7.43	6.20	7.61
	20.57	7.43	7.29	7.61
15.09.07	12.50	8.18	8.19	7.93
	23.21	7.76	6.26	7.56
	0.20	8.06	7.94	7.83
	0.25	8.06	8.02	7.87
16.09.07	11.25	7.62	6.25	7.45
	14.10	8.03	8.00	7.90
		7.60	6.40	7.74
		8.06	8.01	7.79
17.09.07	10.45	7.95	6.18	7.35
	12.20	8.16	7.87	7.92
	22.38	8.17	6.14	7.60
	23.40	8.04	7.74	7.84
18.09.07	12.50	8.09	7.95	7.84
	0.10	8.01	7.90	7.89
19.09.07	13.10	7.95	7.91	8.14
	22.40	6.73	6.21	7.92
	0.20	8.09	8.07	8.03
20.09.07	12.40	7.73	7.80	7.78
	0.35	7.87	8.05	7.84
21.09.07	13.10	7.96	8.05	7.81
	1.50	7.85	7.92	7.77
22.09.07	4.50	8.34	7.58	7.76
	14.10	8.22	8.09	8.04

Table C 7. pH data for reactors R1 (CP), R2 (Sponge) and R3 (Sponge circular) for SBR analysis (Cont.)

Date	Time	R1	R2	R3
23.09.07	1.10	8.15	7.80	7.81
	23.40	8.57	6.57	7.82
24.09.07	0.30	8.07	7.79	7.85
	1.14	8.20	8.02	7.88
25.09.07	13.35	7.95	7.93	7.93
	0.20	8.16	8.08	8.01
26.09.07	12.40	8.26	7.79	7.82
	13.10	8.22	7.94	7.87
	0.10	8.21	7.90	7.99
27.09.07	13.30	8.22	7.84	7.75
	23.00	8.73	6.50	7.57
	1.20	8.15	7.86	7.87
28.09.07	11.30	8.10	6.23	6.12
	15.20	8.18	8.03	8.02
	1.25	7.97	7.76	7.80
29.09.07	11.20	8.38	7.13	7.83
	13.40	8.08	7.83	7.86
	21.00	8.41	6.79	8.08
	1.20	8.10	7.78	7,92
30.09.07	11.30	8.48	7.10	7.72
	14.30	8.20	7.90	8.01
	20.40	8.60	8.18	8.20
	4.20	8.07	7.76	7.79
01.10.07	11.50	8.60	6.61	7.69

Table C 8. DO data for reactors R1 (CP), R2 (Sponge) and R3 (Sponge circular) for SBR analysis

Date	Time	R1 - CP		R2 - Sponge		R3
		Media	Aeration	Media	Aeration	
02.07.07	11.35	6.3	6.9	6.32	7.2	
03.07.07	11:45	5.42	6.45	4.68	6.4	
05.07.07	16:00	3.67	7.23	4.4	7.1	
10.07.07	11:15	3.85	5.2	3.68	4.97	
11.07.07	12:15	5.01	5.35	4.3	4.9	
13.07.07	10:40	2.7	3.35	4.25	4.7	
14.07.07	10:45	5.62	6.01	4.4	5.42	
15.07.07	11:20	3.64	4.43	3.52	4.32	
18.07.07	11:45	2.84	3.45	3.55	4.1	
19.07.07	10:50	4.34	4.81	3.62	4.2	
20.07.07	11:15	3.73	4.33	3.3	3.97	3.12
21.07.07	12:15	4.61	5.37	3.35	4.49	4.08
22.07.07	11:35	4.63	5.26	3.5	4.31	4.09
23.07.07	11:45	4.03	4.91	4.09	4.63	2.63
24.07.07	16:40	2.86	3.77	3.65	4.14	3.8
25.07.07	22:10	2.73	4.36	2.64	3.2	2.96
26.07.07	22:20	0.92	2.8	2.25	2.76	2.66
27.07.07	11:34	3.68	4.67	2.83	3.5	2.4
28.07.07	11:40	0.97	2.58	2.51	3.28	2.09
29.07.07	12:00	3.59	4.23	2.01	2.8	2.37
30.07.07	11:40	3.35	4.08	2.98	3.5	2.62
31.07.07	12:30	3.01	4.14	2.96	3.57	2.54
01.08.07	12:00	3.31	3.77	4.1	4.54	3.33
02.08.07	12:10	3.87	4.48	2.71	3.35	2.81
03.08.07	12:02	3.01	3.84	3.34	3.92	3.06
04.08.07	11:40	4.13	4.53	3.37	4.14	2.57
05.08.07	11:50	2.19	3.87	3.67	4.28	2.56
06.08.07	11:30	3.89	4.3	3.4	4.28	3.55
07.08.07	12:05	0.68	2.25	2.21	2.65	2.7
08.08.07	12:45	4.16	4.56	4.36	4.89	3.16

Table C 8. DO data for reactors R1 (CP), R2 (Sponge) and R3 (Sponge circular) for SBR analysis (Cont.)

Date	Time	R1 - CP		R2 - Sponge		R3
		Media	Aeration	Media	Aeration	
09.08.07	12:50	4.39	5.48	4.44	5.25	3.33
10.08.07	12:20	5.83	6.14	5.51	6.06	3.52
11.08.07	11.45	5.87	3.98	4.49	2.84	1.18
12.08.07	11.55	4.87	3.30	4.81	3.31	0.85
13.08.07	11.45	4.50	2.90	4.87	2.94	0.95
14.08.07	12.55	3.34	1.80	3.06	1.67	0.75
15.08.07	11.00	4.30	3.09	2.95	2.27	0.95
16.08.07	12.10	4.28	3.10	3.08	1.49	0.80
17.08.07	11.45	3.98	2.49	3.04	2.06	0.75
18.08.07	11.25	3.27	2.04	2.70	1.49	0.64
19.08.07	11.20	3.04	2.24	2.76	2.10	0.75
20.08.07	11.35	3.03	1.71	2.41	1.70	0.48
22.08.07	12.20	2.51	0.96	2.65	1.59	0.91
23.08.07	12.15	3.37	2.38	2.14	1.43	0.87
24.08.07	12.10	2.80	1.88	2.81	1.68	0.74
25.08.07	12.25	2.08	1.01	2.41	1.46	0.58
26.08.07	12.20	2.44	0.66	2.52	1.42	0.94
	13.20	4.88	3.36	2.59	1.73	0.76
	14.20	4.73	3.34	3.04	1.73	0.91
	15.20	4.82	3.66	2.97	1.83	0.98
	16.20	5.34	4.26	3.10	2.12	0.81
	18.10	5.71	4.98	5.12	4.70	1.18
	20.10	6.11	5.44	5.77	5.38	1.02
	22.20	6.34	5.53	6.28	5.86	4.74
	23.50	2.02	0.35	2.44	1.71	1.02
27.08.07	12.45	4.28	3.44	2.98	1.79	1.07
28.08.07	12.30	2.08	0.55	3.19	1.71	0.64
29.08.07	12.45	1.86	0.76	3.26	1.36	0.62
30.08.07	12.15	2.89	2.10	2.84	1.54	0.71
01.09.07	12.10	1.92	0.50	2.48	1.01	0.67

Appendix D

MLSS, COD, Nitrogen data for MBR analysis

Table D 1 Variation of MLSS and MLVSS in R1 under HRT 10 h

Date	No of days	MLSS (g/L)	MLVSS (g/L)	MLSS/MLVSS ratio
19.11.07	1	10.13	8.73	0.86
23.11.07	5	10.76	9.80	0.91
26.11.07	8	10.31	8.79	0.85
28.11.07	10	11.63	10.05	0.86
01.12.07	13	12.42	10.95	0.88
03.12.07	15	12.76	11.17	0.88
05.12.07	17	12.54	10.95	0.87
07.12.07	19	12.81	10.79	0.84
12.12.07	24	11.62	10.32	0.89
14.12.07	26	10.62	9.17	0.86
15.12.07	27	11.33	9.55	0.84
22.12.07	34	8.56	8.22	0.96
26.12.07	38	7.03	7.06	1.00
29.12.07	39	7.39	6.98	0.94
31.12.07	41	8.42	8.06	0.96
05.01.08	48	7.90	7.16	0.91
09.01.08	52	9.14	8.37	0.92
13.01.08	56	8.66	7.88	0.91
20.01.08	63	8.95	7.96	0.89
Avg.		10.16	9.02	0.89
Stdev.		1.88	1.44	0.04

Table D 2 Variation of MLSS and MLVSS in R2 under HRT 10 h

Date	No of days	MLSS (g/L)	MLVSS (g/L)	MLSS/MLVSS ratio
19.11.07	1	8.16	7.40	0.91
23.11.07	5	9.49	8.54	0.90
26.11.07	8	9.64	8.24	0.85
28.11.07	10	10.31	9.02	0.87
01.12.07	13	10.71	9.46	0.88
03.12.07	15	11.06	9.75	0.88
05.12.07	17	11.31	10.08	0.89
07.12.07	19	10.24	8.63	0.84
12.12.07	24	11.27	10.05	0.89
14.12.07	26	9.04	7.90	0.87

Table D 2 Variation of MLSS and MLVSS in R2 under HRT 10 h (Cont.)

Date	No of days	MLSS (g/L)	MLVSS (g/L)	MLSS/MLVSS ratio
15.12.07	27	10.23	8.96	0.88
22.12.07	34	9.48	8.76	0.92
26.12.07	38	8.06	7.10	0.88
29.12.07	39	8.77	8.06	0.92
31.12.07	41	8.63	7.83	0.91
05.01.08	48	8.74	7.78	0.89
09.01.08	52	10.22	8.76	0.86
13.01.08	56	9.51	8.57	0.90
20.01.08	63	9.79	8.93	0.91
Avg,		9.72	8.62	0.89
Stdev.		0.99	0.84	0.02

Table D 3 Variation of MLSS and MLVSS in R1 under HRT 7 h

Date	No of days	MLSS (g/L)	MLVSS (g/L)	MLVSS/MLSS
01.02.08	1	8.21	7.33	0.89
12.02.08	12	7.68	7.09	0.92
19.02.08	19	8.04	7.11	0.88
26.02.08	26	8.42	7.97	0.95
04.03.08	33	9.84	9.18	0.93
06.03.08	35	8.99	7.80	0.87
Avg		8.53	7.75	0.91
Stdev		0.78	0.79	0.03

Table D 4 Variations of MLSS and MLVSS in R2 under HRT 7 h

Date	No of days	MLSS (g/L)	MLVSS (g/L)	MLVSS/MLSS
01.02.08	1	9.98	8.18	0.82
12.02.08	12	8.44	7.68	0.91
19.02.08	19	8.49	7.54	0.89
26.02.08	26	9.03	8.29	0.92
04.03.08	33	10.02	9.67	0.97
06.03.08	35	8.06	7.18	0.89
Avg		9.00	8.09	0.90
Stdev		0.83	0.88	0.05

Table D 5 Variations of MLSS and MLVSS in R1 under HRT 13 h

Date	No of days	MLSS (g/L)	MLVSS (g/L)	MLVSS/MLSS
21.03.08	7	10.16	9.06	0.89
01.04.08	16	8.82	8.14	0.92
07.04.08	22	10.20	9.33	0.91
Avg.		9.73	8.84	0.91
Stdev.		0.79	0.62	0.02

Table D 6 Variations of MLSS and MLVSS in R2 under HRT 13 h

Date	No of days	MLSS (g/L)	MLVSS (g/L)	MLVSS/MLSS
21.03.08	7	8.67	7.39	0.85
01.04.08	16	6.71	6.05	0.90
07.04.08	22	6.38	5.86	0.92
Avg.		7.25	6.43	0.89
Stdev.		1.24	0.83	0.03

Table D 7 COD Variation in R1 and R2 during HRT 10 h

Date	Day	Influent COD (mg/L)	R1 COD (mg/L)	Assimilation R1 (mg/L)	COD Removal Efficiency R1 (%)	R2 COD (mg/L)	Assimilation R2 (mg/L)	COD Removal Efficiency R2 (%)
24.11.07	6	999.8	13.4	32.9	98.7	6.7	33.1	99.3
26.11.07	8	1027.3	18.5	33.6	98.2	5.9	34.0	99.4
01.12.07	13	882.6	20.3	28.7	97.7	29.7	28.4	96.6
03.12.07	15	1056.0	23.5	34.4	97.8	26.1	34.3	97.5
05.12.07	17	964.9	25.5	31.3	97.4	22.2	31.4	97.7
07.12.07	19	845.4	14.0	27.7	98.3	13.8	27.7	98.4
09.12.07	21	690.1	14.1	22.5	98.0	16.5	22.5	97.6
11.12.07	23	881.0	20.8	28.7	97.6	17.8	28.8	98.0
15.12.07	27	874.8	34.7	28.0	96.0	18.8	28.5	97.9
17.12.07	29	1008.0	45.9	32.1	95.4	22.8	32.8	97.7
21.12.07	33	926.9	30.5	29.9	96.7	22.3	30.2	97.6
23.12.07	35	893.8	27.1	28.9	97.0	16.1	29.3	98.2
27.12.07	39	732.1	31.4	23.4	95.7	23.6	23.6	96.8
29.12.07	41	1013.4	24.2	33.0	97.6	21.7	33.1	97.9
31.12.07	43	859.8	6.5	28.4	99.2	3.2	28.6	99.6
02.01.08	45	860.5	14.9	28.2	98.3	5.7	28.5	99.3
05.01.08	48	853.4	21.3	27.7	97.5	3.3	28.3	99.6
09.01.08	52	865.9	24.0	28.1	97.2	12.4	28.4	98.6
10.01.08	53	972.3	22.8	31.6	97.7	14.5	31.9	98.5
13.01.08	56	861.5	20.1	28.0	97.7	8.2	28.4	99.0
15.01.08	58	989.1	38.4	31.7	96.1	24.7	32.1	97.5
17.01.08	60	872.9	24.1	28.3	97.2	5.3	28.9	99.4
Avg		906.0	23.5		97.4	15.5		98.3
St. dev.		92.0	8.9		1.0	8.2		0.9

Table D 8 COD Variation in R1 and R2 during HRT 7 h

Date	Day	Influent COD (mg/L)	R1 COD (mg/L)	Assimilation R1 (mg/L)	Removal eff in R1 (%)	R2 COD (mg/L)	Assimilation R2 (mg/L)	Removal eff in R2 (%)
12.02.08	2	624.2	19.7	20.1	96.8	12.2	20.4	98.0
14.02.08	4	600.6	23.2	19.2	96.1	8.4	19.7	98.6
15.02.08	5	630.7	19.4	20.4	96.9	7.4	20.8	98.8
19.02.08	9	636.5	22.4	20.5	96.5	9.3	20.9	98.5
21.02.08	11	641.1	18.2	20.8	97.2	5.7	21.2	99.1
24.02.08	14	658.1	16.7	21.4	97.5	9.6	21.6	98.5
28.02.08	18	638.4	16.9	20.7	97.4	7.3	21.0	98.9
01.03.08	20	655.7	15.4	21.3	97.7	8.1	21.6	98.8
07.03.08	26	680.9	17.3	22.1	97.5	10.4	22.4	98.5
12.03.08	31	663.7	16.8	21.6	97.5	5.6	21.9	99.2
Avg		643.0	18.6		97.1	8.4		98.7
Stdev		22.7	2.6		0.5	2.1		0.3

Table D 9 COD Variation in R1 and R2 during HRT 13 h

Date	Day	Influent COD (mg/L)	R1 COD (mg/L)	Assimilation R1 (mg/L)	Removal Eff in R1 (%)	R2 COD (mg/L)	Assimilation R2 (mg/L)	Removal Eff in R2 (%)
16.03.08	2	1260.0	14.5	41.5	98.8	7.7	41.7	99.4
18.03.08	4	1295.2	27.7	42.3	97.9	19.3	42.5	98.5
20.03.08	6	1280.0	23.8	41.9	98.1	14.2	42.2	98.9
22.03.08	8	1209.5	26.2	39.4	97.8	12.1	39.9	99.0
24.03.08	10	1196.7	24.6	39.1	97.9	16.3	39.3	98.6
27.03.08	13	1180.3	25.9	38.5	97.8	15.4	38.8	98.7
29.03.08	15	1202.8	21.5	39.4	98.2	15.9	39.6	98.7
31.03.08	17	1210.5	24.8	39.5	98.0	14.8	39.9	98.8
03.04.08	20	1180.5	22.1	38.6	98.1	12.7	38.9	98.9
07.04.08	24	1055.1	24.9	34.3	97.6	13.3	34.7	98.7
09.04.08	26	1110.1	19.3	36.4	98.3	13.8	36.5	98.8
Avg.		1198.2	23.2	39.2	98.1	14.1		98.8
St. dev.		70.1	3.7	2.3	0.3	2.9		0.2

