# INVESTIGATION ON SIMULTANEOUS NITRIFICATION/DENITRIFICATION AND FOULING OF AN AEROBIC GRANULAR MEMBRANE AIRLIFT BIOREACTOR

by

Prashanthini Vijayalayan

A thesis submitted in partial fulfillment of the requirements for the
Degree of Master of Engineering in
Environmental Engineering and Management

Examination Committee: Prof. C. Visvanathan (Chairperson)
Dr Oleg Shipin
Dr Preeda Parkpian

Nationality: Sri Lankan
Previous Degree: Bachelor of Science of Engineering in Civil Engineering
University of Moratuwa
Moratuwa, Sri Lanka

Scholarship Donor: AIT Fellowship

Asian Institute of Technology
School of Environment, Resources and Development
Thailand
May 2008

# INVESTIGATION ON SIMULTANEOUS NITRIFICATION/DENITRIFICATION AND FOULING OF AN AEROBIC GRANULAR MEMBRANE AIRLIFT BIOREACTOR

by

Prashanthini Vijayalayan

A thesis submitted in partial fulfillment of the requirements for the
Degree of Master of Engineering in
Environmental Engineering and Management

Examination Committee: Prof. C. Visvanathan (Chairperson)
Dr Oleg Shipin
Dr Preeda Parkpian

Nationality: Sri Lankan
Previous Degree: Bachelor of Science of Engineering in Civil Engineering
University of Moratuwa
Moratuwa, Sri Lanka

Scholarship Donor: AIT Fellowship

Asian Institute of Technology
School of Environment, Resources and Development
Thailand
May 2008

**Acknowledgement**

I would like to take this opportunity to express my deep and sincere gratitude to all individuals who supported me to complete this thesis successfully.

First of all I would like to express my deepest gratefulness to my supervisor, Professor C. Visvanathan, for his detailed and constructive comments, vital guidance and support throughout this research work. He had been accessible for me for consultation round the clock during this period. I too owe my sincere gratitude to my committee members Dr. Oleg Shipin and Dr. Preeda Parkpian for their valuable comments and suggestions during this period.

My special thanks go to Mr. Bui Xuan Thanh for assisting me for the detailed studies during my research work. His wide knowledge and logical thinking have been of great value for me. His understanding, encouragement and guidance contributed a lot to complete my thesis. My warmest thanks to Mr. Pradeep Munasinghe and other colleagues of my class who helped me in several occasions.

Furthermore, I would like to thank the faculty and the staff of Environmental Engineering and Management Program for guidance and sharing of their knowledge and resources to complete the research work successfully and in time. Especially, I would like to thank EEM laboratory supervisors and technicians for rendering their fullest support in experimental works.

I am grateful to Asian Institute of Technology for providing me the opportunity to pursue the master program and offering the partial fellowship.

I owe my loving thanks to my beloved husband K.S. Vijayalayan for his encouragement and understanding for the last 1 ½ years to complete this research work and masters program. My special gratitude goes to my parents and in-laws for their loving support.

Finally, I am deeply indebted to my teachers in Sri Lanka, for providing the strong foundation in education which helped me to complete the masters program with great success.

## Abstract

Aerobic granulation is a novel biological process developed to treat the high strength organic wastewater. It could be coupled with membrane airlift bioreactor (MABR) which would create an attractive alternative treatment technology in the near future. The objective of this study is to investigate the performance of the aerobic granular membrane airlift bioreactor based on organic and nitrogen removal efficiencies and membrane fouling behavior. Further, the stability of granular sludge with long sludge retention time and simultaneous nitrification and denitrification (SND) in the MABR were also evaluated.

For this study, the organic and nitrogen loading of sequencing batch airlift reactor (SBAR) were maintained at 4 kg COD/$m^3$.d and 0.4 kg N/$m^3$.d respectively. Subsequently, the supernatant from the batch granulation reactor was discharged into the MABR to treat further where both aerobic and anoxic zones were existing. Due to the long sludge retention time (SRT) of the granular sludge and sudden changes in OLR, the granules commenced to disintegrate after 300 days of operation. As a result of this, the performance of SBAR and MABR based on removal efficiencies were unable to evaluate and the nitrogen loading was reduced to 0.4 from 0.6 kgN/$m^3$.d. However, it was identified that the SVI of MABR was 2.5 fold higher than that of granular sludge. Later, the SBAR and MABR were separated to evaluate the performance of MABR alone. Eventually, it was found that the MABR could achieve maximum of 70% of nitrogen removal including 50% of denitrification and 80% organic removal with external carbon source addition.

The organic and nitrogen removal in AGMABR were 99% and 61% including 35% of denitrification respectively after combining SBAR and MABR. On the other hand in conventional MBR the organic and nitrogen removal achieved were 98% and 27% respectively. Hence, the AGMABR system could remove both organic and nitrogen more when compared to the conventional MBR. During this research the granule size was 1.7±0.1 mm and flocs were seen in the SBAR. Flocs had low settling ability and they were washed out to MABR during each cycle of operation. The EPS of flocs was 19.1 mgEPS/mgVSS which lead to rapid fouling in MABR. Once, the granules become matured and bigger, the flocs would be less and the nitrogen removal through denitrification would be more in the system. As a result the fouling in MABR would also be reduced. The production of soluble EPS in conventional MBR was 2 fold higher than that of MABR which shows that the fouling due to soluble EPS is less in MABR. Hence, the AGMABR system would be an attractive alternative option for water reuse and recycling in near future.

## Table of Content

## List of Figures

## List of Tables

## List of Abbreviations

| | |
|---|---|
| AGMABR | Aerobic Granular Membrane Airlift Bioreactor |
| ASP | Activated Sludge Process |
| BOD | Biochemical Oxygen Demand |
| BASR | Biofilm Airlift Suspension Reactor |
| CA | Contact Angle |
| CST | Capillary Suction Time |
| COD | Chemical Oxygen Demand |
| CER | Cation Exchange Resin |
| EPS | Extracelluar Polymeric Substances |
| EBPR | Enhanced Biofilm Phosphorous Reactor |
| FISH | Fluorescent In Stitu Hybridization |
| HRT | Hydraulic Retention Time |
| MBR | Membrane Bioreactor |
| MABR | Membrane Airlift Bioreactor |
| MFI | Membrane Fouling Index |
| MLSS | Mixed Liquor Suspended Solids |
| MLVSS | Mixed Liquor Volatile Suspended Solids |
| NLR | Nitrogen Loading Rate |
| OLR | Organic Loading Rate |
| PS | Polysaccharides |
| PN | Protein |
| SND | Simultaneous Nitrification and Denitrification |
| SBAR | Sequencing Batch Airlift Reactor |
| SMP | Soluble Microbial Product |
| SRT | Sludge Retention Time |
| SVI | Sludge Volume Index |
| SOUR | Specific Oxygen Utilization Rate |
| SEM | Scanning Electron Microscope |
| SBAR | Sequencing Batch Airlift Bioreactor |
| SBR | Sequencing Batch Reactor |
| SBBC | Sequencing Batch Bubble column |
| TOC | Total Organic Carbon |
| TMP | Trans Membrane Pressure |
| VSS | Volatile Suspended Solids |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background of the Study

There are wide ranges of treatment technologies available in the global to treat the wastewaters discharged from domestic, commercial, and industrial uses. Since, the wastewater from the above mentioned users have different characteristics, the treatment technologies also differ from each other and each treatment technology has its own advantages and disadvantages. The selection of the appropriate technology for treatment depend on several factors such as characteristics of wastewater, end use, availability of appropriate technology, funding, land, etc.

The water demand is increasing in the day to day life with the rapid growth of population. Hence, the water available in the earth may not be adequate to satisfy the entire demand of the population in the world after a few decades. In the recent past, the governing authorities had forced all industries to implement appropriate treatment technologies to slow down the rapid degradation of the water environment by introducing stringent standards. Hence, the treatment technologies of industries have to move from conventional biological to advanced biological or membrane treatment processes. In addition, the domestic wastewater treatment plants too have to adopt these advanced treatment technologies.

Good quality of effluent could be achieved with the advanced biological and membrane treatment process and such effluent could be reused by recycling with appropriate operations. One of the attractive treatment processes satisfying the above is an aerobic granular membrane airlift bioreactor which operates on a basis of a combination of biological process and membrane filtration. Up to now, many researches had been conducted regarding developing aerobic granules in sequencing batch airlift reactor (SBAR). It has several advantages including ability to withstand high organic loading rate, good sludge settling ability, produce denser and stronger microbial structure, retention of high biomass and produce effluent with good quality than that of conventional bioflocs (Tay et al., 2002).

## 1.2 Statement of the Problem

Due to the water scarcity, wastewater reuse and recycling is becoming more popular around the world. To achieve better effluent quality, engineers and scientists have introduced membrane technology, especially the membrane bioreactor (MBR). The MBR is a combination of the activated sludge process (ASP), and a membrane system. This membrane system replaces the traditional gravity sedimentation tank in the ASP. This system carries several advantages including high volumetric loading rate, better effluent quality than that of the conventional ASP, and less space requirement for erection of necessary infrastructure. Even though the MBR system has several benefits, it has disadvantages too; namely weak sludge settling characteristics due to fine size of sludge flocs and membrane fouling. To avoid the said drawbacks of MBR it is coupled with aerobic granulation and a new technology called aerobic granular membrane bioreactor has

been developed. Aerobic granulation is being used to treat wide variety of wastewaters in sequencing batch reactors due to its characteristics such as excellent settling ability of sludge, toleration of high organic, nitrogenous loading and toxic substances and retention of high biomass. However, aerobic granules alone could not achieve the effluent standards as the granulation process produce high suspended solids in the effluent. Hence, the combination of aerobic granulation and MBR system could reduce the suspended solid concentration in the effluent.

According to Thanh (2005), shell carrier is a good support media which assist microbial adhesion and granulation. In addition, the granule surface is smoother with small cavities and compacted which lead to better biomass concentration and shock loading ability. Hence, the shell carrier media sequencing batch airlift reactor (SBAR) was used in this study. The membrane airlift bioreactor (MABR) system could treat nitrogenous substances through simultaneous nitrification and denitrification than that of MBR due to its configuration where both aerobic and anoxic zones exist. As such, the combination of SBAR and MABR provides an attractive solution for water reuse and recycling.

### 1.3 Objectives of the Study

The main objectives of this study were to investigate the performance of aerobic granule MABR based on organic and nitrogen removal capacities and membrane fouling behavior.

1. To study the simultaneous nitrification and denitrification in MABR.
2. To study the organic and nitrogen removal patterns in the aerobic granular MABR system.
3. To study the membrane fouling behavior of membrane by sending the granulation supernatant through MABR system.

### 1.4 Scope of the Study

Aerobic granulation is known as a novel biological process when compared with the conventional activated sludge process. It is coupled with membrane airlift bioreactor which would create an attractive alternative treatment technology for adoption in the near future. The scope of this study is brief below:

- Investigation of simultaneous nitrification and denitrification in MABR at different nitrogen loadings.
- Investigation of granule characteristics and stability at various organic loadings at 2 and 4 kg COD/$m^3$ d.
- Investigation of organic removal with simultaneous nitrification & denitrification of the aerobic granule MABR system based on nitrogen species and total organic carbon (TOC) for the different organic loadings of 2 and 4 kg COD/$m^3$.d and nitrogen loading of 0.4 kg N/$m^3$.d. The results achieved from the above were compared with the conventional MBR system.
- Investigation of membrane fouling behavior based on parameters such as trans-membrane pressure (TMP), extra cellular polymeric substances (EPS), capillary suction time (CST), and sludge volume index (SVI).

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Development and application of biological treatment process

The biological treatment uses microorganisms to treat biodegradable organic wastewater mainly from industries and households. The main objectives of this treatment are to oxidize the dissolved and particulate biodegradable substances into harmless end products, capture the suspended and non settlable colloids into bioflocs, and remove excess nutrients (Metcalf and Eddy, 2004).

Biological processes are environmentally friendly and they operate at moderate temperatures to generate harmless by-products. There are two types of biological process namely attached growth and suspended growth processes which includes aerobic, anaerobic and anoxic conditions to produce harmless end products. The major biological treatment processes used for wastewater treatment are listed in Table 2.1.

Table 2.1 Major biological treatment processes used for wastewater treatment

| **Type** | **Common Name** | **Use** |
|---|---|---|
| ***Aerobic Process*** | | |
| Suspended Growth | Activated sludge process, Aerated lagoon, Aerobic digestion | BOD* removal, nitrification |
| Attached Growth | Trickling filter, Rotating biological contactors, packed bed reactors | BOD removal, nitrification |
| ***Anoxic Process*** | | |
| Suspended Growth | Suspended growth denitrification | Denitrification |
| Attached Growth | Attached growth denitrification | Denitrification |
| ***Anaerobic Process*** | | |
| Suspended Growth | Anaerobic contact process<br>Anaerobic digestion | BOD removal<br>Stabilization, solids destruction |
| Attached Growth | Anaerobic packed and fluidized bed | BOD removal, waste stabilization, denitrification |
| Sludge Blanket | Upflow anaerobic sludge blanket (UASB) | BOD removal specially high strength wastes |
| ***Combined aerobic, anoxic, and anaerobic processes*** | | BOD removal, nitrification, denitrification and phosphorous removal |
| ***Lagoon processes*** | Aerobic lagoons, Facultative lagoons, Anaerobic lagoons | BOD removal |

Source: Modified from Metcalf and Eddy (2004)
* BOD – Biochemical Oxygen Demand

Due to water scarcity water recovery, reuse and recycling are becoming more and more popular, which require alternative treatment systems. The wastewater from industries contain high organic and nitrogenous substances, hence the conventional treatment processes could not be used to get the good quality effluent for reuse. Hence, the need for a new treatment technology that has higher loading rate, high settling ability of sludge and high toleration with toxic substances is inevitable. To meet this requirement, biological process using aerobic granular system combined with the membrane technology could be an attractive alternative treatment process.