Table D 10 Variation of nitrogen species in R1 during HRT 10 h

Date	Day	TN in (mg/L)	TN out (mg/L)	NH_3-N (mg/L)	NO_3- N (mg/L)	NO_2-N (mg/L)	TN removal rate (%)	Assimilation (mg/L)	SND (mg/L)	SND %
24.11.07	6	183.7	132.6	2.8	126.4	2.6	27.8	32.9	18.2	9.9
01.12.07	13	226.6	147.7	5.6	132.5	7.8	34.8	33.6	45.3	20.0
05.12.07	17	229.1	142.8	14.0	120.1	8.7	37.7	28.7	57.6	25.1
07.12.07	19	231.8	149.8	8.4	134.1	10.6	35.4	34.4	47.6	20.5
09.12.07	21	216.0	152.2	2.8	130.1	17.3	29.5	31.3	32.5	15.0
11.12.07	23	226.4	159.3	26.4	130.9	1.1	29.6	27.7	39.4	17.4
15.12.07	27	178.0	164.0	0.0	163.9	0.2	7.9	22.5	0.0	0.0
17.12.07	29	191.9	166.6	1.4	165.8	0.0	13.2	28.7	0.0	0.0
21.12.07	33	185.7	159.9	5.6	146.4	1.8	13.9	28.0	0.0	0.0
23.12.07	35	191.1	154.5	0.0	157.0	0.5	19.2	32.1	4.5	2.4
27.12.07	39	185.1	148.0	5.6	137.1	0.5	20.0	29.9	7.2	3.9
29.12.07	41	188.4	115.1	2.8	109.3	1.1	38.9	28.9	44.4	23.6
31.12.07	43	194.7	113.2	0.0	110.5	4.4	41.9	23.4	58.1	29.9
02.01.08	45	201.0	110.2	0.0	85.1	22.6	45.2	33.0	57.8	28.8
05.01.08	48	186.4	147.9	5.6	143.4	0.1	20.7	28.4	10.1	5.4
09.01.08	52	177.6	147.9	5.6	134.0	8.1	16.7	28.2	1.5	0.9
10.01.08	53	184.7	126.3	11.2	103.8	10.3	31.6	27.7	30.7	16.6
13.01.08	56	183.0	140.3	2.8	133.8	1.1	23.3	28.1	14.6	8.0
15.01.08	58	185.4	142.5	2.8	133.1	18.5	23.1	31.6	11.3	6.1
17.01.08	60	183.1	138.8	0.0	134.3	1.5	24.2	28.0	16.3	8.9
Avg.		196.5	143.0	5.2	131.6	5.9	26.7	31.7		12.1
St. dev.		11.9	16.3	6.3	19.6	6.9	10.2	28.3		10.1

Table D 11 Variation of nitrogen species in R2 during HRT 10 h

Date	Day	TN in (mg/L)	TN out (mg/L)	NH_3-N (mg/L)	NO_3- N (mg/L)	NO_2-N (mg/L)	TN removal rate (%)	Assimilation (mg/L)	SND (mg/L)	SND %
24.11.07	6	183.7	52.5	19.6	11.5	25.9	71.4	33.1	98.1	53.4
01.12.07	13	226.6	72.4	61.0	0.0	1.8	68.0	34.0	120.2	53.0
05.12.07	17	229.1	81.8	72.8	0.0	1.1	64.3	28.4	118.9	51.9
07.12.07	19	231.8	54.1	38.6	0.6	13.7	76.7	34.3	143.4	61.9
09.12.07	21	216.0	49.1	22.4	1.1	20.5	77.3	31.4	135.5	62.7
11.12.07	23	226.4	128.7	5.4	102.8	11.2	43.2	27.7	70.0	30.9
15.12.07	27	178.0	121.1	2.8	117.9	0.7	32.0	22.5	34.4	19.4
17.12.07	29	191.9	116.4	0.0	123.3	0.9	39.3	28.8	46.7	24.3
21.12.07	33	185.7	122.1	0.0	126.3	1.8	34.2	28.5	35.1	18.9
23.12.07	35	191.1	118.0	0.0	116.3	1.1	38.3	32.8	40.3	21.1
27.12.07	39	175.3	107.0	5.4	101.0	0.5	39.0	30.2	38.1	21.8
29.12.07	41	188.4	109.3	2.8	106.5	0.4	42.0	29.3	49.8	26.5
31.12.07	43	194.7	96.9	0.0	94.9	0.8	50.2	23.6	74.2	38.1
02.01.08	45	201.0	96.5	0.0	92.0	4.9	52.0	33.1	71.4	35.5
05.01.08	48	186.4	36.8	2.8	22.6	8.8	80.3	28.6	121.0	64.9
09.01.08	52	177.6	22.6	19.6	0.4	1.3	87.3	28.5	126.5	71.2
10.01.08	53	184.7	26.9	22.4	0.1	2.1	85.4	28.3	129.5	70.1
13.01.08	56	183.0	11.7	5.6	0.2	4.3	93.6	28.4	142.9	78.1
15.01.08	58	185.4	20.4	5.6	7.6	9.2	89.0	31.9	133.1	71.8
17.01.08	60	183.1	26.5	5.6	8.8	9.5	85.5	28.4	128.2	70.0
Avg.		183.4	24.2	10.3	6.6	5.9	86.8			71.0
St. dev.		3.1	8.3	8.4	8.8	3.8	4.4			4.2

Note : Average and Standard deviation for TN_{out} , NH3 –N, NO3-N, NO2- N, TN removal and SND rate calculated from data after 15.01.08 (after restoring the original configuration for R2).

Table D 12 Variation of nitrogen species in R1 during HRT 7 h

Date	Day	TN in (mg/L)	TN out (mg/L)	NH_3-N (mg/L)	NO_3- N (mg/L)	NO_2-N (mg/L)	TN removal rate (%)	Assimilation (mg/L)	SND (mg/L)	SND %
12.02.08	2	127.6	103.0	2.8	98.3	1.6	19.3	20.1	4.5	3.5
14.02.08	4	130.0	104.7	0.0	102.1	2.6	19.5	19.2	6.1	4.7
15.02.08	5	134.5	107.1	2.8	102.6	2.4	20.4	20.4	7.0	5.2
19.02.08	9	132.7	109.5	2.8	106.1	2.2	17.5	20.5	2.7	2.1
21.02.08	11	130.0	102.1	0.0	101.1	0.2	21.5	20.8	7.1	5.5
24.02.08	14	129.4	98.3	2.8	94.1	0.7	24.0	21.4	9.7	7.5
28.02.08	18	139.3	108.7	5.6	98.5	2.8	22.0	20.7	9.9	7.1
01.03.08	20	127.6	103.4	2.8	93.8	3.2	19.0	21.3	2.9	2.2
07.03.08	26	135.2	104.0	2.8	99.4	0.6	23.1	22.1	9.1	6.7
12.03.08	31	131.0	97.7	2.8	94.3	2.3	25.4	21.6	11.7	9.0
Avg		131.7	103.9	2.5	99.0	1.9	21.2			5.3
St. dev		3.7	3.9	1.6	4.1	1.0	2.5			2.3

Table D 13 Variation of nitrogen species in R2 during HRT 7 h

Date	Day	TN in (mg/L)	TN out (mg/L)	NH_3-N (mg/L)	NO_3- N (mg/L)	NO_2-N (mg/L)	TN removal rate (%)	Assimilation (mg/L)	SND (mg/L)	SND %
12.02.08	2	127.6	63.1	58.8	1.5	0.0	50.5	20.4	44.1	34.6
14.02.08	4	130.0	81.2	76.8	2.1	0.0	37.5	19.7	29.1	22.4
15.02.08	5	134.5	52.0	47.6	0.0	0.0	61.3	20.8	61.7	45.9
19.02.08	9	132.7	74.2	70.0	0.0	0.0	44.1	20.9	37.6	28.3
21.02.08	11	130.0	47.7	44.8	0.0	0.0	63.3	21.2	61.1	47.0
24.02.08	14	129.4	93.9	89.6	0.0	0.0	27.4	21.6	13.9	10.7
28.02.08	18	139.3	108.5	103.6	0.0	0.0	22.1	21.0	9.8	7.0
01.03.08	20	127.6	96.3	95.2	0.0	0.0	24.5	21.6	9.7	7.6
07.03.08	26	135.2	108.4	103.6	0.0	0.0	19.8	22.4	4.4	3.3
12.03.08	31	131.0	105.4	100.8	0.0	0.0	19.5	21.9	3.7	2.8
Avg		131.7	83.1	79.1	0.4	0.0	37.0			21.0
St. dev		3.7	23.0	22.9	0.8	0.0	17.0			17.2

Table D 14 Variation of nitrogen species in R1 during HRT 13 h

Date	Day	TN in (mg/L)	TN out (mg/L)	NH_3-N (mg/L)	NO_3- N (mg/L)	NO_2-N (mg/L)	TN removal rate (%)	Assimilation (mg/L)	SND (mg/L)	SND %
16.03.08	2	247.0	156.2	2.8	154.9	1.2	36.8	41.5	49.3	20.0
18.03.08	4	240.2	161.7	2.8	150.9	2.3	32.7	42.3	36.3	15.1
20.03.08	6	242.0	156.4	2.8	149.3	8.9	35.4	41.9	43.7	18.1
22.03.08	8	233.3	184.5	1.4	174.9	1.2	20.9	39.4	9.4	4.0
24.03.08	10	241.7	177.4	1.4	168.7	1.9	26.6	39.1	25.2	10.4
27.03.08	13	241.2	179.6	2.8	170.4	0.7	25.5	38.5	23.1	9.6
29.03.08	15	223.1	181.1	1.4	177.3	1.5	18.8	39.4	2.6	1.2
31.03.08	17	236.8	184.4	1.4	182.2	0.7	22.1	39.5	12.9	5.4
03.04.08	20	239.5	163.0	1.4	159.4	0.2	31.9	38.6	37.9	15.8
07.04.08	24	240.8	173.0	1.4	170.0	1.2	28.2	34.3	33.5	13.9
09.04.08	26	240.0	175.2	1.4	173.3	0.3	27.0	36.4	28.4	11.9
Ave		238.7	172.0	1.9	166.5	1.8	27.8		27.5	11.4
St. dev		6.2	10.8	0.7	11.1	2.4	5.9		14.6	6.0

Table D 15 Variation of nitrogen species in R2 during HRT 13 h

Date	Day	TN in (mg/L)	TN out (mg/L)	NH_3-N (mg/L)	NO_3- N (mg/L)	NO_2-N (mg/L)	TN removal rate (%)	Assimilation (mg/L)	SND (mg/L)	SND %
16.03.08	2	247.0	91.3	2.8	30.3	61.2	63.0	41.7	114.0	46.1
18.03.08	4	240.2	52.4	8.4	19.1	21.0	78.2	42.5	145.3	60.5
20.03.08	6	242.0	46.7	8.4	15.4	20.4	80.7	42.2	153.1	63.3
22.03.08	8	233.3	44.1	5.6	18.4	27.2	81.1	39.9	149.3	64.0
24.03.08	10	241.7	83.4	5.6	13.5	75.4	65.5	39.3	119.0	49.2
27.03.08	13	241.2	137.7	2.8	72.3	72.9	42.9	38.8	64.7	26.8
29.03.08	15	223.1	137.9	2.8	105.9	41.4	38.2	39.6	45.6	20.5
31.03.08	17	236.8	138.2	1.4	95.8	42.9	41.6	39.9	58.7	24.8
03.04.08	20	239.5	101.3	1.4	66.4	35.9	57.7	38.9	99.3	41.5
07.04.08	24	240.8	100.4	1.4	60.1	38.7	58.3	34.7	105.7	43.9
09.04.08	26	240.0	97.2	1.4	61.6	35.3	59.5	36.5	106.3	44.3
Ave		238.7	93.7	3.8	50.8	42.9	60.6		105.5	44.1
St. dev		6.2	35.3	2.7	33.3	19.1	15.3		36.7	15.2

Table D 16 TMP and pH variation with time under 10 h HRT for R1 and R2

Date	Day	pH variation		TMP (kPa)	
		R1	R2	R1	R2
19.11.07	1	7.19	7.29	1.3	2.2
20.11.07	2	7.12	7.57	1.3	2.1
21.11.07	3	7.22	7.52	1.3	2.1
22.11.07	4	7.35	7.56	1.3	2.1
23.11.07	5	7.59	7.77	1.3	2.1
24.11.07	6	7.54	7.77	1.3	2.2
25.11.07	7	7.44	7.57	1.4	2.3
26.11.07	8	7.24	7.73	1.3	2.3
27.11.07	9	7.07	7.76	1.4	2.3
28.11.07	10	7.41	7.97	1.4	2.4
29.11.07	11	7.39	7.89	1.5	2.4
30.11.07	12	7.40	7.74	1.5	2.4
01.12.07	13	7.36	7.80	1.5	2.5
02.12.07	14	7.42	7.75	1.5	2.6
03.12.07	15	7.30	7.63	1.9	2.9
04.12.07	16	7.37	7.68	1.9	3.0
05.12.07	17	7.29	7.69	1.9	3.0
06.12.07	18	7.30	7.70	1.7	3.1
07.12.07	19	7.28	7.67	1.9	3.2
08.12.07	20	7.35	7.66	1.9	3.3
09.12.07	21	7.28	7.62	1.9	3.2
10.12.07	22	7.36	7.48	1.9	3.1
11.12.07	23	7.42	7.60	1.8	3.1
12.12.07	24	7.47	7.53	1.7	3.0
13.12.07	25	7.58	7.64	1.7	2.9
14.12.07	26	7.34	7.50	1.7	3.0
15.12.07	27	7.23	7.71	1.7	2.9
16.12.07	28	7.32	7.77	1.7	3.0
17.12.07	29	7.38	7.70	1.7	3.1
18.12.07	30	7.37	7.63	1.8	3.0
19.12.07	31	7.41	7.59	1.7	3.0
20.12.07	32	7.23	7.58	1.8	3.1
21.12.07	33	7.38	7.66	1.8	3.1
22.12.07	34	7.51	7.68	1.9	3.1
23.12.07	35	7.49	7.85	1.9	3.1
24.12.07	36	7.63	7.94	2.0	3.1
25.12.07	37	7.48	7.72	2.0	3.1
26.12.07	38	7.41	7.70	2.0	3.1
27.12.07	39	7.56	7.76	2.1	3.2
28.12.07	40	7.63	7.93	2.1	3.2
29.12.07	41	7.68	7.74	2.2	3.3
30.12.07	42	7.62	7.71	2.2	3.5
31.12.07	43	7.52	7.62	2.3	3.6
01.01.08	44	7.64	7.74	2.5	3.6
02.01.08	45	7.74	7.74	2.6	3.8
03.01.08	46	7.59	7.61	2.6	3.9
04.01.08	47	7.70	7.70	2.6	3.9
05.01.08	48	7.95	7.73	2.3	4.1
06.01.08	49	7.90	7.74	2.5	4.1
07.01.08	50	8.08	7.67	2.6	4.2
08.01.08	51	8.05	7.69	2.7	4.3
09.01.08	52	7.95	7.72	2.7	4.7
10.01.08	53	7.58	7.71	2.7	5.0
11.01.08	54	7.49	7.81	2.8	5.1
12.01.08	55	7.53	7.78	2.6	5.2
13.01.08	56	7.64	7.78	2.2	5.7
14.01.08	57	7.64	7.83	2.4	6.1
15.01.08	58	7.44	7.73	2.5	6.5
16.01.08	59	7.43	7.76	2.7	6.9
17.01.08	60	7.50	7.71	2.9	7.7
18.01.08	61	7.36	7.76	3.2	8.5
19.01.08	62	7.53	7.83	3.2	8.8
20.01.08	63	7.57	7.72	3.5	8.8
21.01.08	64	7.53	7.71	3.5	8.7
22.01.08	65	7.36	7.70	3.8	8.6
23.01.08	66	7.37	7.77	4.1	9.0
24.01.08	67	7.47	7.72	4.4	9.9
25.01.08	68	7.45	7.77	5.0	13.6
26.01.08	69	7.33	7.75	8.1	16.1
27.01.08	70	7.47	7.79	19.0	19.4
28.01.08	71	7.37	7.89	32.2	22.3
29.01.08	72	7.29	7.78		25.4
30.01.08	73	7.30	7.78		27.2
31.01.08	74	7.57	7.86		30.0
Aveg.		7.47	7.71		
Std Dev.		0.22	0.14		

Table D 17 TMP and pH variation with time under 7 h HRT for R1 and R2

Date	Day	R1		R2	
		pH	TMP	pH	TMP
01.02.08	1	7.40	1.8	7.59	2.0
02.02.08	2	7.45	1.9	7.78	2.7
03.02.08	3	7.45	2.4	7.80	2.9
04.02.08	4	7.41	2.6	7.77	3.0
05.02.08	5	7.38	3.1	7.83	3.1
06.02.08	6	7.10	3.5	7.75	3.0
07.02.08	7	7.05	3.9	7.81	3.2
08.02.08	8	7.20	4.2	7.85	3.4
09.02.08	9	7.05	4.1	7.82	3.7
10.02.08	10	6.95	4.2	7.82	3.8
11.02.08	11	7.25	4.3	7.87	4.4
12.02.08	12	7.28	4.5	7.86	6.0
13.02.08	13	7.37	4.6	7.97	7.8
14.02.08	14	7.39	5.0	7.97	9.6
15.02.08	15	7.14	5.3	8.03	10.5
16.02.08	16	7.41	5.7	8.12	11.5
17.02.08	17	7.28	6.2	7.90	11.9
18.02.08	18	7.25	6.3	7.76	12.7
19.02.08	19	7.37	6.6	7.87	13.6
20.02.08	20	7.33	7.0	8.06	14.5
21.02.08	21	7.17	7.4	7.92	15.5
22.02.08	22	7.41	7.7	7.95	15.9
23.02.08	23	7.34	8.1	7.94	17.8
24.02.08	24	7.60	8.1	8.01	22.0
25.02.08	25	7.35	8.2	8.05	31.2
26.02.08	26	7.46	8.4		
27.02.08	27	7.40	9.2		
28.02.08	28	7.48	10.6		
29.02.08	29	7.36	13.0		
01.03.08	30	7.37	13.5		
02.03.08	31	7.43	14.1		
03.03.08	32	7.52	15.4		
04.03.08	33	7.42	16.8		
05.03.08	34	7.46	19.6		
06.03.08	35	7.59	23.0		
07.03.08	36	7.39	27.0		
08.03.08	37		31.1		
Avg.		7.34		7.88	
St. Dev.		0.15		0.12	