## 2.2 Granular sludge

The bio-granulation can be divided into aerobic and anaerobic granulation and it is formed through self cell immobilization process of microorganisms. The anaerobic granulation has been extensively used in up flow anaerobic sludge blanket (UASB) by several industries to treat high strength of wastewaters. But the anaerobic granulation has some shortcomings such as long start up period, a relatively high operation temperature, unsuitability for low strength wastewater and not suitable for nutrient removal (Liu and Tay, 2004). Hence, the aerobic granulation has been introduced to overcome these problems.

Cell immobilization technology has been used in environmental engineering field for several years and can be classified into three categories namely,

- Biofilm: Microorganisms are immobilized or attached onto a solid surface, such as activated carbon, basalts, plastics, polymers, ceramics and others (Liu and Tay, 2002).
- Microbial aggregates and granular sludge: Aerobic and anaerobic granules can be regarded as a self-immobilization community of bacteria.
- Entrapped Microorganisms: Microorganisms may be entrapped in hydrophobic gels of photo-cross linked polymers or in other types of gels, such as polyacrylamide (Liu and Tay, 2002).

Biofilm and granular sludge can be regarded as different forms of cell immobilization. So far, it has been recognized that the formation of biofilm and microbial aggregates are multiple-step process, to which physico-chemical and biological forces make significant contributions (Beun et al., 1998; Tay et al., 2001; Tay et al., 2004). Based on previous studies, it is encouraged to propose that cell immobilization can be roughly described as a four-step process as follows:

*Step 1:* Physical movement to initiate cell-to-cell contact or bacterial attachment onto a solid surface. The forces involved in this step are hydrodynamic force, diffusion force, gravity force, thermodynamic force and cell mobility.

*Step 2:* Initial attractive forces to keep stable bacteria solid surface and multicellular contacts Figure 2.1.

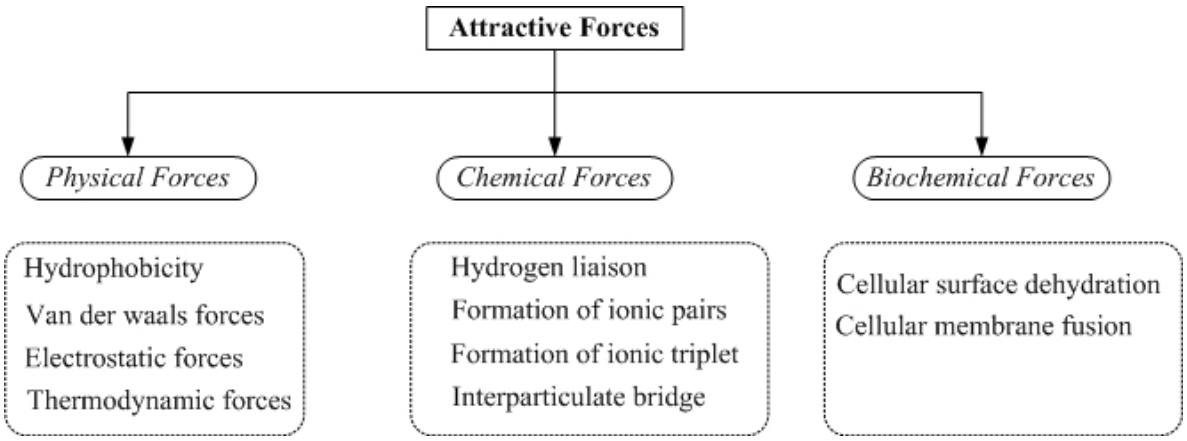



Figure 2.1 Classification of initial attractive forces in immobilization process

*Step 3:* Microbial forces to make attached bacteria or aggregated bacteria nature:

- Production of extracellular polymer such as exopolymer saccharides etc;
- Growth of cellular cluster;
- Metabolic change and genetic competence induced by environment, which facilitate and further strengthen the cell-cell interaction and result in the high density of adhering cells.

*Step 4:* The outer shape and size of microbial aggregates are finally determined by the interactive strength between aggregate and shear force, microbial species, and substrate loading rate and so on.

## 2.3 Aerobic Granular Sludge

### 2.3.1. Aerobic Granule characteristics

The aerobic granule sludge has several advantages over the conventional sludge such as excellent settling ability leading to good solid-liquid separation, high biomass retention and, ability to withstand high organic and nitrogen loading with regular and denser structure (Tay et al., 2002). The aerobic granules are suspended spherical biofilm including microbial cells, inert particles, degradable particles and extracellular polymeric substances (EPS) (Tijhuis et al., 1994; Jang et al., 2003). The aerobic granules have spherical compact structure which favors aerobic and anaerobic conditions within granules due to the oxygen diffusivity limitation. Anaerobic condition exists in central core and aerobic condition in the outer layer of the granule (Figure 2.2). Hence, simultaneous nitrification and denitrification could be achieved inside the granule.

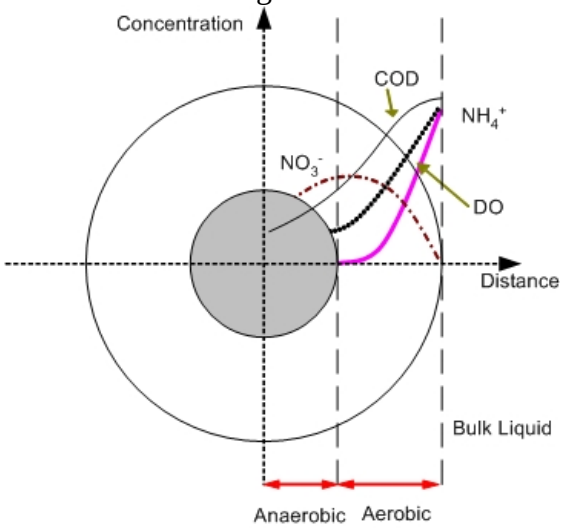



Figure 2.2 Structure of Aerobic Granule

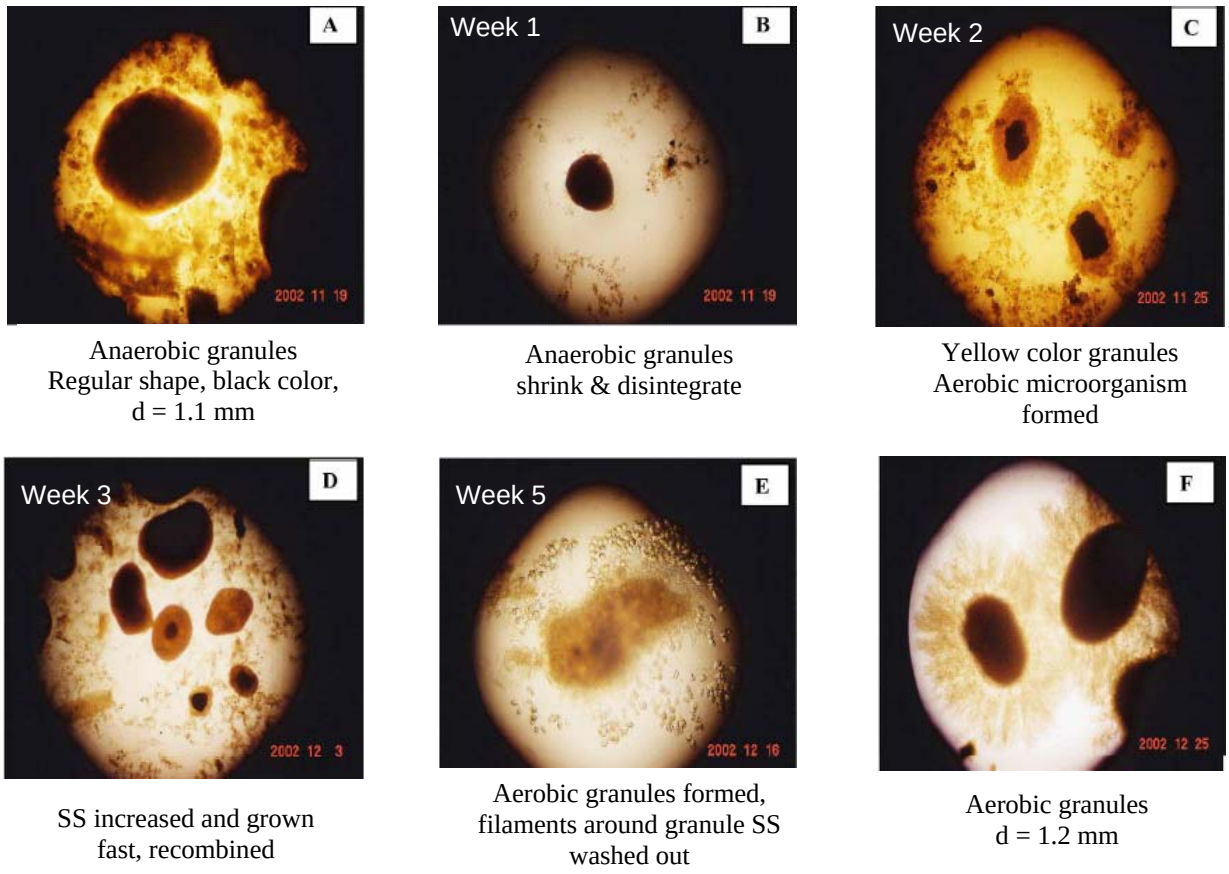
There are several special characteristics of aerobic granule sludge when compared with other sludge such as

- Consists of various bacteria like heterotroph, nitrifying and denitrification bacteria which render the organic and nitrogen substances removal
- Can operate at wide temperature range
- Fast recovery after long period of storage
- Limited substrate diffusion especially the oxygen resulting in simultaneous nitrification and denitrification in aerobic granules.

2.3.1.1 Morphology

The numerous researches show that the morphology of the aerobic granules is completely different from the biofloc sludge which is spherical in shape with a clear outline structure. The average diameter of the aerobic granule varies from 0.2 – 5 mm due to strong shear force which causes detachment of granule (Liu and Tay, 2004). The morphological scanning electron microscopic (SEM) images from different researches are as follows

According to Linlin et al. (2005), the morphological change of aerobic granules during formation in the reactor is described by the following Figure 2.3.




Anaerobic granules
Regular shape, black color,
d = 1.1 mm

Anaerobic granules
shrink & disintegrate

Yellow color granules
Aerobic microorganism
formed

SS increased and grown
fast, recombined

Aerobic granules formed,
filaments around granule SS
washed out

Aerobic granules
d = 1.2 mm

Figure 2.3 The morphological change of granules (modified from Linlin et al., 2005)

Wang et al. (2003) found that the sludge inoculated in the SBR was a mixture of filamentous sludge which had difficultly in settling. Due to the filamentous sludge the washout of biomass had taken place with the short settling time. Hence the sludge concentration in the reactor decreased and more sludge was observed in the effluent due to inefficient settling ability of filamentous sludge. After 8 weeks of operation, the floc-like sludge gradually changed to granular sludge and in 67 days of operation, granular sludge were appeared in the reactor while floc-like sludge remained dominant.

The initial granular sludge formed in the SBR was smaller in size, had fluffy edges. After 11 weeks of operation, the most of the sludge in the reactor was completely become to granular sludge which was visually observed without suspended biomass in the reactor.

Due to the high turbulent mixing through aeration, the granular sludge became spherical with a smooth surface and diameter of 6.0–9.0 mm which had good settleability. Hence, the most of the biomass was kept in the reactor (Figure 2.4).

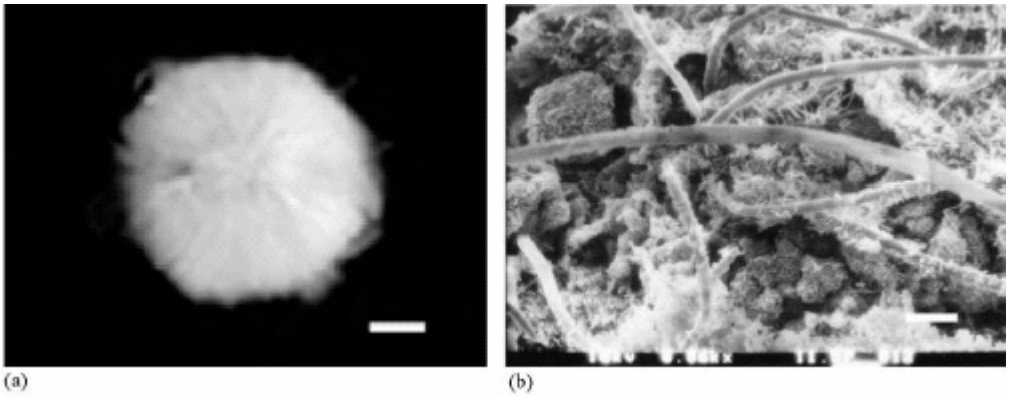



Figure 2.4 Microscopy images of mature granules after 120 days. (a) Microscope overview image, bar = 2 mm, (b) SEM of the granules surface, bar =11 µm.