Table D 18 TMP and pH variation with time under 13 h HRT for R1 and R2

Date	Day	pH		TMP (kPa)	
		R1	R2	R1	R2
15.03.08	1	7.40	7.57	1.2	1.7
16.03.08	2	7.45	7.67	1.6	1.8
17.03.08	3	7.45	7.69	1.6	1.9
18.03.08	4	7.41	7.68	1.8	2.0
19.03.08	5	7.38	7.76	1.9	2.1
20.03.08	6	7.10	7.76	1.8	2.2
21.03.08	7	7.05	7.84	1.8	2.2
22.03.08	8	7.20	7.84	1.9	2.4
23.03.08	9	7.05	7.75	2.0	2.3
24.03.08	10	6.95	7.59	2.0	2.3
25.03.08	11	7.25	7.78	1.9	2.4
26.03.08	12	7.28	7.80	2.0	2.8
27.03.08	13	7.37	7.77	2.0	3.1
28.03.08	14	7.39	7.83	2.1	3.0
29.03.08	15	7.14	7.75	2.1	3.1
30.03.08	16	7.41	7.81	2.2	3.1
31.03.08	17	7.28	7.85	2.3	3.1
01.04.08	18	7.25	7.82	2.4	3.1
02.04.08	19	7.37	7.82	2.1	3.0
03.04.08	20	7.33	7.87	2.2	3.0
04.04.08	21	7.17	7.86	2.4	2.9
05.04.08	22	7.41	7.97	2.4	2.9
06.04.08	23	7.34	7.97	2.6	2.9
07.04.08	24	7.45	8.03	2.1	2.9
08.04.08	25	7.55	7.63	2.3	2.9
Avg.		7.30	7.79		
St. Dev.		0.15	0.11		

Table D 19 EPS variation with three HRTs for R1 and R2

HRT	PS				PN			
	Bound (mg)/gVSS		Soluble (mg/L)		Bound (mg)/gVSS		Soluble (mg/L)	
	R1	R2	R1	R2	R1	R2	R1	R2
10	3.45	2.60	16.36	13.81	13.61	11.21	0.00	0.43
	9.58	5.39	16.73	12.21	40.78	19.51	5.80	0.00
	9.87	5.76	3.32	4.27	19.34	11.15	0.00	0.00
	8.38	4.49	8.28	5.58	30.41	18.05	0.75	0.00
	6.50	4.29	15.11	13.22	27.77	19.91	3.16	3.01
Aveg.	7.55	4.50	11.96	9.82	26.38	15.97	4.48	3.01
St. dev.	2.65	1.23	5.92	4.53	10.47	4.42	1.86	0.00
7	11.07	5.82	7.91	3.69	8.36	4.11	2.23	3.10
	8.73	6.13	5.65	1.06	7.81	6.22	1.72	2.01
	10.23	6.51	8.57	9.15	7.26	5.33	2.01	5.44
	9.97	5.86	7.51	4.40	13.36	7.24	1.68	2.64
Aveg.	10.00	6.08	7.41	4.57	9.20	5.73	1.91	3.30
St. dev.	0.97	0.32	1.25	3.37	2.81	1.33	0.26	1.49
13	8.08	5.94	10.32	5.87	6.29	9.38	1.79	2.89
	6.80	6.83	10.68	6.53	3.93	6.21	1.87	2.52
	7.14	5.99	9.66	5.05	4.79	6.59	1.57	2.81
Aveg.	7.34	6.25	10.22	5.82	5.01	7.39	1.74	2.74
St. dev.	0.66	0.50	0.52	0.74	1.20	1.73	0.15	0.19

Table D 20 Particle size distribution for R1

Size low	In %	Size high	Under %		Size low	In %	Size high	Under %
0.05	2.35	0.06	2.35		6.63	0	7.72	99.99
0.06	3.72	0.07	6.07		7.72	0	9	100
0.07	4.73	0.08	10.8		9	0	10.48	100
0.08	5.72	0.09	16.52		10.48	0	12.21	100
0.09	6.63	0.11	23.35		12.21	0	14.22	100
0.11	8.01	0.13	31.35		14.22	0	16.57	100
0.13	9.12	0.15	40.45		16.57	0	19.31	100
0.15	10	0.17	50.58		19.31	0	22.49	100
0.17	10.47	0.2	60.95		22.49	0	26.2	100
0.2	10.32	0.23	71.27		26.2	0	30.53	100
0.23	9.25	0.27	80.52		30.53	0	35.56	100
0.27	7.21	0.31	87.73		35.58	0	41.43	100
0.31	4.5	0.36	92.53		41.43	0	48.27	100
0.36	2.89	0.42	95.42		48.27	0	58.23	100
0.42	1.72	0.49	97.14		56.23	0	65.51	100
0.49	1.02	0.58	98.16		65.51	0	76.32	100
0.58	0.58	0.67	98.74		76.32	0	88.91	100
0.67	0.34	0.78	99.06		88.91	0	103.58	100
0.78	0.23	0.91	99.3		103.58	0	120.67	100
0.91	0.16	1.06	99.46		120.67	0	140.58	100
1.06	0.12	1.24	99.57		140.58	0	163.77	100
1.24	0.09	1.44	99.66		163.77	0	190.8	100
1.44	0.07	1.68	99.74		190.8	0	222.28	100
1.68	0.06	1.95	99.8		222.28	0	258.95	100
1.95	0.05	2.28	99.85		258.95	0	301.68	100
2.28	0.04	2.65	99.89		301.68	0	351.46	100
2.65	0.03	3.09	99.92		351.46	0	409.45	100
3.09	0.03	3.6	99.94		409.45	0	477.01	100
3.6	0.02	4.19	99.96		477.01	0	555.71	100
4.19	0.01	4.88	99.98		555.71	0	647.41	100
4.88	0.01	5.69	99.99		647.41	0	754.23	100
5.69	0.01	6.63	99.99		754.23	0	878.87	100

Table D 21 Particle size distribution for R2

Size low	In %	Size high	Under %		Size low	In %	Size high	Under %
0.05	0.04	0.06	0.04		6.63	0.01	7.72	99.99
0.06	0.08	0.07	0.12		7.72	0	9	99.99
0.07	0.14	0.08	0.26		9	0	10.48	99.99
0.08	0.25	0.09	0.51		10.48	0	12.21	100
0.09	0.49	0.11	1		12.21	0	14.22	100
0.11	0.98	0.13	1.98		14.22	0	16.57	100
0.13	1.99	0.15	3.97		16.57	0	19.31	100
0.15	3.91	0.17	7.88		19.31	0	22.49	100
0.17	7.35	0.2	15.23		22.49	0	26.2	100
0.2	12.59	0.23	27.82		26.2	0	30.53	100
0.23	16.04	0.27	45.86		30.53	0	35.56	100
0.27	19.17	0.31	65.04		35.58	0	41.43	100
0.31	14.48	0.36	79.52		41.43	0	48.27	100
0.36	8.85	0.42	88.37		48.27	0	58.23	100
0.42	5.35	0.49	93.72		56.23	0	65.51	100
0.49	3.13	0.58	96.86		65.51	0	76.32	100
0.58	1.54	0.67	98.39		76.32	0	88.91	100
0.67	0.74	0.78	99.13		88.91	0	103.58	100
0.78	0.34	0.91	99.47		103.58	0	120.67	100
0.91	0.16	1.06	99.63		120.67	0	140.58	100
1.06	0.08	1.24	99.71		140.58	0	163.77	100
1.24	0.05	1.44	99.76		163.77	0	190.8	100
1.44	0.04	1.68	99.8		190.8	0	222.28	100
1.68	0.03	1.95	99.83		222.28	0	258.95	100
1.95	0.03	2.28	99.86		258.95	0	301.68	100
2.28	0.03	2.65	99.89		301.68	0	351.46	100
2.65	0.02	3.09	99.91		351.46	0	409.45	100
3.09	0.02	3.6	99.93		409.45	0	477.01	100
3.6	0.02	4.19	99.95		477.01	0	555.71	100
4.19	0.01	4.88	99.97		555.71	0	647.41	100
4.88	0.01	5.69	99.98		647.41	0	754.23	100
5.69	0.01	6.63	99.98		754.23	0	878.87	100

Appendix E

Standard Curve Details

Table E 1 NO_2^- N Standard curve details

Date 09.11.2007

ID	Concentration. (µg/L)	ABS
1	0	0
2	5	0.015
3	10	0.031
4	15	0.046
5	20	0.060
6	25	0.074

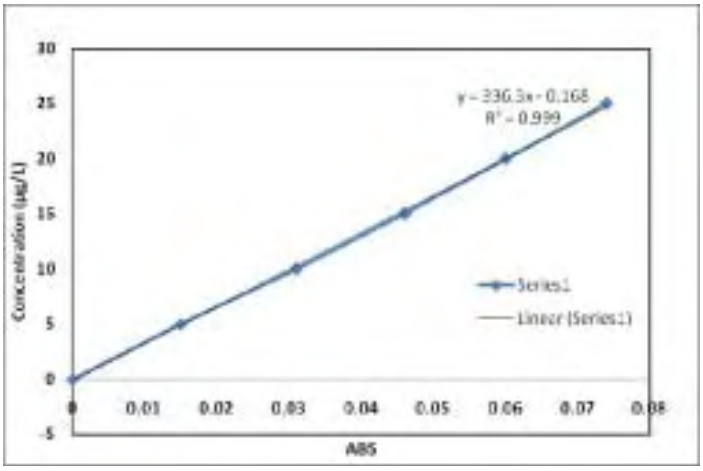

Figure E 1 NO_2^- N Standard curve details on 09.11.07

Table E 2 NO_3^- N Standard curve details

Date 09.11.2007

ID	Concentration (mg/L)	ABS
1	0	0
2	1	0.395
3	2	0.688
4	3	0.988
5	4	1.341
6	5	1.592

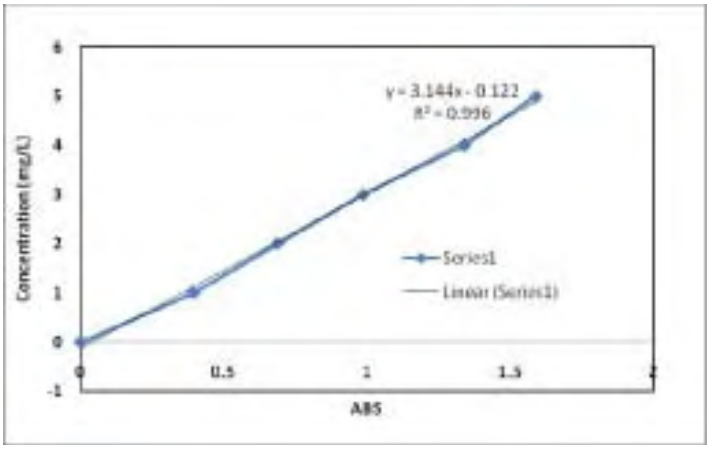

Figure E 2 NO_3^- N Standard curve details on 09.11.07

Table E 3 NO_3^- N Standard curve details

Date 05.01.08

ID	Concentration (mg/L)	ABS
1	0	0
2	1	0.359
3	2	0.689
4	3	1.019
5	4	1.359
6	5	1.61

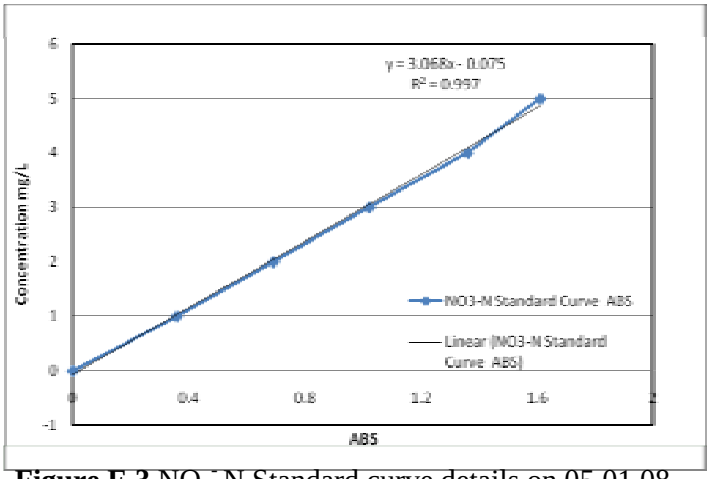

Figure E 3 NO_3^- N Standard curve details on 05.01.08

Table E 4 NO_2^- N Standard curve details

Date 09.03.08

ID	Concentration. (µg/L)	ABS
1	0	0
2	5	0.015
3	10	0.030
4	15	0.045
5	20	0.059
6	25	0.074

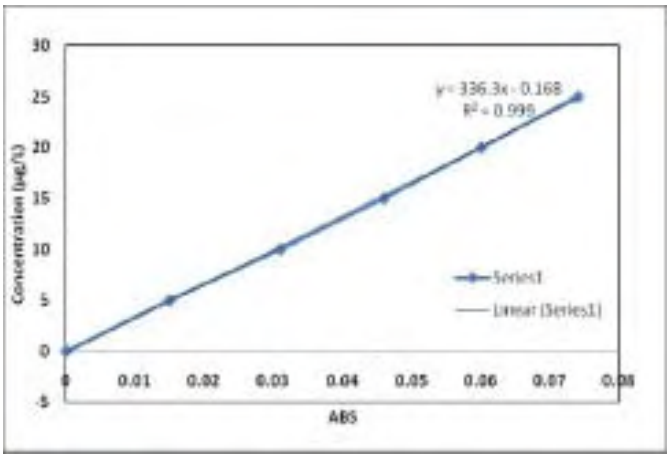

Figure E 4 NO_2^- N Standard curve details on 09.03.08

Table E 5 NO_3^- N Standard curve details

Date 09.03.08

ID	Concentration. (mg/L)	ABS
1	0	0
2	1	0.364
3	2	0.689
4	3	0.994
5	4	1.408
6	5	1.847

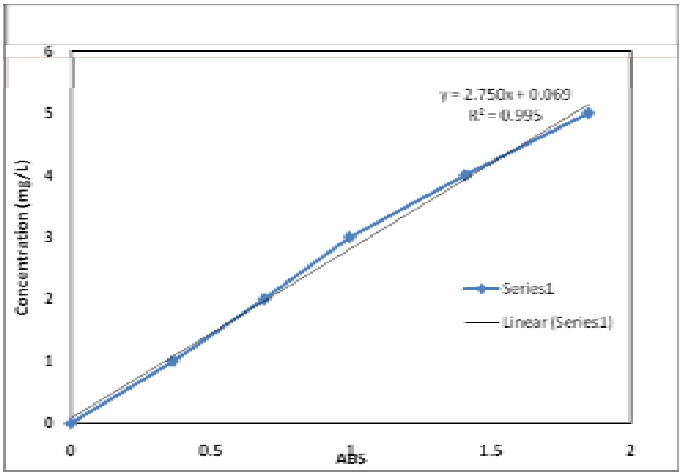

Figure E 5 NO_3^- N Standard curve details on 09.03.08

Table E 6 Standard curve details for Polysaccharides

Polysaccharides (D-Glucose)						
1g/L	makes	0.1g/L (Sol.A)		100 micro g/1mL		
No	1	2	3	4	5	6
micro gram Glucose	0	10	20	40	80	160
Volume A, ml	0	0.1	0.2	0.4	0.8	1.6
Volume DI, ml	2	1.9	1.8	1.6	1.2	0.4
phenol 5%, ml	1	1	1	1	1	1
H2SO4 conc., ml	5	5	5	5	5	5
Glucose concen, mg/L (in 2 mL)	0	5	10	20	40	80
ABS at 490 nm	0	0.067	0.111	0.255	0.511	1.096
standard curve	conc = 72.851 (ABS) + 1.064					

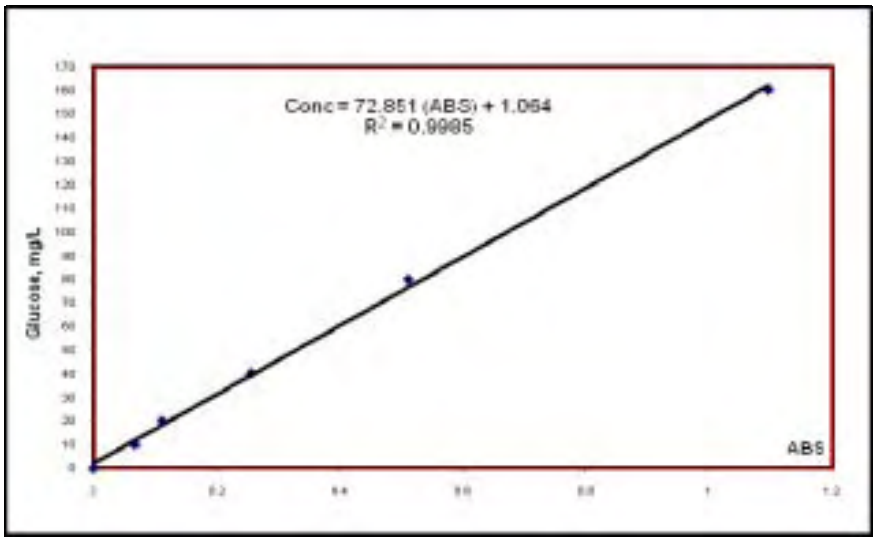

Figure E 6 Standard curve for Polysaccharides

Table E 7 Standard curve details for Proteins

Protein standard		V = 1ml/ampu		1mg/ml (1000 mg/L)		10 time diluted
No	1	2	3	4	5	6
V of BSA stock solution, mL	0	0.1	0.2	0.3	0.4	0.5
V of DW, mL	0.5	0.4	0.3	0.2	0.1	0
V of solution C, mL	2.5	2.5	2.5	2.5	2.5	2.5
V of solution D, mL	0.25	0.25	0.25	0.25	0.25	0.25
BSA conc. of solution (in 0.5 mL), mg/L	0	20	40	60	80	100
ABS at 750 nm	0	0.085	0.148	0.218	0.262	0.319

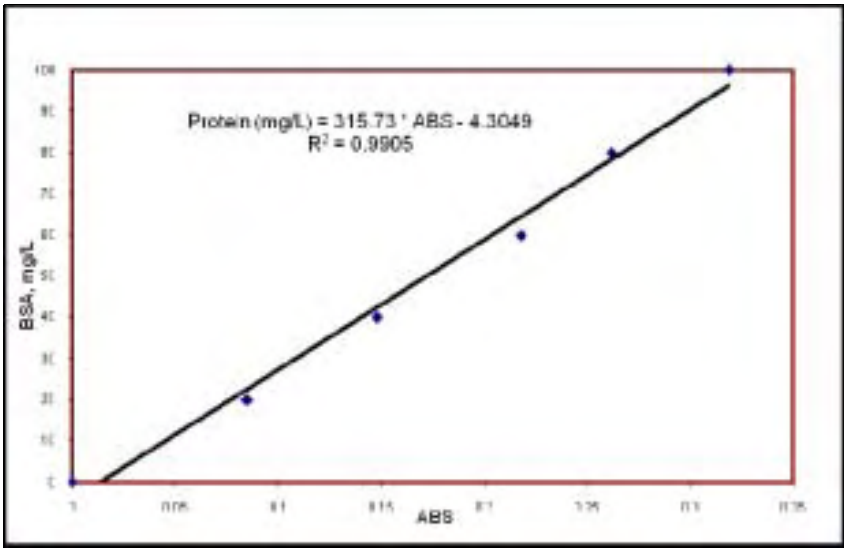

Figure E 7 Standard curve for Proteins

Comparison of Nitrogen Removal between Conventional Membrane Bioreactor and Attached Growth Membrane Bioreactor

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Examination Committee:

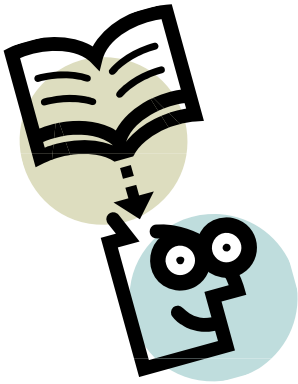
Prof. C. Visvanathan (Chairperson)

Prof. Chongrak Polprasert

Prof. Ajit P. Annachhatre

Contents of the Presentation

- Introduction
  - Objectives of the Study
    - Methodology
      - Result and Discussions
        - Conclusions
          - Recommendations for Further Research



Introduction

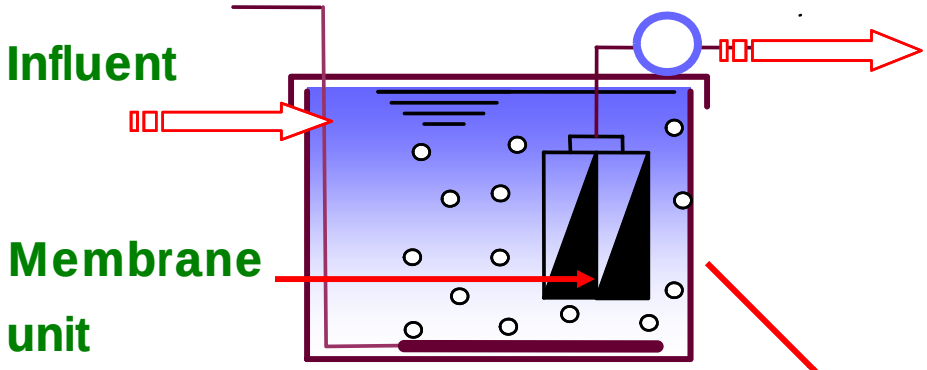
Why nitrogen removal is important?

- Surface and Ground water contamination
- Stringent disposal standards of treated effluent
- Reuse wastewater
- Eutrophication of lakes

Methods of nitrogen removal from wastewater

- Conventional biological nitrification and denitrification process
- Membrane bioreactor (MBR) system
  - Suspended growth (No media)
  - Attached growth
    - Moving media
    - Fixed bed

Membrane Bioreactor (MBR)

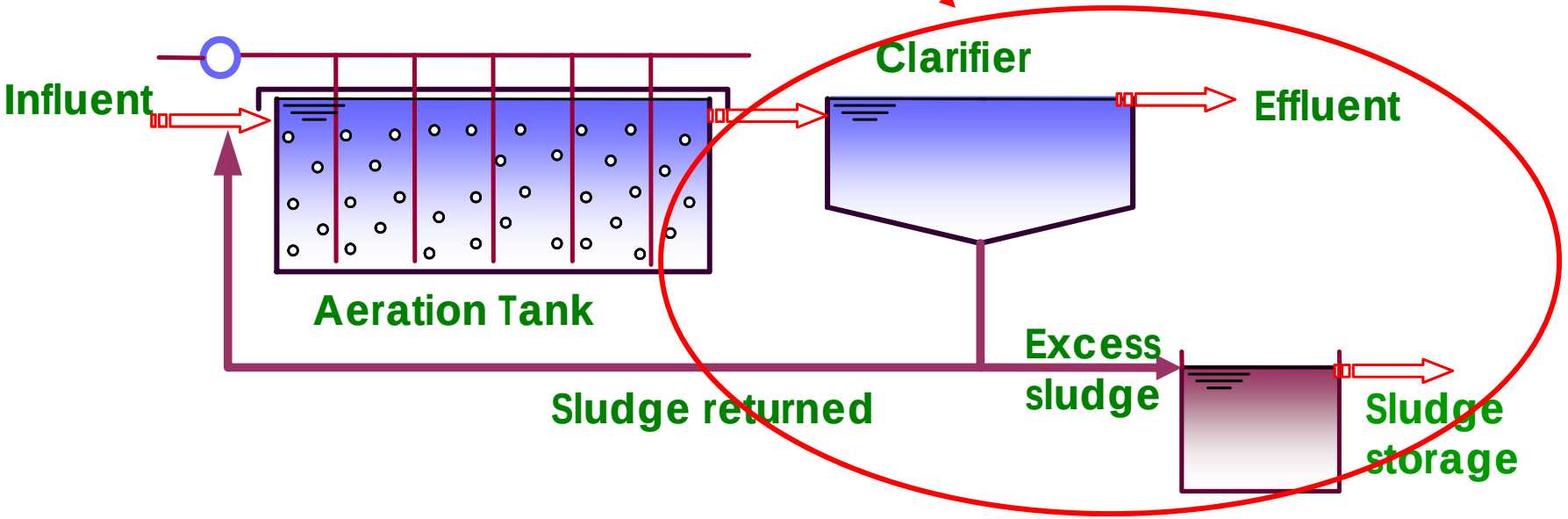


Advantages

- Better effluent quality
- Smaller foot print
- Low Sludge production

Disadvantages

- Membrane fouling
- High membrane cost



Objectives of the Study

- To select the better performance media out of cylindrical polypropylene (CP) and porous sponge media to be used in attached growth MBR
- To compare the nitrogen removal between conventional and attached growth MBR systems
- To compare the fouling characteristics between the conventional and attached growth systems

Porous sponge
(1cm*1cm*1cm cubes)

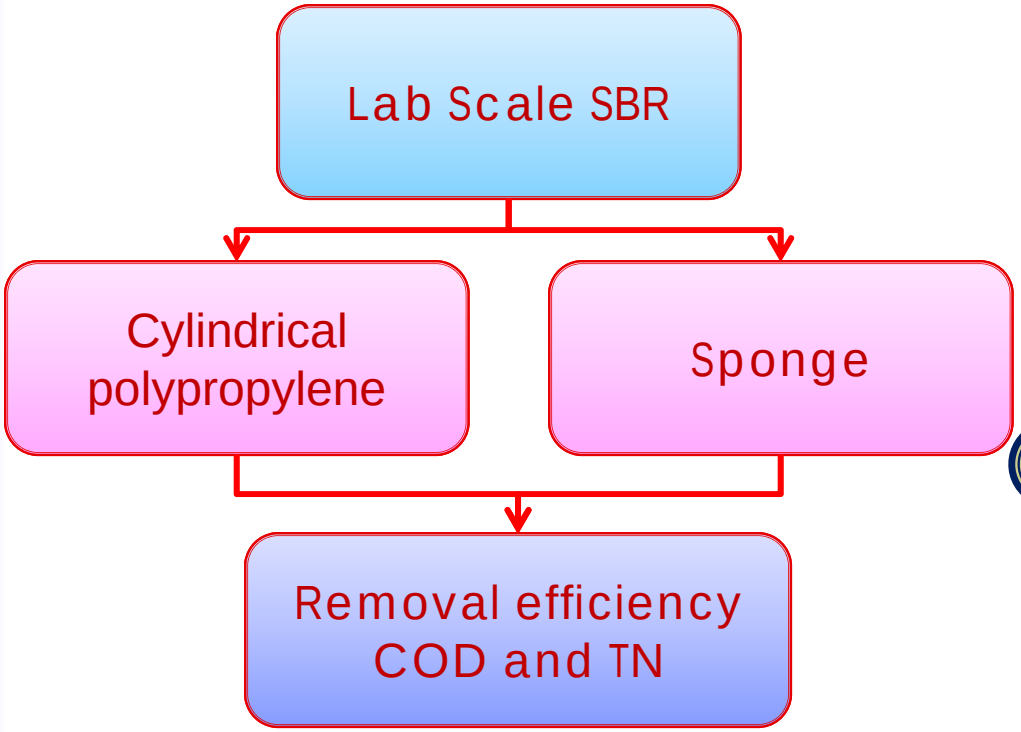
Cylindrical polypropylene
(CP; inner Ø 3mm, outer Ø 4mm, length 5mm)

Phase I of the Study

- To select the best performing media to be used in the attached growth MBR system in Phase II

Methodology for Phase I

Phase I: SBR operation



Operational Conditions

HRT :	24 h
SRT :	20 d
DO:	2-3 mg/L
MLSS:	≈ 8000 mg/L
OLR:	2.5 kgCOD/m^3.d
pH:	7-8
NLR:	0.7 kg N/ m^3.d

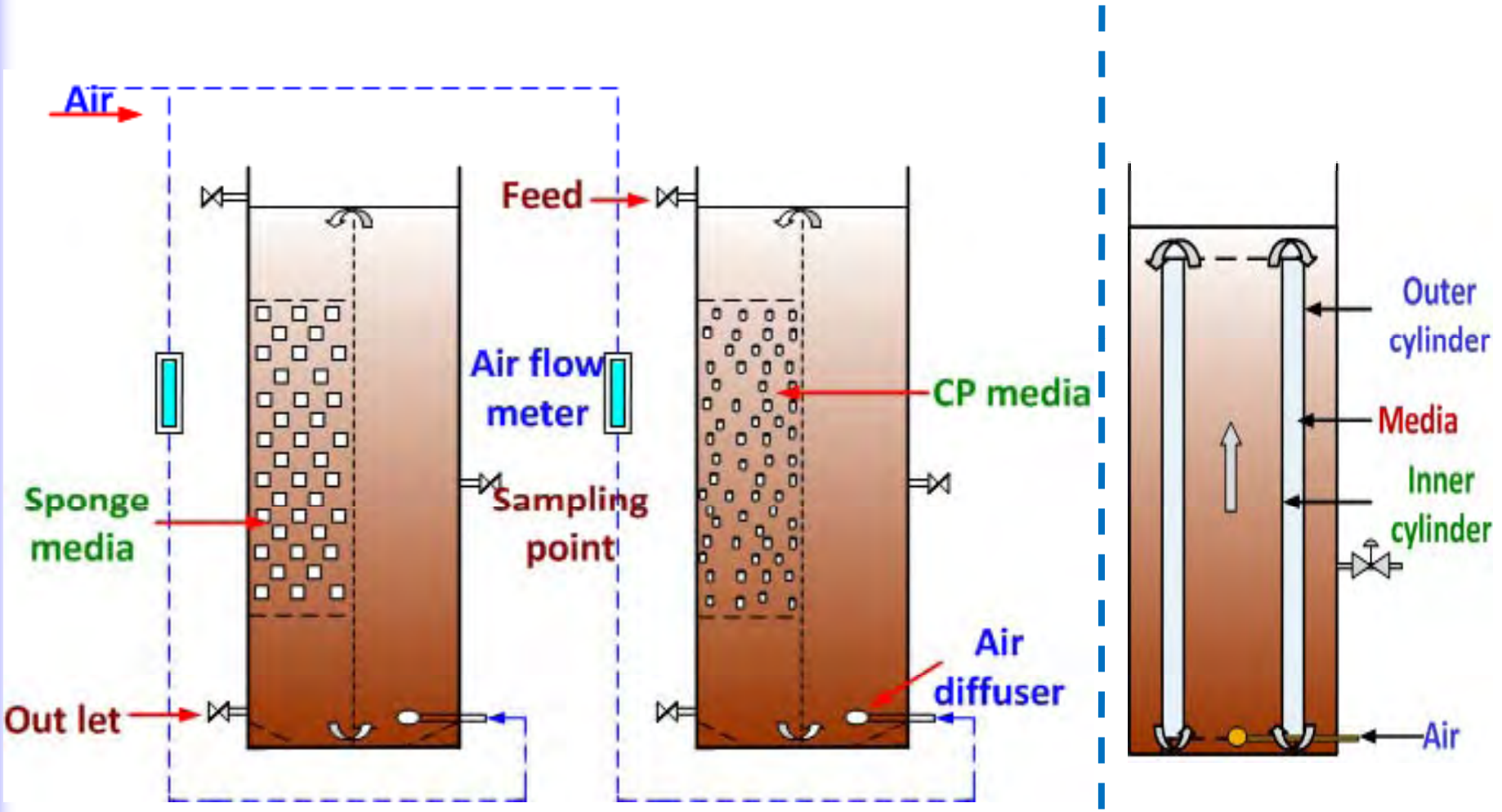
Sequence of operation

Feeding:	15 min
Reacting:	11 h
Settling:	30 min
Drawing:	15 min

Analytical tests

- COD
- TN
- NO_2^- N
- NO_3^- N
- NH_3- N

Experimental Set-up for Phase I



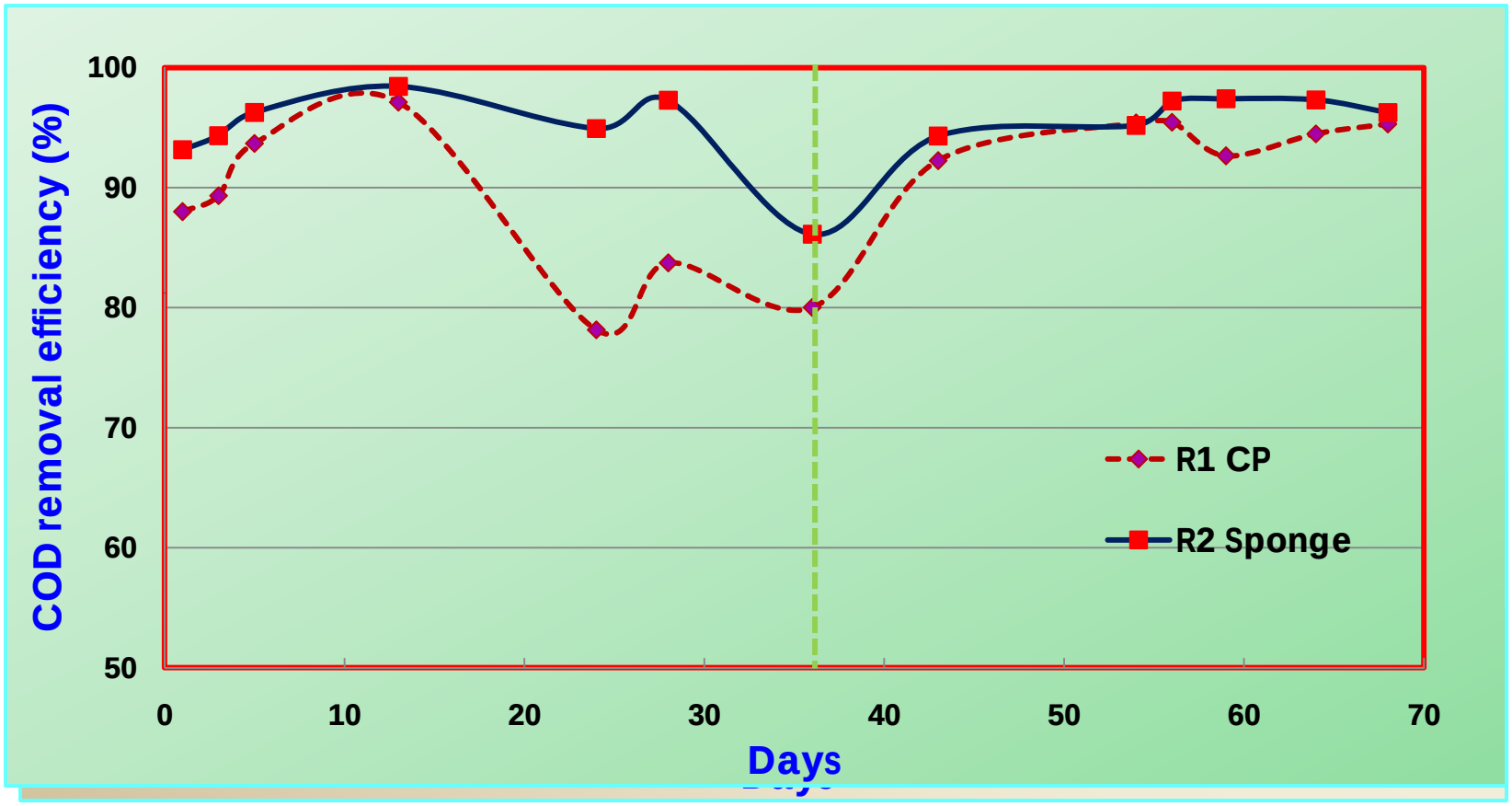
Sponge (R2)