From the research of Jang et al. (2003) after 50days of operation of the SBR reactor the initial seed sludge has size of 0.08-0.18 mm and SVI of 210-230 ml/g had increased to the size of 0.95-1.35 mm and SVI of 70-90 ml/g. After 40 days of operation, the seed sludge in the reactor was totally become to granular sludge. The development of granule morphology is presented in the Figure 2.5.

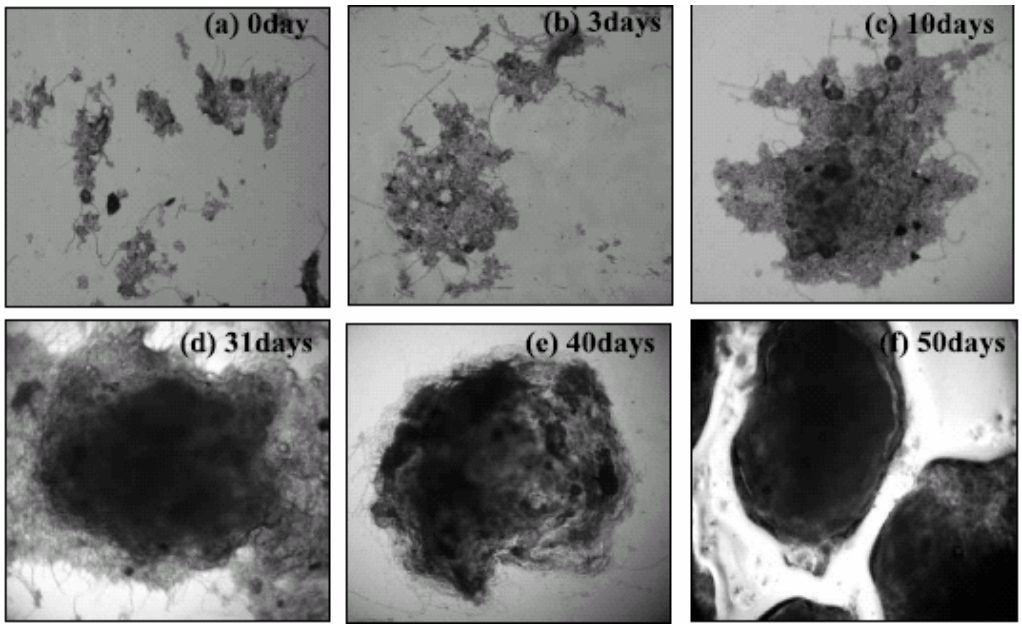



Figure 2.5 Time dependent development of granules, extending from the seed sludge to granules, of: (a) 0 day, seed sludge; (b) 3 days; (c) 10 days; (d) 31 days, flocs-like; (e) 40 days and (f) 50 days, granular sludge (Jang et al., 2003)

Therefore, the aerobic granule formation consists of different phases such as seed sludge phase, microorganism multiplication phase, floc appearance phase, floc cohesion phase, mature floc phase and aerobic granule phase.

2.3.1.2 Characteristics of granular sludge

Table 2.2 Physico chemical and biological characteristics of granular sludge

| Reference | Carbon source | OLR $kg/m^3.d$ | Formation time | Physico Chemical | | | Biological | |
|---|---|---|---|---|---|---|---|---|
| | | | | Granule diameter (mm) | SVI (mL/g) | Settling Velocity (m/hr) | Settled biomass conc. (gVSS/L) | MLVSS (gVSS/L) |
| Tijhuis et al., 1994 | Acetate | 5 | - | 0.35 | | - | 15-20 | - |
| Morgenroth et al., 1997 | Molasses | 2.9 | 40 days | 2.35 | - | - | - | - |
| Beun et al., 1998 | Acetate | 2.3 | 50 days | 1 | | 24 | 11.9 | - |
| Etterer & Wilderer, 2001 | Acetate; glucose & peptone | 3.6 | 56 days | 1.1-6.5 | - | 35 | | - |
| Beun et al., 2002 | Acetate | 2.5 | > 63 days | 2.5 | - | > 10 | 60 | 7-10 |
| Tay et al., 2002 | Acetate | 6.0 | - | 0.35 | 50 | - | - | 6 |
| Yang et al., 2003 | Ethanol | - | 40 days | 0.4-1.9 | - | - | - | - |
| Jang et al. 2003 | Glucose & acetate | 2.5 | 50 days | 1.0-1.3 | 70-90 | 25.2-28.8 | - | - |
| Jiang et al., 2004 | Phenol | < 2.5 | - | | 40-65 | - | | - |
| Qin et al., 2004 | Sodium acetate | - | 3 weeks | 0.35 | 50-140 | - | - | - |
| Yang et al., 2004 | Sodium acetate | - | 4 weeks | 0.25-0.32 | - | - | - | - |
| McSwain et al., 2004 | Glucose & peptone | 2.4 | 120 days | | 46-114 | - | | - |
| Wang et al., 2004 | Glucose | 4.8 | 67 days | 6-9 | 40 | 32.7 | - | 7.8 (SS) |
| Cai et al., 2004 | Glucose | 5 | 50 days | 1.2 | < 65 | - | 45.2-45.7 | - |
| Tay et al., 2004 | Acetate | 6 | 21 days | 0.33 -0.39 | 46-62 | - | 40-60 | - |
| Zheng et al., 2004 | Sucrose | - | 68 days | 0.5-1.2 | 23 | - | - | - |
| Swazenbeck et al., 2004 | Barley dust WW | 3.4 | 4 weeks | 2-4 | 30-40 | - | - | - |
| Arrojo et al., 2004 | Dairy WW | 7 | 60 days | 0.25-4 | 60 | - | 10-15 | - |
| Linlin et al.., 2005 | Acetate | - | 50 days | 1.2 | 30-40 | 22-60 | - | 5 (SS) |
| Thanh, 2005 | Glucose | 2.5 - 30 | 4 weeks | 0.5-4 | 18-35 | - | 20-62 | - |
| Liu et al., 2005 | Sodium acetate | 4 | - | 1.2-1.8 | - | - | - | - |
| Zheng et al., 2005 | Sucrose | 6 | 30 days | 1 | 44 | 130 | - | 6.43 |
| Zhuang et al., 2005 | Tert butyl alcohol | 0.6 | 90 days | 0.32 | 57 | - | - | 4.54 |
| Qiang et al., 2005 | Phenol | 20 mg/L | 3 weeks | 0.53-0.67 | 19-25 | - | - | - |
| De Kreuk et al., 2005 | Sodium acetate | 1.2 - 1.6 | 48 days | 1.2 | 12-15 | - | - | - |
| Wang et al., 2006 | Sodium acetate | 6.0 | - | 0.85-3.67 | 31-88 | - | - | - |
| Li et al., 2006 | Sodium acetate & peptone | 8 | 15 days | 0.2 | 30-40 | - | - | - |
| Liu & Tay, 2006 | Synthetic wastewater | 3.0 | 27 days | 0.4 | 50 | - | - | 4 |
| Wang et al., 2007 | Brewery wastewater | 3.5 | 41 days | 2-7 | 32 | 91 | - | 8-11 |
| Kim et al., 2008 | Glucose & Acetate | 1.76-2.84 | 51 days | 0.35 | 83 | - | - | 9.5 |

Source : Modified from Thanh (2005)

Granule size is an important factor for excellent physical performance of aerobic granules as it decides the ability of simultaneous nitrification and denitrification in the granules based on oxygen diffusivity. The sludge volume index (SVI) of aerobic granular sludge is less than 70 mL/g which is much lower than the conventional sludge. Due to high settling velocity of granules, the biomass washout is less from the reactor (Beun et al., 2000) which will favor the high biomass retention in the reactor. In several researches the settled biomass concentration is named as biomass density. According to table 2, the settled biomass concentration of aerobic granules is around 60 gVSS/L.