CP (R1)

Sponge (R3 Circular)

Results and Discussions for Phase I

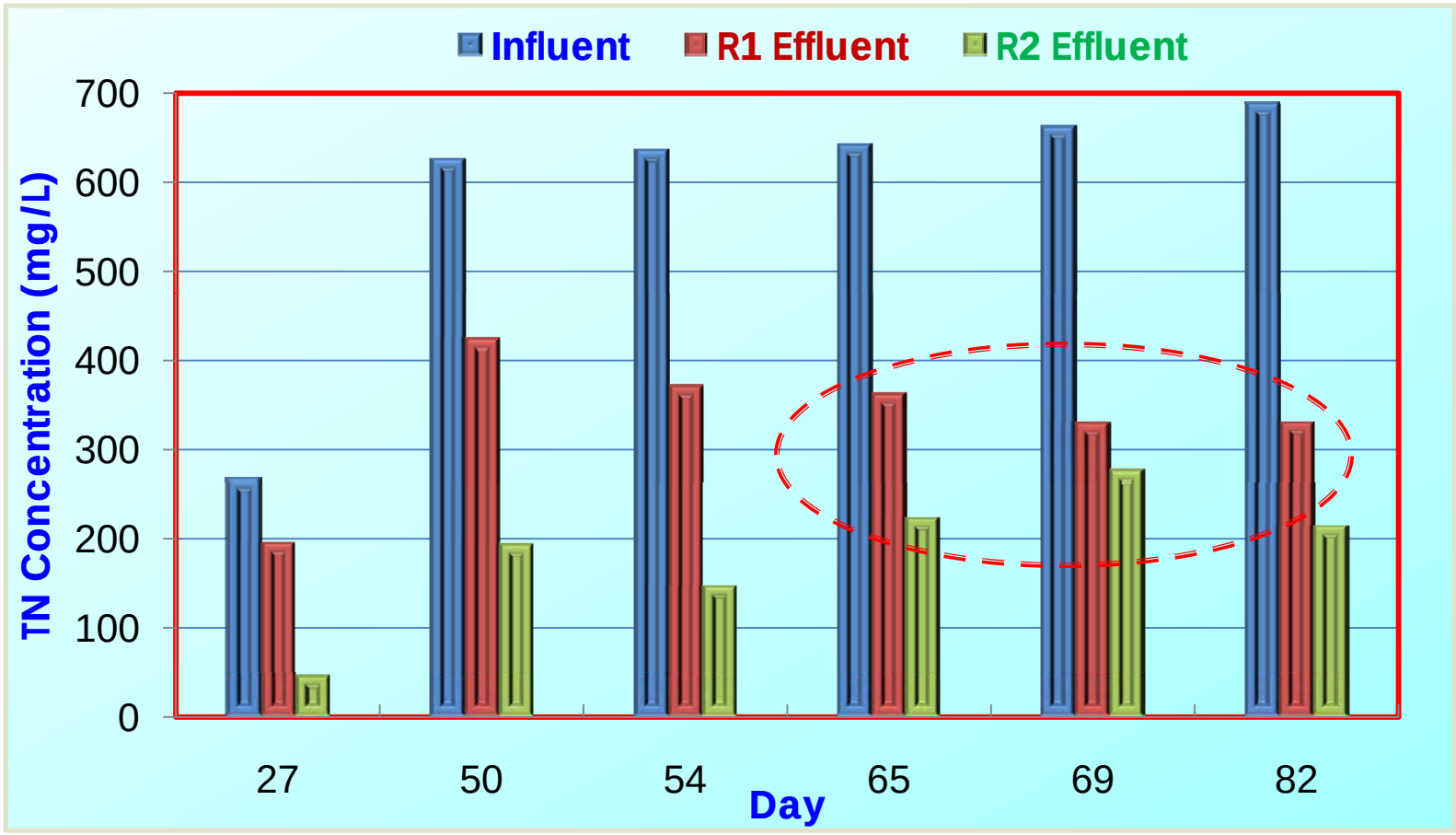
COD Removal Efficiency fluent and Effluent



COD Removal was more than 95% in both R1 and R2

Results and Discussions for Phase I

TN Concentration in Influent and Effluent of SBR

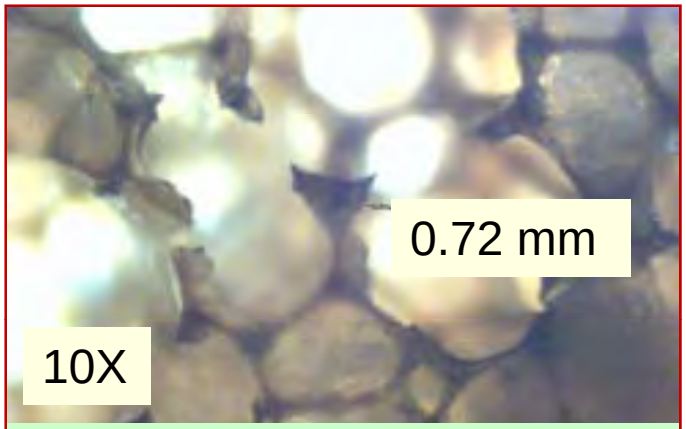


TN Removal efficiency was around 70% in R2 (Sponge) and 50% for R1 (CP)

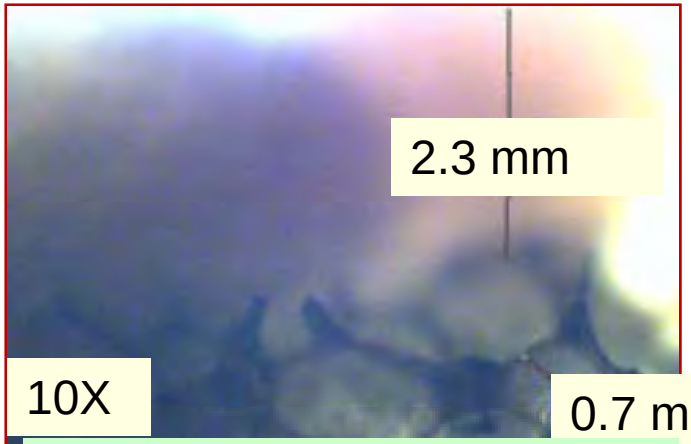
Results and Discussions for Phase I

Biofilm over Media

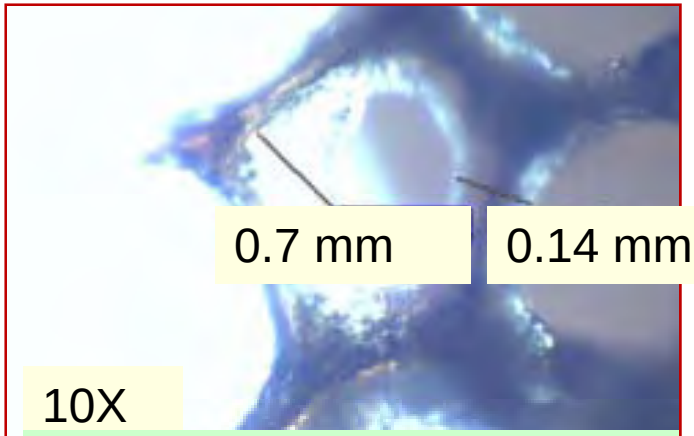
CP media Sectional view



Sponge; Cross sectional view



Sponge; Elevation view



Sponge; Thin Slice

Conclusions for Phase I

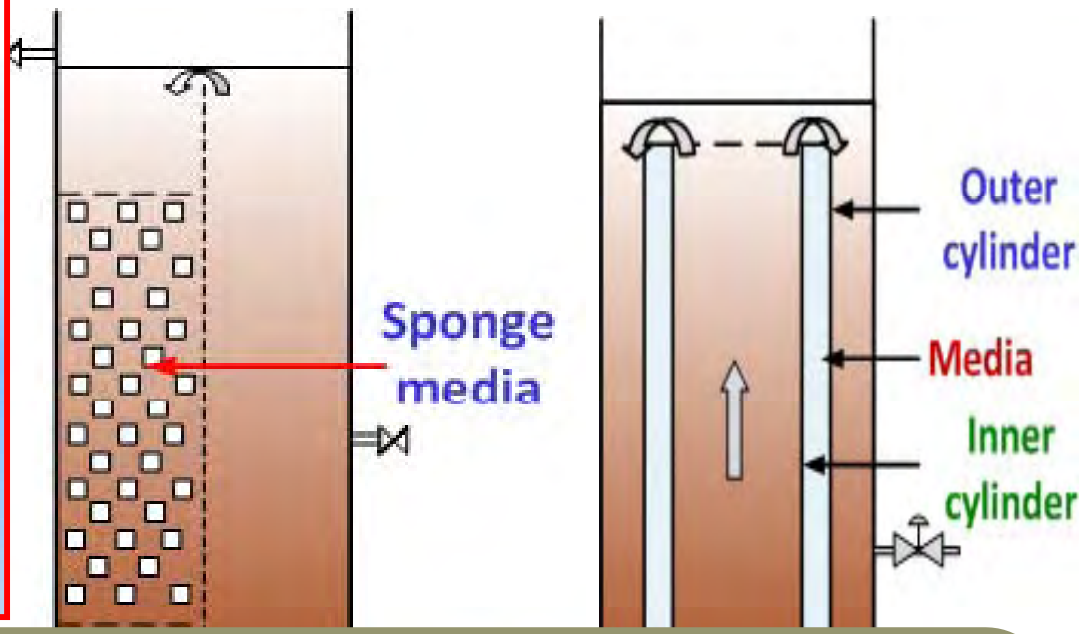
- **No significant difference in COD removal in CP and Sponge media reactors**
- **TN removal efficiency was reported as 70% in Sponge (R2) media reactor and around 50% in CP (R1) reactor**
- **Sponge media was more suitable than CP for the partially fixed bed rector;**
  - **Less biomass settlement**
  - **Higher surface and internal area for biofilm growth**

Sponge media was selected as the attached growth media for MBR

Suitable Configuration for MBR

Conditions:

- OLR same for the two reactors
- Same number of sponge media used
- HRT = 24 h for both reactors
- = 20 days



- ❖ COD Removal was 95% to 97%
- ❖ TN removal of Circular reactor was observed to be 10 % higher than the Rectangular configuration
- ❖ Demonstrated better hydrodynamic conditions with out sludge settlement

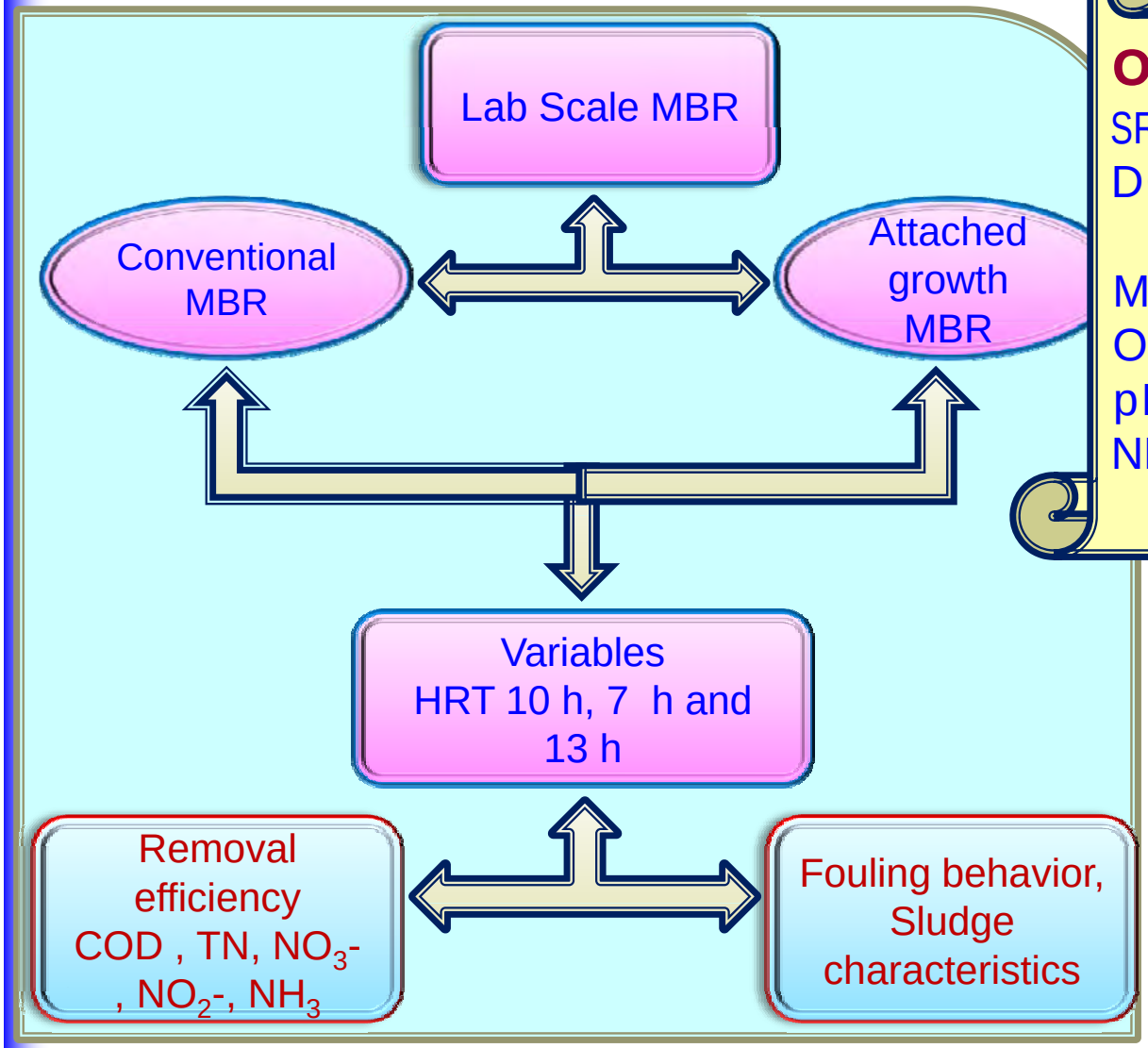
Circular configuration was selected as the configuration for the MBR

Phase II

- To compare the nitrogen removal in conventional MBR (R1) and attached growth MBR (R2)
- To compare the fouling propensity of the conventional and attached growth systems

Methodology for Phase II

Phase II: Study plan

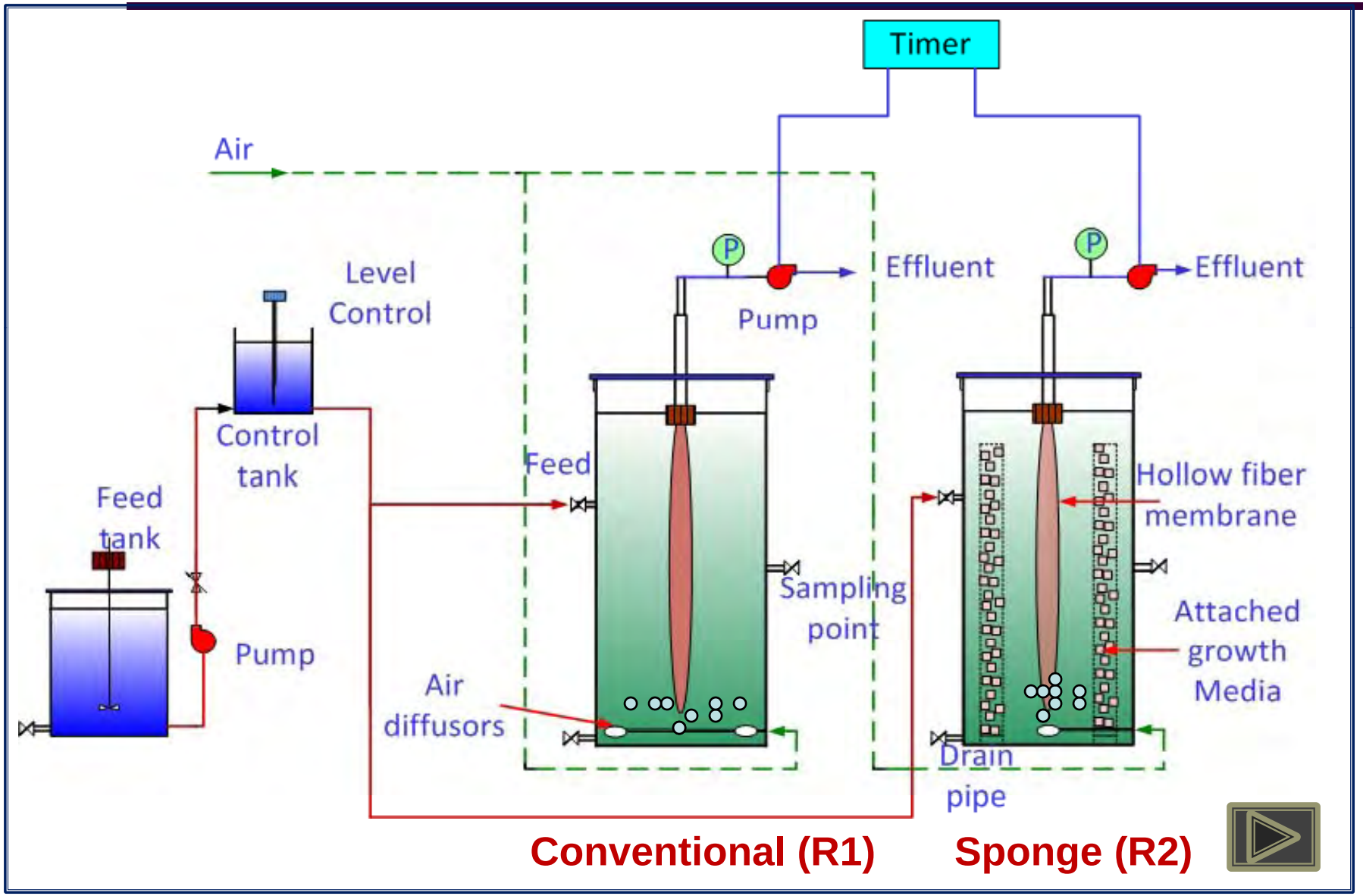


Operational Conditions

SRT :	30 d
DO:	2-3 mg/L(attached growth system)
MLSS:	≈ 8 - 10 g/L
OLR:	2.3 kgCOD/m^3.d
pH:	7.6-8.2
NLR:	0.4 kg N/ m^3.d

Analytical testing

MBR Experimental Set-up



Results and Discussions for Phase II

Operational data

		Permeate flow rate (mL/min)	Net permeate flux (L/m².h)	R1 Conventional (d)	R2 Attached growth (d)
HRT (h)	7	43	5.1	40	40
	10	30	3.6	90	90
	13	23	1.2	30	30

COD Concentration Variation

HRT (h)	7		10		13	
	R1	R2	R1	R2	R1	R2
Influent (mg/L)	643		909		1198	
Effluent (mg/L)	19	9	24	16	25	14
Removal efficiency (%)	97	99	97	98	98	99

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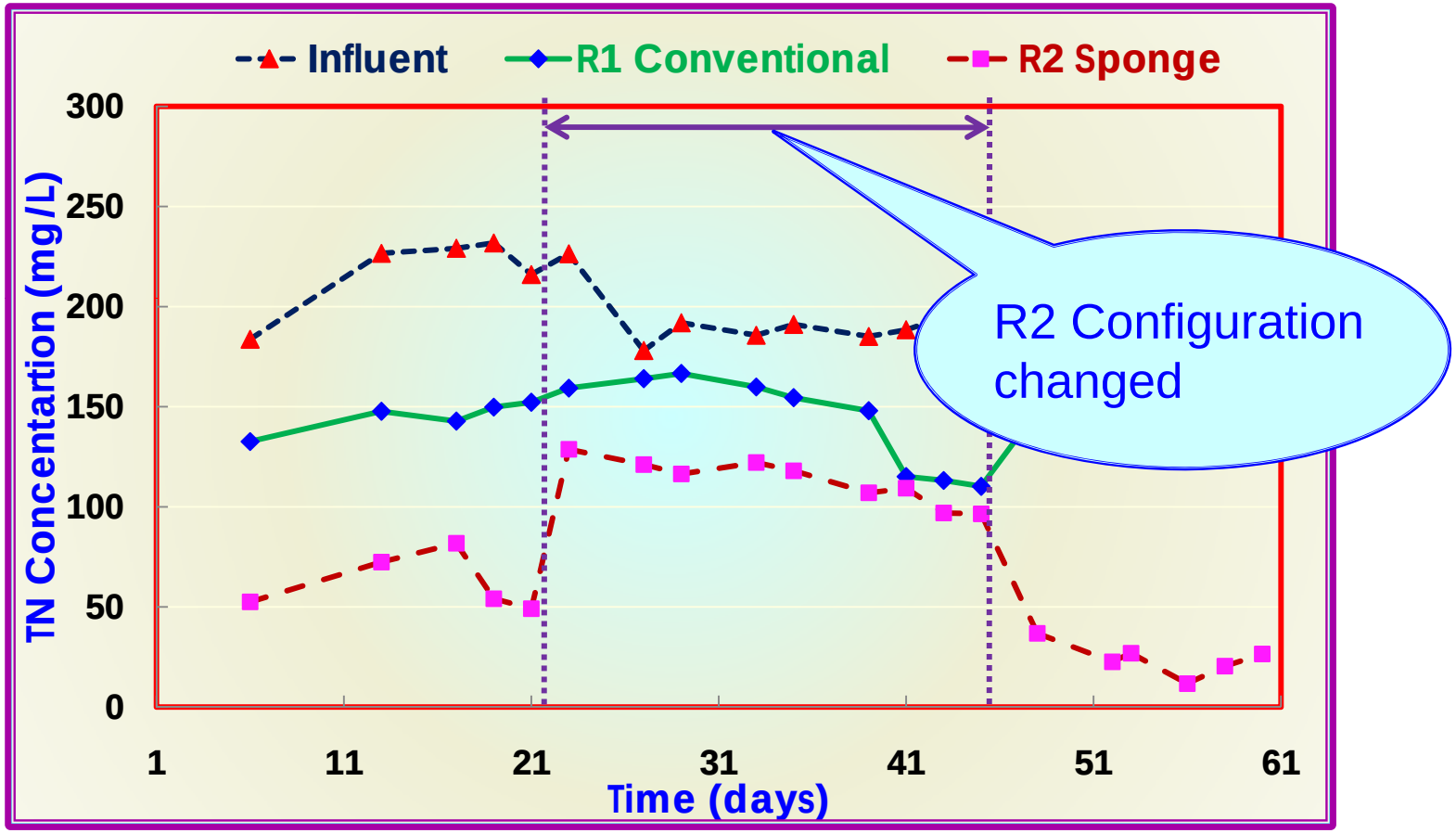
Results and Discussions for Phase II

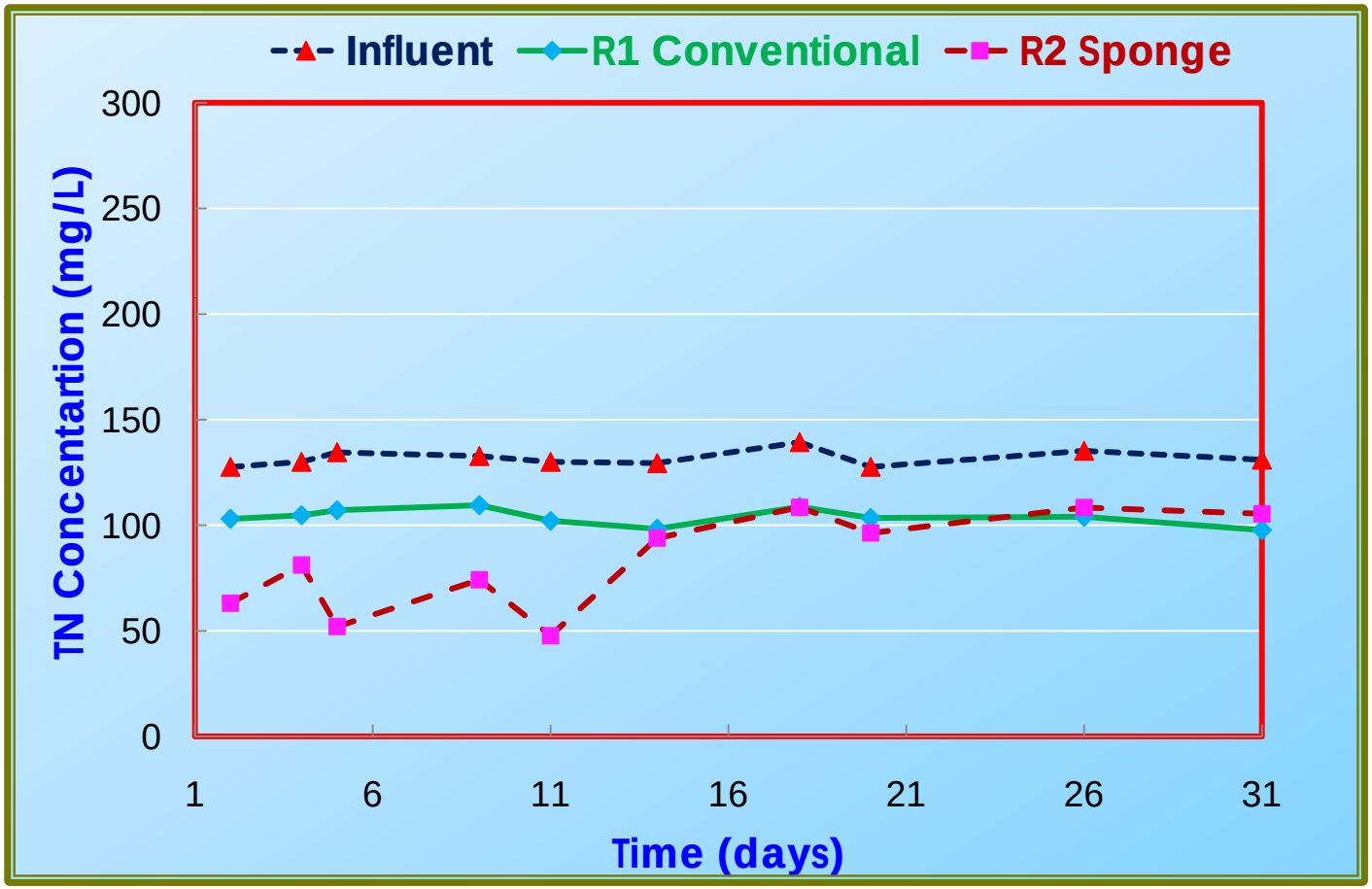
Influent and Effluent TN concentrations under 10 h HRT



TN in effluent reduced to 40 mg/L towards the end of the cycle

Results and Discussions for Phase II

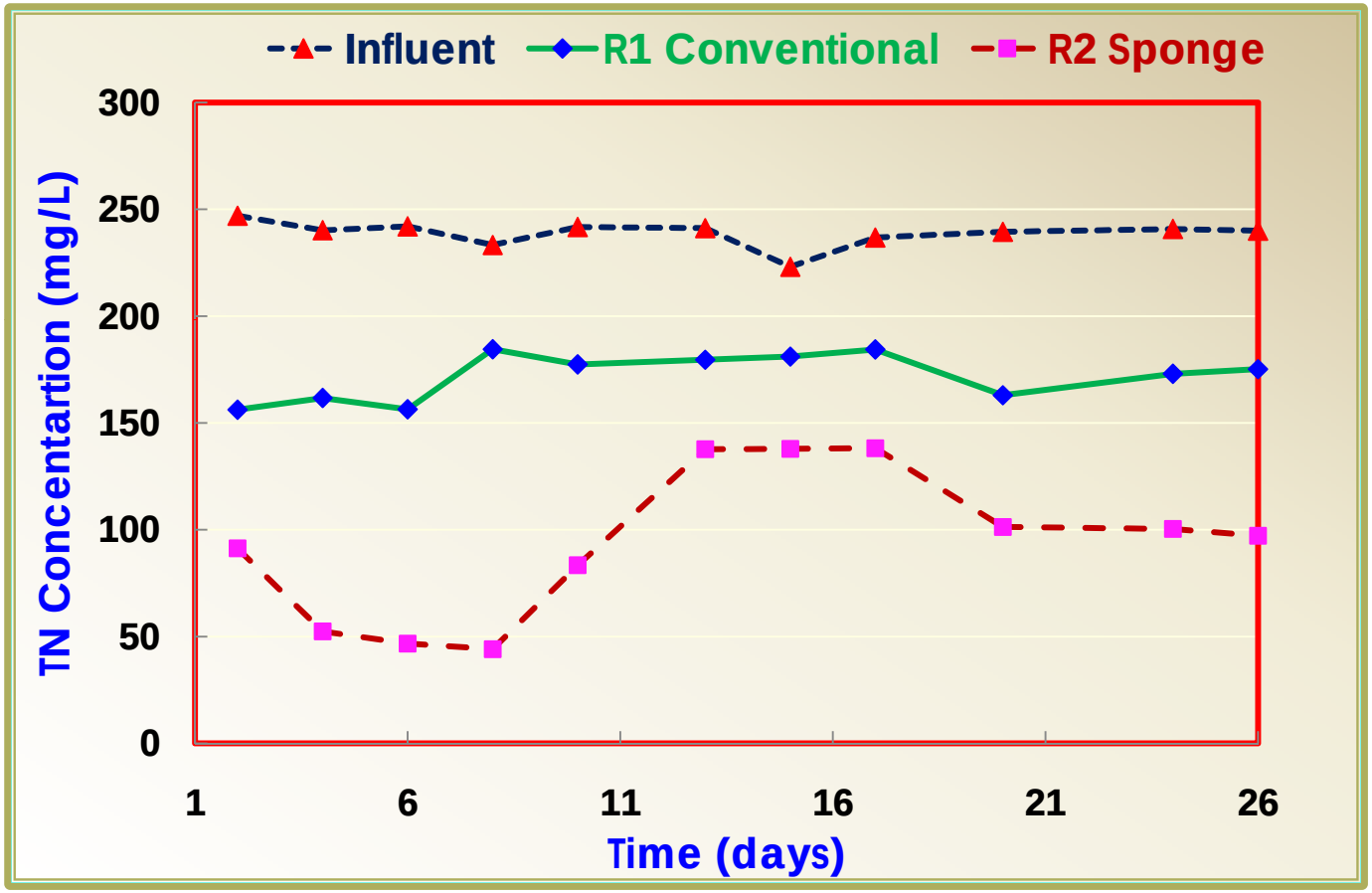
Influent and Effluent TN concentrations under 7 h HRT



R2 Effluent TN concentrations were high (around 100 mg/L)

Results and Discussions for Phase II

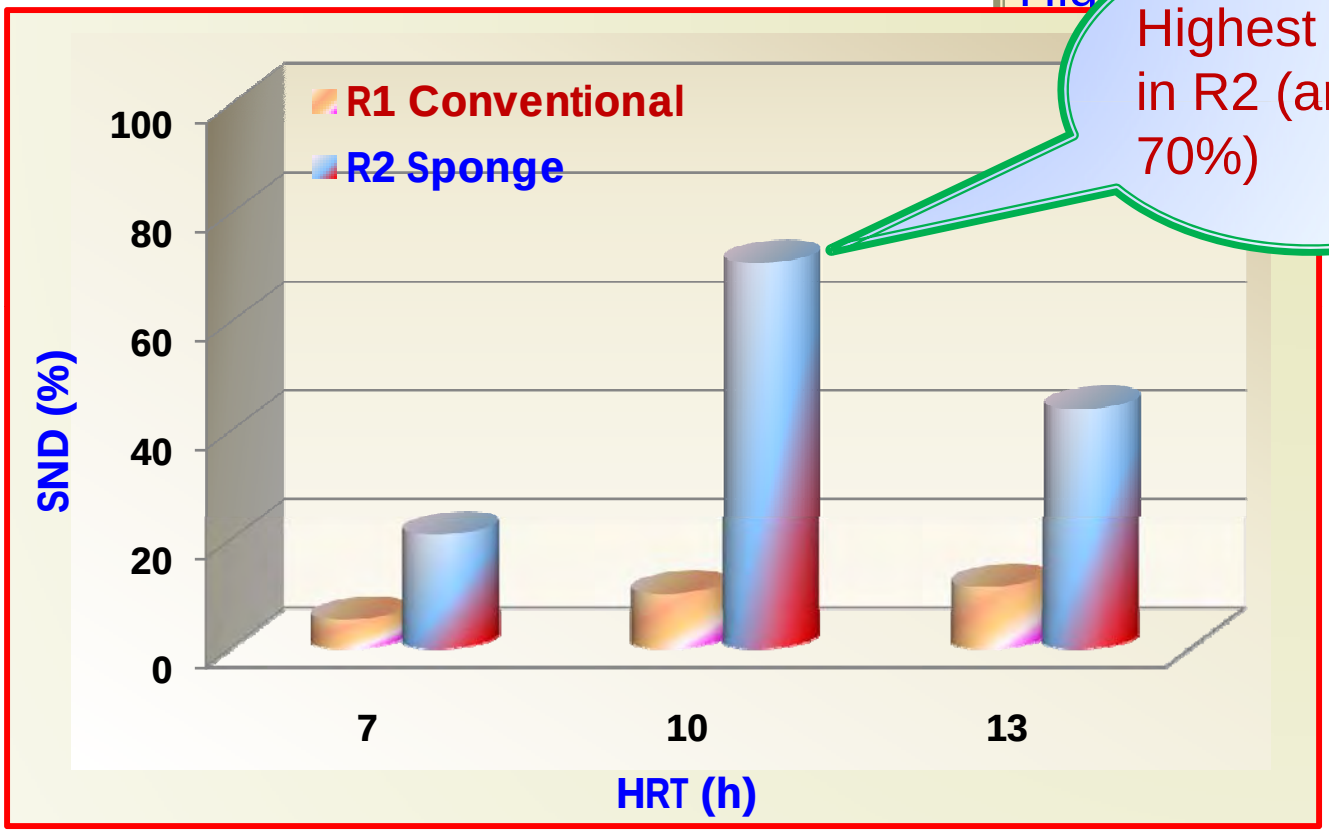
Influent and Effluent TN concentrations under 13 h HRT



TN in R2 effluent was around 100 mg/L

Results and Discussions for Phase II

TN Removal efficiencies and SND



Highest SND in R2 (around 70%)

It was proved single reactor SND process, achieving highest SND efficiency in R2 under 10 h HRT