Another important factor is hydrophobicity which assists cell self immobilization and attachment processes of granules. Before formation of aerobic granules the value of hydrophobicity is around 50.6 % and after formation is around 75.1% (Tay at al., 2002). The water content of aerobic and anaerobic granules is 94.3% and 97.2% respectively (Linlin et al., 2005). The specific gravity of the aerobic granules represents the compactness of microbial community. This value increased from 1.0008 to 1.0069 kg/L during granulation period (Tay et al., 2002).

The value of VSS/SS ratio of aerobic and anaerobic granule are 0.71 and 0.57 respectively. These values are less than that of the conventional activated sludge which is around 0.85 (Linlin et al., 2005). EPS could help for both adhesion and cohesion of cells of granules and pays an important role in maintaining structural integrity of the biofilm matrix. The content of biofilm polysaccharides (PS) was at least 4.5-fold higher than that of biofilm-proteins (PN) (Liu and Tay, 2002) which is still on research level in the case of aerobic granules.

The microbial activity of microorganism is characterized by the SOUR and the SOUR is used for assessing the ability of aerobic granules to handle the high strength wastewater. The microbial diversity of the aerobic granules mainly depends on the composition of culture media like bivalve shell carrier, sponge, sand, plastic bead, etc.

Table 2.3 Nitrogen removal by aerobic granular sludge

| **Reference** | **Nitrogen source** | **NLR (NH4-N) mg/L** | **Nitrogen Removal (%)** |
|---|---|---|---|
| Etterer & Wilderer, 2001 | Ammonium Chloride | 30 | 99 |
| Tsuneda et al., 2003 | Synthetic inorganic wastewater | 500 | > 98 |
| Casidy & Belia, 2005 | Slaughter house wastewater | 1057 (TKN) | 97 |
| Qin & Liu, 2005 | Ammonium Chloride | 37.5 – 112.5 | 99-100 |
| Liu & Tay, 2005 | Ammonium Chloride | 175 | - |
| Yu & Tay, 2005 | Synthetic wastewater | 300 | 94 |
| Trigo et al., 2006 | Ammonium sulphate | 75 - 1800 | 99 |
| Wang et al., 2007 | Brewary Plant wastewater | 30 – 37 (TN) | 89 |
| Gong et al., 2007 | Ammonium sulfate | 300 | - |

Most of the synthetic wastewater contains nitrogen in the form of ammonium chloride and more than 85% of the NH4-N is removed from the wastewater. The major part of the nitrogen source is used as nutrient for organic removal of wastewater and the remaining nitrogen is removed through simultaneous nitrification and denitrification in the aerobic granules.

2.3.2. Aerobic granule formation

The mechanism for aerobic granule formation suggested by Beun et al. (1998) is described by the following schematic diagram.

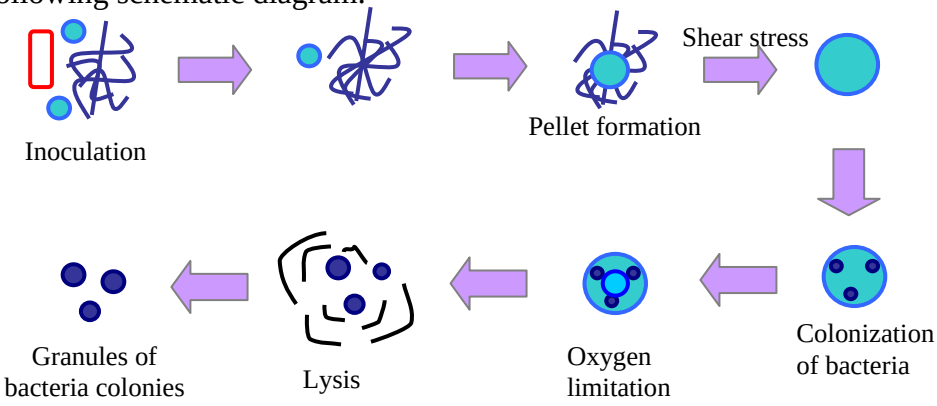



Figure 2.6 Mechanism of granulation of aerobic granule (Beun et al., 1998)

After inoculation process with bacterial sludge fungi become dominating species which can easily form mycelial pellets with good settleability. On the other hand, bacteria will be washed out almost completely as it does not have good settleability. Hence, during the start-up, the biomass in reactor will contain mainly filamentous mycelial pellets. Detachment of the filaments on the surface of pellets takes place due to the shear stress in the reactor which will favour the pellets formation further. Then the pellets start to grow upto a diameter of 5-6 mm. Due to the oxygen limitation into the inner core of the pellats, lysis will occur in which bacteria can produce colonies which grow as granules.

According to Tay et al. (2001), Beun et al. (1999), Jang et al. (2003), Wang et al. (2003), Schwarzenbeck et al. (2004), Beun et al. (2000), Jang et al. (2003), and Tay et al. (2002) the aerobic granules could be cultivated from conventional aerobic activated sludge. Also it could be cultivated from anaerobic sludge too (Linlin et al., 2005).

The process for granule formation suggested by Linlin et al., (2005) is described below. During the inoculation irregular and small flocs and filamentous granules are formed which are not stable and broken up into pieces after few days of operation. Hence, most of the biomass is washed out leaving the debris in the reactor which is then favour the granulation in the aerobic condition. The formation process is illustrated by the Figure 2.7.