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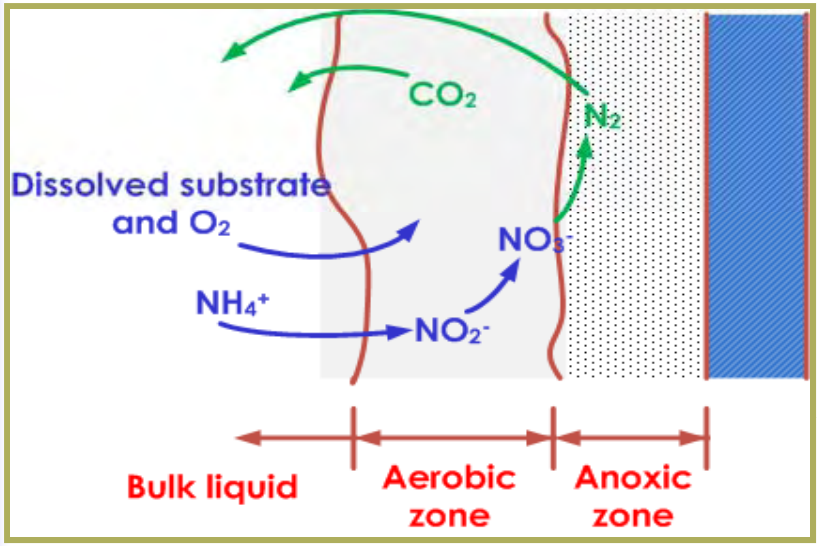
Nitrogen Removal Mechanisms



Attached Growth System

❖ **SND was observed to be the major mechanism for TN removal**

Nitrification +Denitrification (SND)

$TN_{in} = NH_3\ N + NO_3^-\ N + NO_2^-\ N$ → System → $TN_{eff} = NH_3\ N + NO_3^-\ N + NO_2^-\ N$

Conventional system

❖ **Assimilation was observed to be the major mechanism for TN removal**

Assimilation (in biomass)

Results and Discussions for Phase II

Nitrogen mass balance for R1 (Conventional)

HRT (h)	TN_{inf} (mg/L)	TN_{eff} (mg/L)	TN Removal	Assimilation (mg/L)	SND (mg/L)
7	131.7	103.9	21	20.8	7
10	196.5	143.0	27	29.4	25
13	238.7	172.0	28		

Most desirable operational condition for attached growth system to operate with maximum removal efficiencies

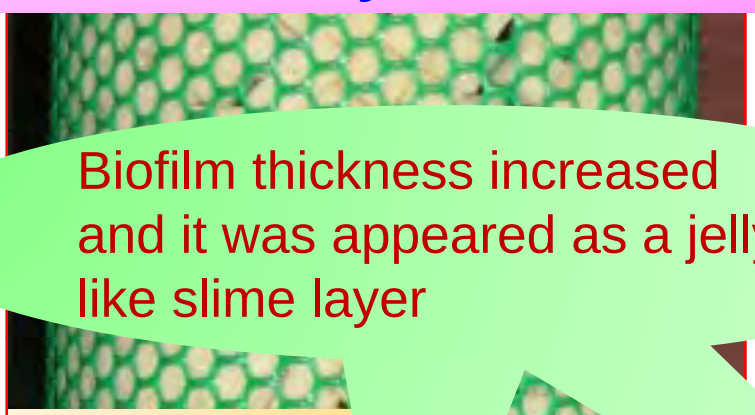
Nitrogen mass balance for R2 (

HRT (h)	TN_{inf} (mg/L)	TN_{eff} (mg/L)	TN Rem	(mg/L)	(mg/L)
7	131.7	83.1	37	21.2	27.5
10	196.5	24.2	86	29.6	130.2
13	238.7	93.7	60	39.5	105.5

Results and Discussions for Phase II

Inner media cylinder with biofilm growth over the surface

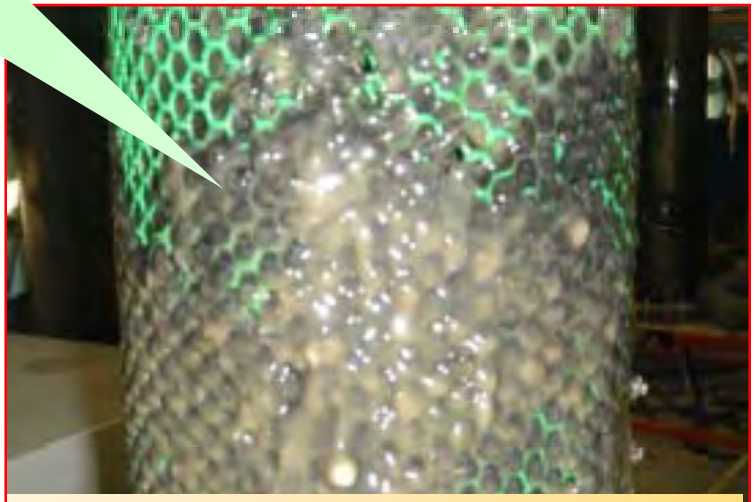
Biofilm thickness increased and it was appeared as a jelly like slime layer



Virgin (Day 0)

During 10 h HRT (Day 90)

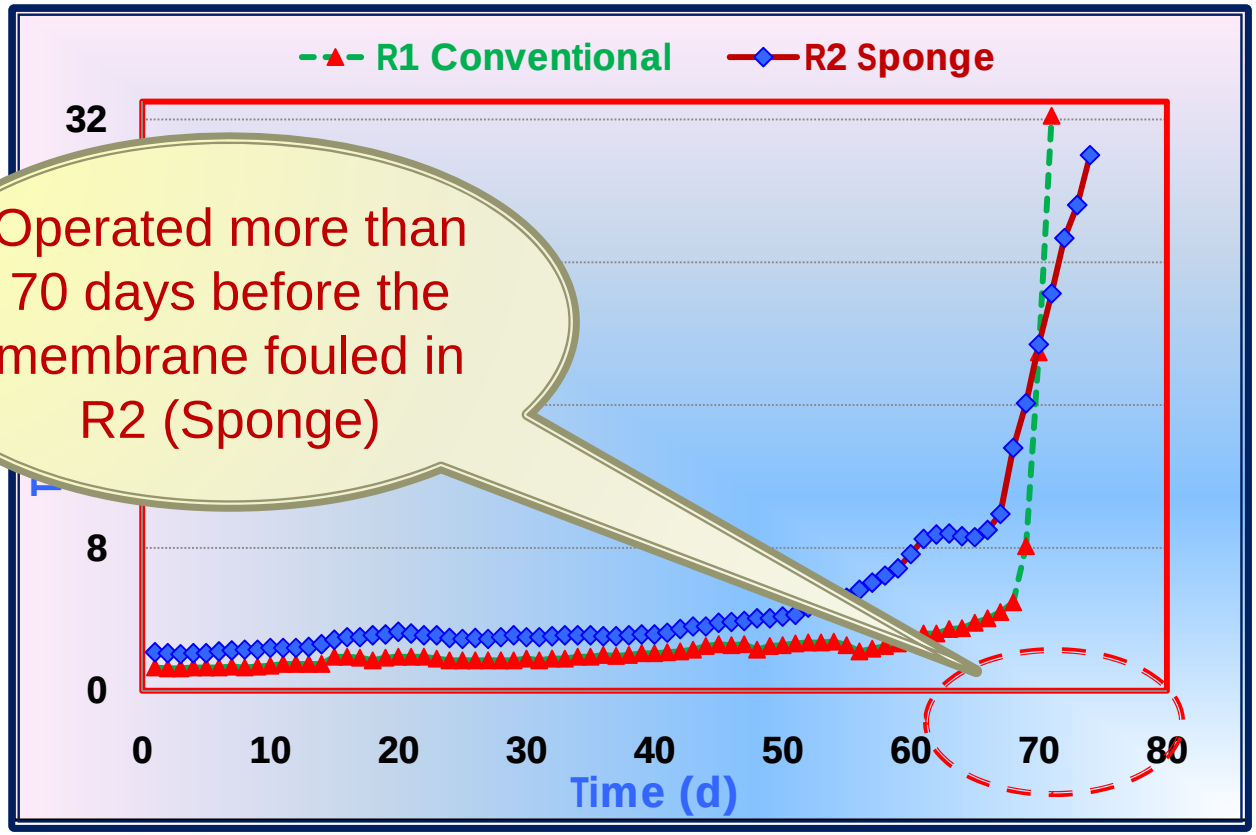
During 7 h HRT(Day 130)



During 13 h HRT (Day 150)

Membrane Fouling Behavior

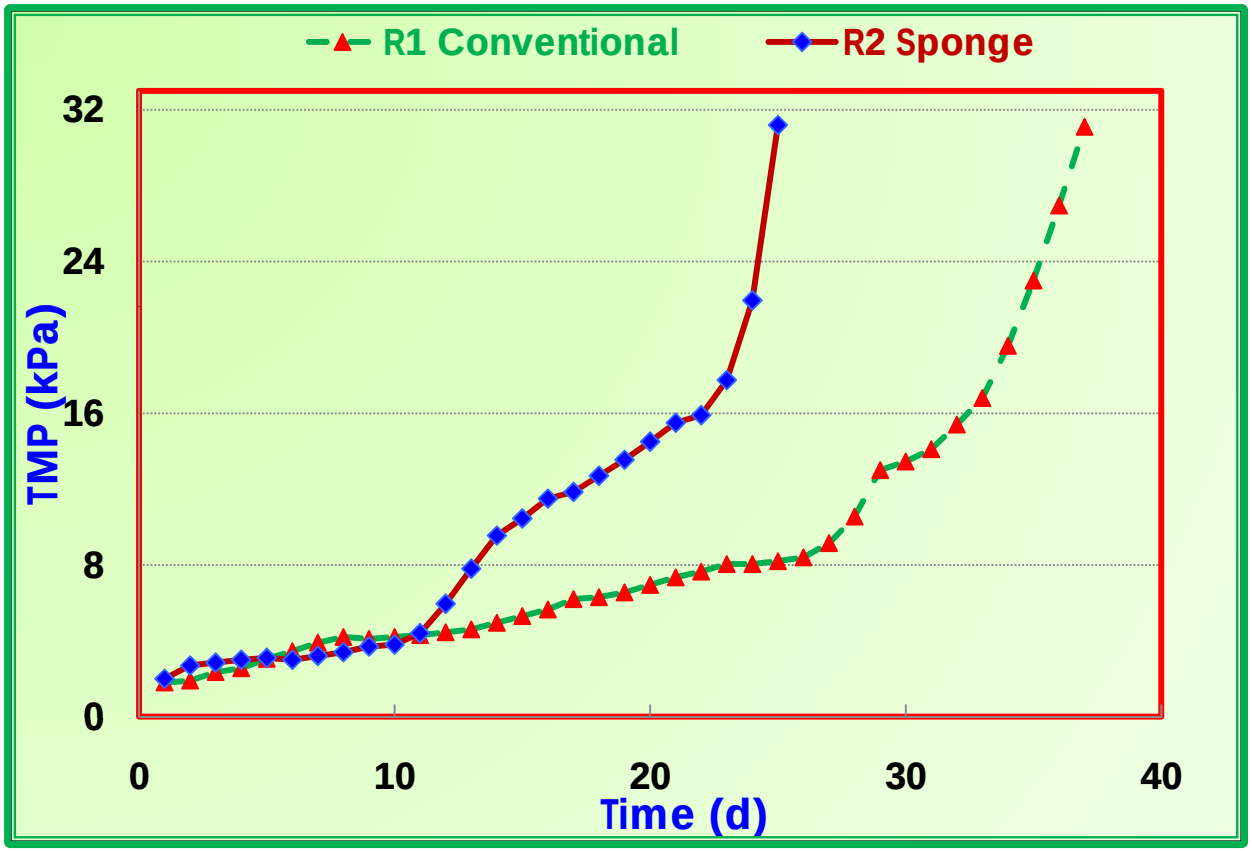
TMP Variation during 10 h HRT



Same fouling propensity was observed in both Sponge and Conventional MBRs

Membrane Fouling Behavior

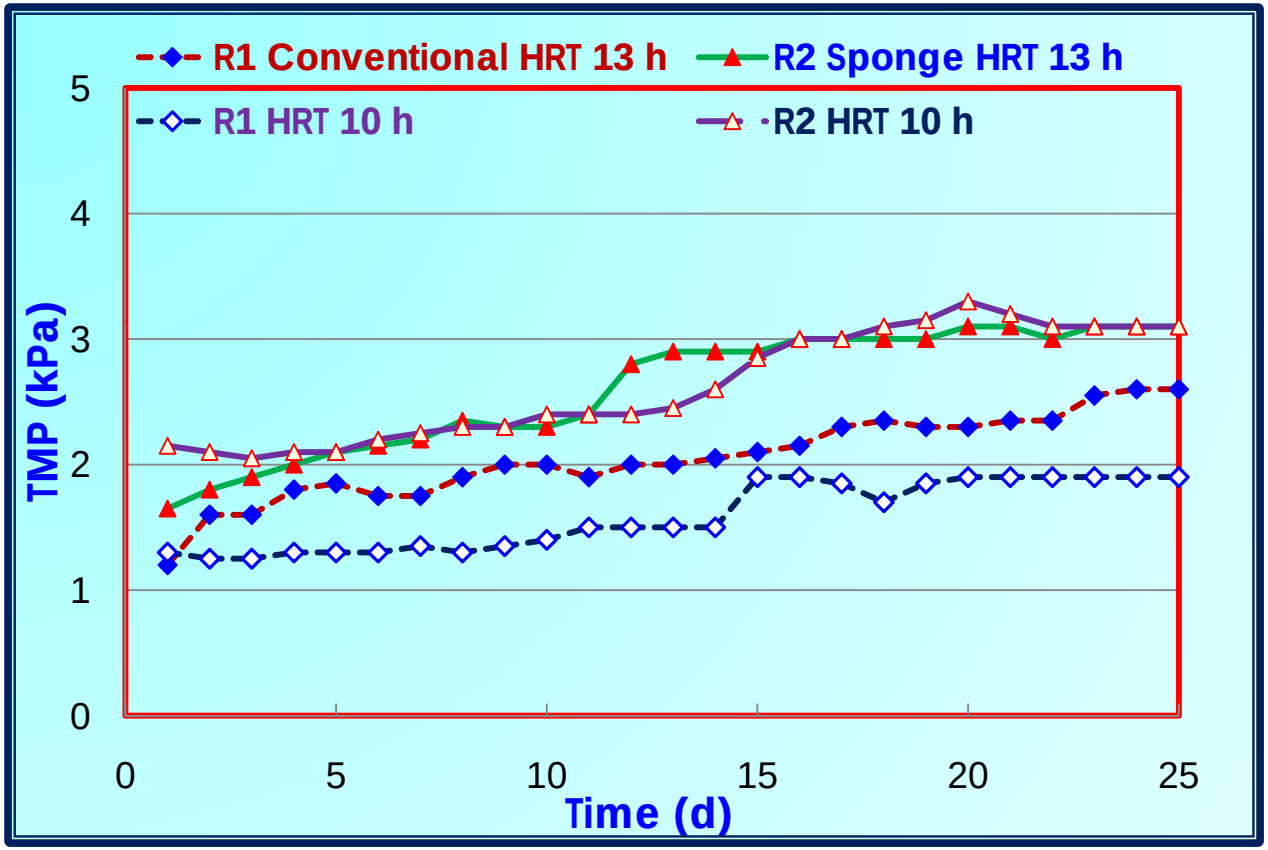
TMP Variation during 7 h HRT



Attached growth MBR fouled 1.5 times faster than the conventional MBR

Membrane Fouling Behavior

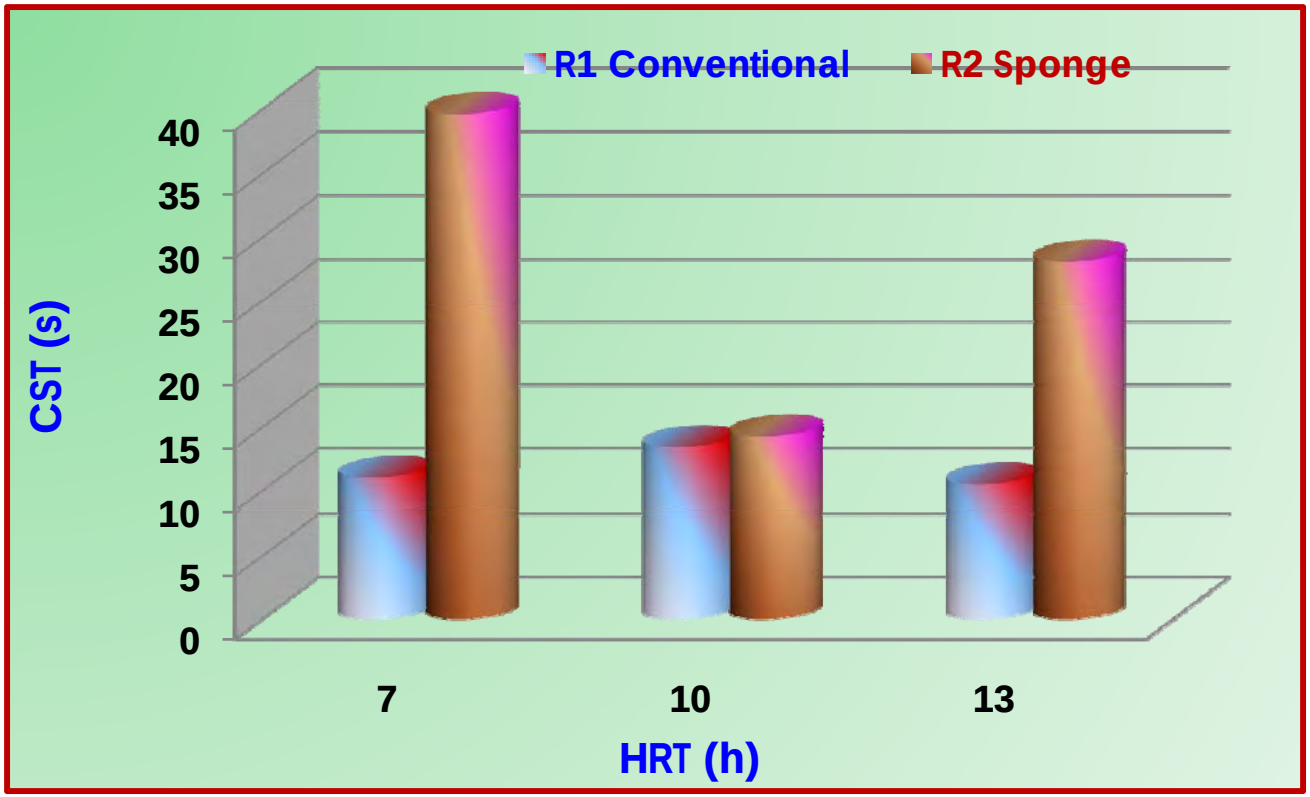
Comparison of TMP Variation between 10 h and 13 h HRT



Fouling behavior was observed to be more or less same during the early stage of fouling

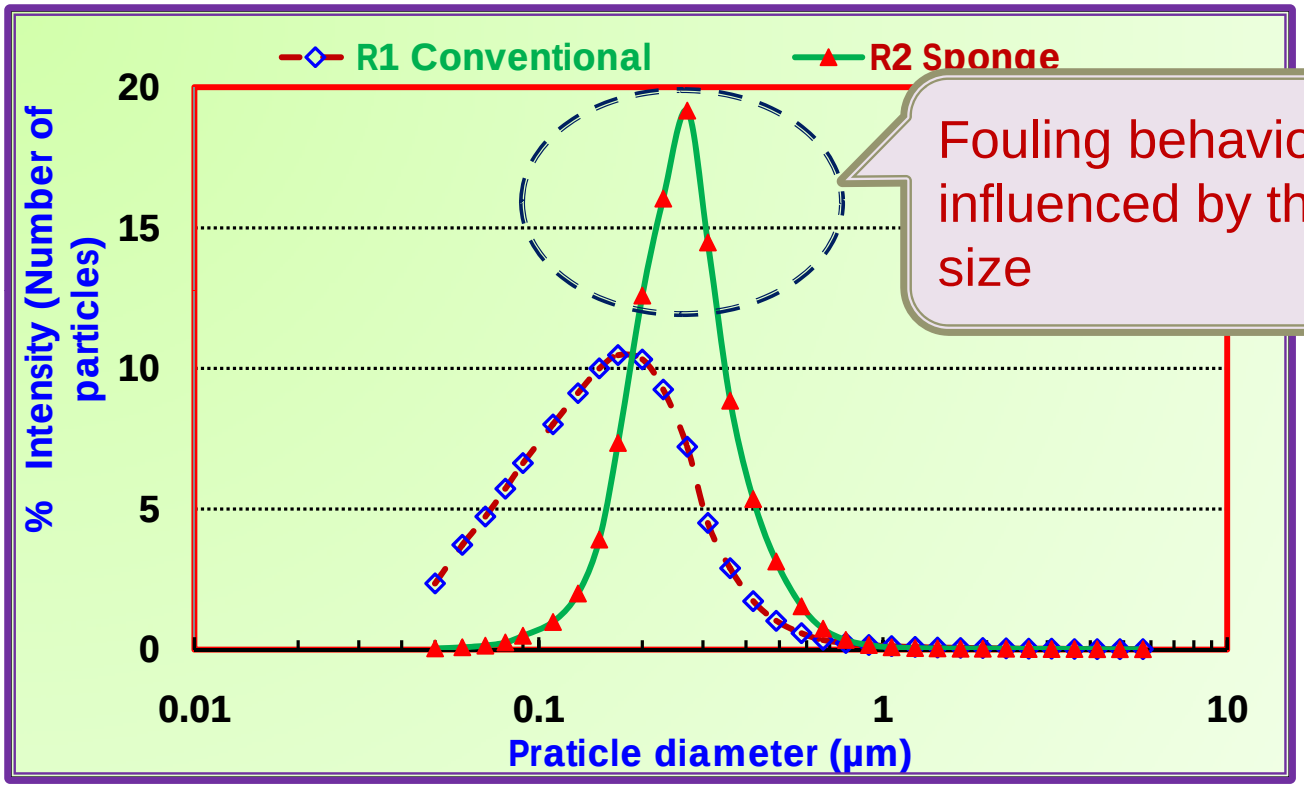
Sludge Dewaterability

CST measurements for R1 and R2



CST measurements exactly interpret the fouling behavior of the two systems. It was observed during the operation sludge dewaterability of sponge reactor reduced.

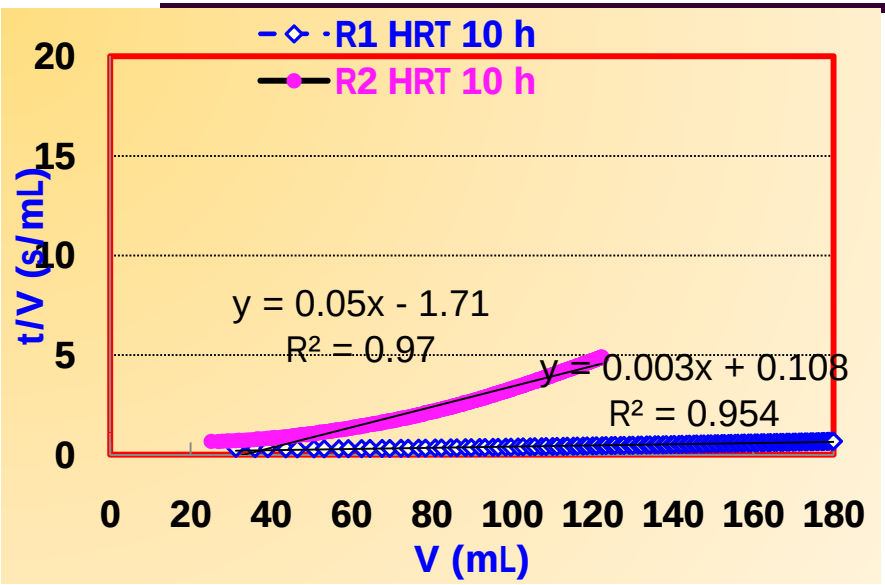
Particle Size Distribution

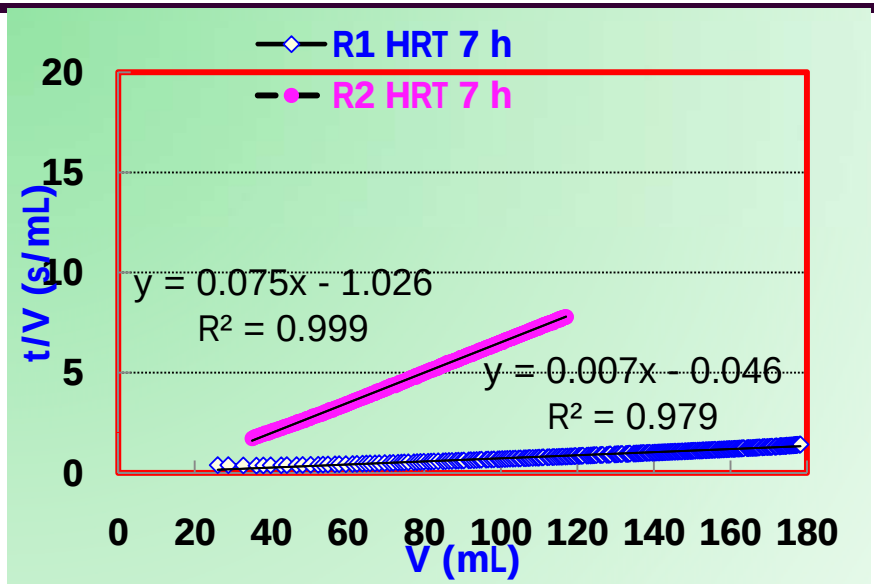


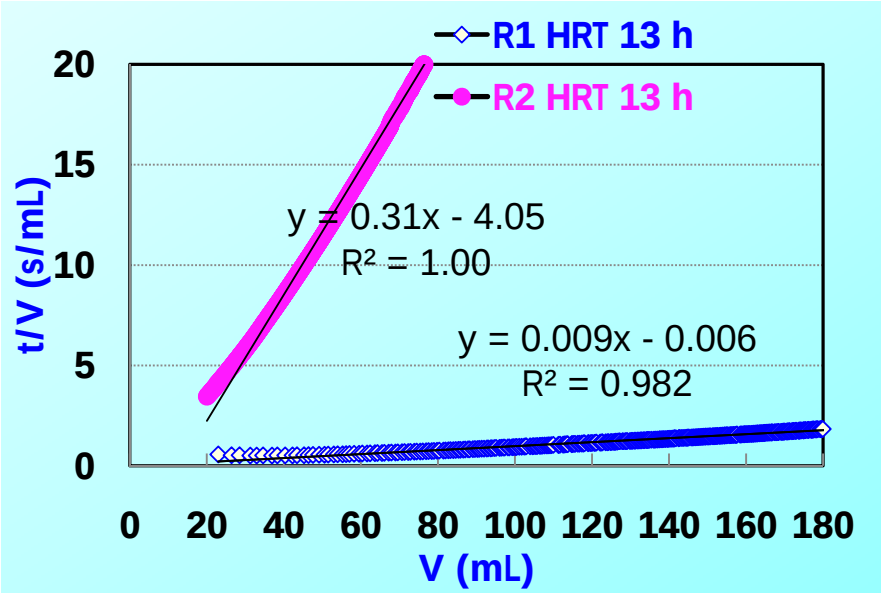
Fouling behavior was not influenced by the particle size

Average particle size of the (R1) conventional reactor was 0.17 µm and for the R2 (sponge) reactor the size was 0.28 µm.

Modified Fouling Index (MFI)







- **MFI was observed to be increased in R2 (Sponge) due to continuous operation**
- **MFI in conventional reactor showed same variation during the three HRTs**

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Conclusions

- COD removal was observed as 97% and 98% for conventional and attached growth systems respectively
- SND was observed to be the principle TN removal mechanism for the attached growth system, while assimilation was the major TN removal process for conventional system
- The maximum TN removal was observed in R2 as 86% under the operation of 10 h HRT. Therefore 10 h HRT was selected as the most favorable operational condition for the fixed bed sponge media attached growth MBR

Conclusions

- **R2 MBR system was operated for more than 70 days before membrane fouled under 10 h HRT.**
- **Under 10 h HRT the fouling was similar in R1 and R2, but under the operation of 7 h HRT, R2 (Sponge) was fouled 1.5 times faster than the conventional system**
- **It was further observed that the attached growth system configuration used in the study, might have influenced in changing the microbial structure of the sludge.**

Recommendations for Further Study

- Microbial changes in terms of species and quantity should be investigated for varying HRTs
- It was proved by this study SND could be achieved in single reactor attached growth MBR. However there are limitations in current study such as periodic biofilm removal from the media cylinder.
- To overcome the limitations it is recommended to investigate the attached growth system with sponge media under fluidized bed configuration.

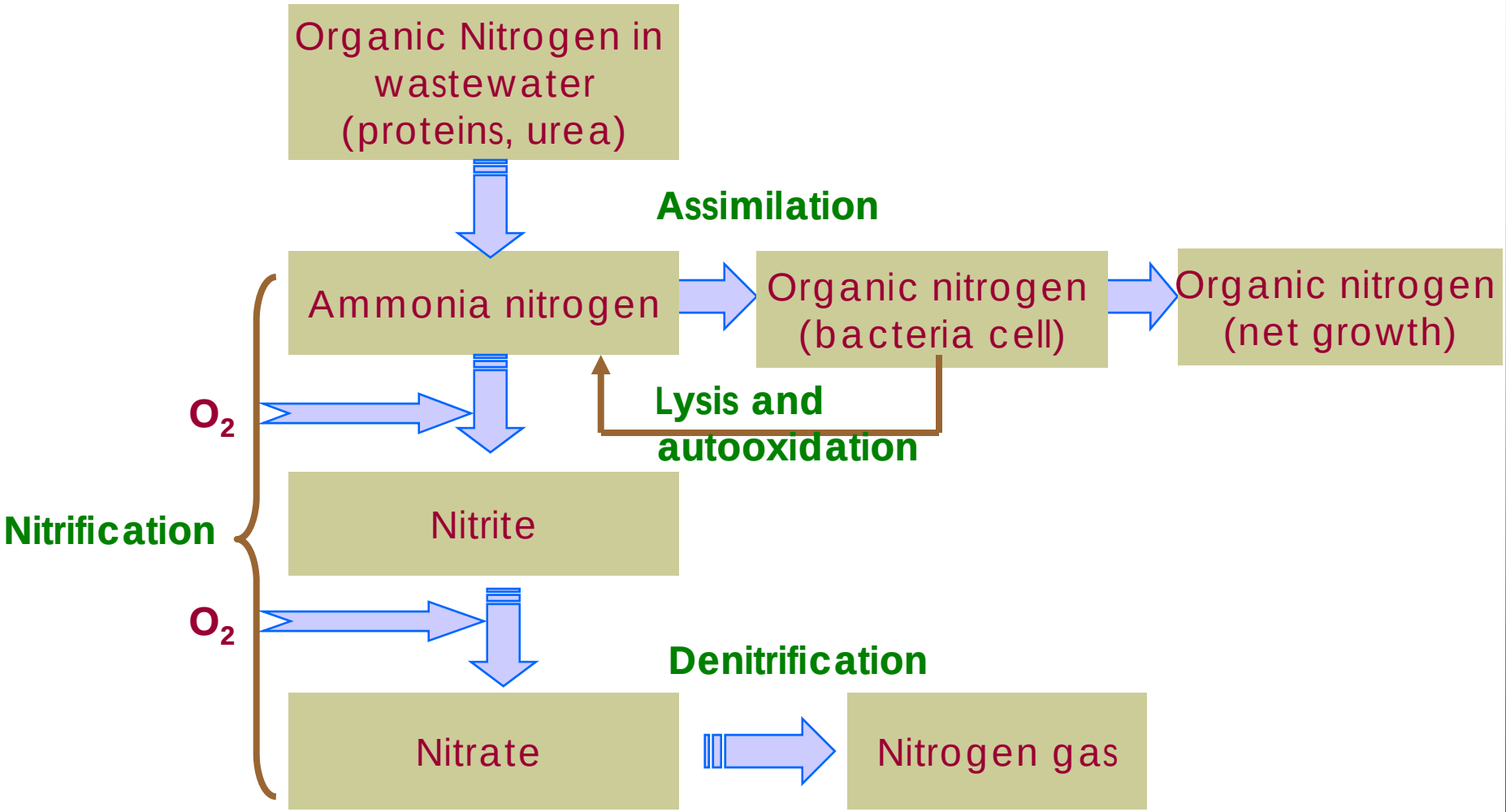
Thank you for your attention!

Media Types

Sponge media

CP media

Nitrogen Transformation in Biological Process



Adopted from: Metcalf & Eddy, 2004

Other Nitrogen Transformation Processes

- **SHARON (Partial Nitrification process)**
  - Single reactor system for High Ammonia Removal Over Nitrite
  - $NH_4^+ \longrightarrow NO_2^-$
- **ANAMMOX**
  - Anaerobic Ammonia Oxidation Process
  - $NO_2^- + NH_4^+ \longrightarrow N_2 + H_2O$
- **Combination of SHARON and ANAMMOX Processes**
  - $NH_4^+ \longrightarrow NO_2^-$

    $NO_2^- + NH_4^+ \longrightarrow N_2 + H_2O$

Comparison with Previous Study

Study by Sombatsompop, (2007)

Objectives

- Organic removal
- Fouling Behavior of MBR
- Low nitrogen concentration

Reactor configuration

- CP media
- Moving Bed

Variables

- HRT (2, 4,6 and 8 h) and MLSS (6, 10 and 15 g/L)

Present Study

Objectives

- TN removal with SND
- High nitrogen concentration
- Two reactors with conventional and fixed bed MBRs

Media selection

- Sponge media
- Fixed bed air Lift reactor

Variables

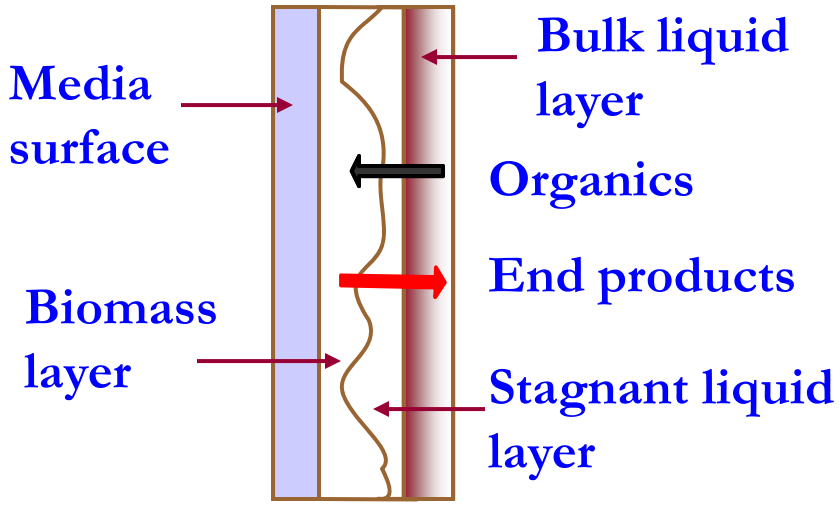
- HRT (7, 10 and 13 h)

Attached Growth MBR

Attached growth MBR

- **Fixed bed**
  - Media types: Ring lace ®, Biomatrix ®, Bio-2-Sludge ®
- **Moving media**
  - Captor ®, Linpor ®, other sponge or plastic carriers

Biofilm



Adopted from: Metcalf & Eddy, 2004

- **Specific carrier media is used enhance biological processes**
- **Biofilm enhance the Simultaneous Nitrification-Denitrification (SND) process**