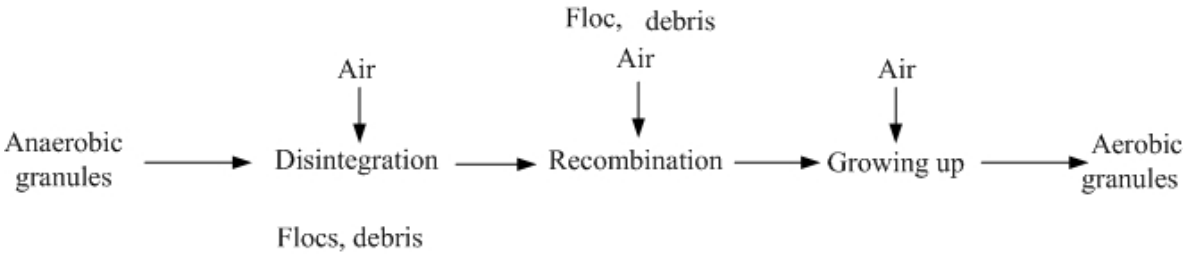



Figure 2.7 Formation process of aerobic granule from anaerobic granular sludge

Wang et al. (2003) suggested another method for formation of aerobic granules from conventional aerobic activated sludge process. According to their findings the granulation process could be divided into three phases namely acclimation, granulation and maturation. At the granules initiation phase the granules are initiated as mycelial pellets and grow

rapidly. The period from the start-up operation to the granules initiation is named as sludge acclimation phase. Then the granules grow to its maturation point which is called as maturation phase of the granules. From the above research, the granule formation process identified is described in the Figure 2.8.

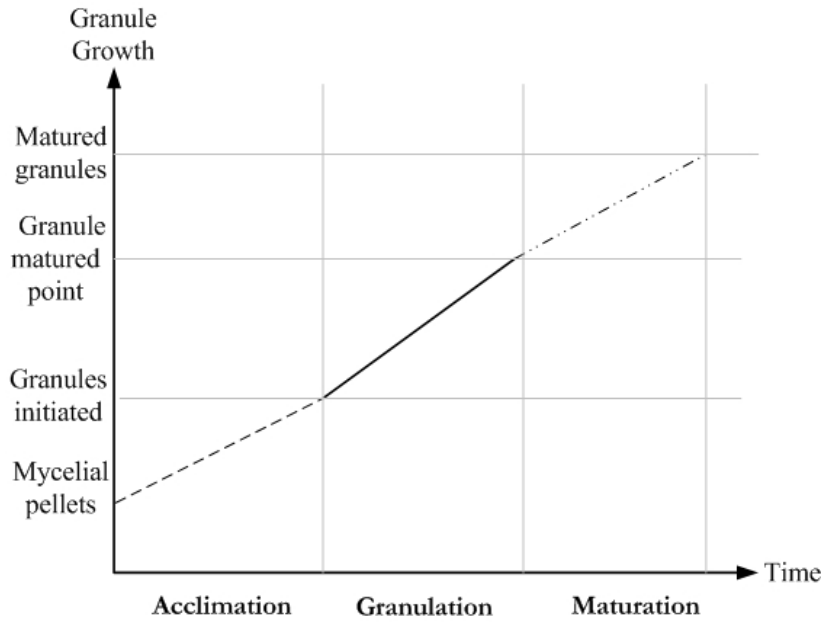



Figure 2.8 Formation process of aerobic granule by Wang et al. (2004)

From Etterer and Wilderer, (2001)'s research, the biomass in the reactor is washed out during the start up period due to short settling time of biomass. After10-15 days of operation the filamentous granules appeared but flocs remained dominant in the reactor. After 3-4 weeks of operation the granules started to appear with spherical smooth surface due to high aeration. In the light microscopic observation, the presence of fungi and filamentous organisms is seen in the overall structure. On the other hand when using fluorescent in situ hybridisation (FISH), only filaments were detected. The formation process of granules by Etterer and Wilderer, (2001) is shown in Figure 2.9.

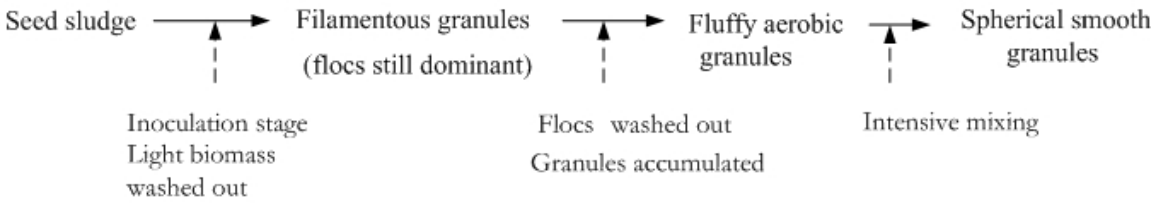



Figure 2.9 Formation process of aerobic granule by Etterer and Wilder (2001)

2.3.3 Factors stimulating aerobic granulation formation

2.3.3.1 Reactor configuration for aerobic granule formation

The aerobic granules could be cultivated by batch or continuous system namely sequencing batch airlift reactor (SBAR) and biofilm airlift suspension reactor (BASR) respectively. However, from several researches, it was revealed that the granules could be cultivated in batch system such as SBAR (Sequencing Batch Airlift Reactor), SBR (Sequencing Batch

Reactor), SBBR (sequencing batch bubble column) and continuous system like BAS (Biofilm Airlift Suspension Reactor).
The density of the granules formed by SBAR (batch) is much higher than that of BASR (continuous). The reason for the difference in density of aerobic granules may be due to different feeding. This is becuase the wastewater is fed intermittently in SBAR and continuously in BASR (Beun et al., 2002). SBAR has excellent mixing conditions with simple design, possibility for easy dealing with peak-load and high ratio of height to diameter (H/D since, reactor is compacted. Therefore, the SABR system would be the better option for aerobic granule formation. The comparison method among different types of reactors to cultivate granule is shown in the Table 2.4.

Table 2.4.Comparison among the SBR, SBAR, SBBC and BAS

| **SBR (Beun et al., 1998)** | **SBAR (Beun et al., 2000)** | **SBBC (Beun et al., 1999)** | **BAS (Tijhuis et al., 1994)** |
|---|---|---|---|
| Discontinuous system | Discontinuous system | Discontinuous system | Continuous system |
| No external settler needed | No external settler needed | No external settler needed | No external settler needed |
| Riser needed | Riser needed | Riser needed | Riser, 3 phase separator needed |
| No carrier needed | No carrier needed | No carrier needed | Carrier needed |
| Settling time is selection variable | Settling time is selection variable | Settling time is selection variable | HRT is selection variable |
| Detachment determined by hydrodynamic conditions | Detachment determined by hydrodynamic conditions | Detachment determined by hydrodynamic conditions | Detachment determined by bare carrier concentration |
| - | Nitrification and denitrification occurred | - | No denitrification occurred |
| Settled biomass con. $\rho = 11.9\ g/L_{granules}$ | $\rho = 48 g/L_{granules}$ | $\rho = 12 g/L_{granules}$ | $\rho = 15 g/L_{granules}$ |
| Granule diameter d = 3.3 mm | d = 1 mm | d = 2 mm | d = 0.35 mm ($d_{carrier}$ = 0.26 mm) |

Source: Modified from Thanh (2005)

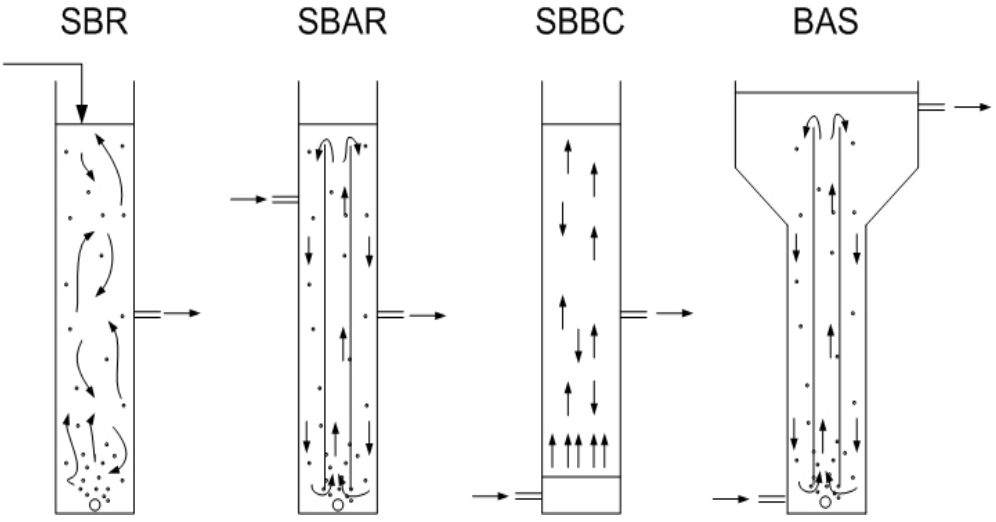



Figure 2.10 Schematic diagram of SBR, SBAR, SBBC and BAS

From the Table 2.4 above, it is evident that the dense and small aerobic granules could be cultivated in SBAR system. The conventional activated sludge process could be upgraded with some specific modification to SBAR for treatment improvement by granular sludge.

However, the main problem in the SBAR system is the excessive growth of filamentous bacteria which may reduce the performance of the reactor. The possible causes for the excessive growth of filamentous bacteria could be wastewater composition, long solid retention time, low substrate concentration, dissolved oxygen deficiency, low nutrients in the granules and temperature variation (Yu and Qi-Shan, 2006).

Yu and Qi-Shan (2006) recommended some control strategies to overcome the excessive growth of filamentous bacteria. These are listed in Figure 2.11.

| **Control Strategies** |
|---|
| SRT ≤ 10 days |
| Granule biomass concentration ≤ 10 g/L |
| Control the size of the granules |
| Intermittent feeding |
| Select slow growing bacteria |

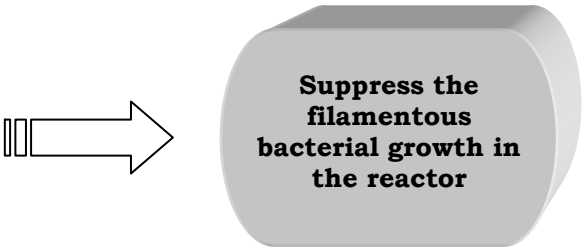



Figure 2.11 Control Strategies for Filament growth (Yu and Qi-Shan, 2006)

2.3.3.2 Support media for aerobic granules

There are various support media available to cultivate the aerobic granules such as basalt (Tijhuis et al., 1994), sponge, sand, plastic bead, shells, etc (Table 2.5). These support media act as a seed for granule formation and enhance the settleability of granular sludge.

According to Tijhuis et al. (1994), the usage of basalt as the support media or carrier showed the good potential for biofilm development when compared to other media which is commonly found solidified lava (a type of igneous rock) mainly consisting of calcium rich feldspar and pyroxene. Calcium is also said to play an important role in cultivation of aerobic sludge granule (Wang et al., 2004). As such, with the proper use of support media we could increase the settleability and enhance the formation of the granules.

2.3.3.3 Hydrodynamic shear force

Hydrodynamic force in the reactor favors the formation, structure and metabolism of microbial community of the aerobic granules where hydrodynamic shear force is created by superficial air velocity. At high hydrodynamic shear force, more compacted, stable and, denser aerobic and anaerobic granules could be formed. The shear force has significant influences on the structure, mass transfer, production of extra polysaccharides and, metabolic/genetic behavior of biofilm, aerobic and anaerobic granules.

When up flow sequencing batch reactor (USBR) was operated at a low superficial air velocity of 0.008 m/s, no granules were observed in the system but only fluffy flocs were observed (Figure 2.13a). On the contrary, when it was of high superficial velocity of 0.025 m/s, regular shaped granules were successfully developed in the USBR (figure 2.13b) (Tay et al., 2001).

Table 2.5 Type of studied support media

| Support materials | Morphological features | Macro-structure | Porosity | Surface area ($m^2/m^3$) | Reference |
|---|---|---|---|---|---|
| Smooth | | | | | |
| PVC | Even surface; pore absent | Size, shape variable | 0.96 | 140 | Kenedy & Droste, 1983 |
| PAC | Smooth surface; pores absent | Fine power | - | - | Ng et al, 1988 |
| Porcelain | Smooth surface even; pore absent | Size, shape variable | - | - | - |
| Perspex | | | | | |
| Uneven | | | | | |
| Nylon | Densely distributed | Size, shape variable | - | - | - |
| Stone | Highly corrugated with randomly distributed crevices | Amorphous | 0.42-0.53 | - | Henze & Harremoes, 1983 |
| Sand | Crests and troughs | ~ 0.7 mm | 0.38-0.43 | 2500-4000 | Henze & Harremoes, 1983 |
| Sintered glass | Rough, jagged surface, shallow pore up to 20μm width, loosely distributed | Open-pore structures | 0.57 | 90,000 | Anderson et al., 1994 |
| Porous | | | | | |
| Basalt | Rough surface | 0.26 mm | - | 1150 | Tijhuis et al., 1994 |
| Bivalve shell (*) | Crests and troughs with deep pores, 10μm with densely distributed | Concave, convex | 0.77-0.82 | | Henze & Harremoes, 1983 |
| Granulated clay | A moisiac of particulates, 1-10μm width, pores of 5μm width, uniformed distributed | Amorphous aggregate | ~ 0.7 | 53-397 | Henze & Harremoes, 1983 |
| Gravel | Pores of 5μm, loosely distributed, irregular ridges present | Amorphous | 0.4 | - | Henze & Harremoes, 1983 |
| Ceramic | Thorny surface with polygonal pores 1-10μm width | Variable size and shape | 0.6 | 274 | Cordora & sinerriz, 1990 |
| Refractory bridge | Crystalline, pointed structure and pores, densely distributed | Amorphous | - | 149 | Henze & Harremoes, 1983 |
| Diatomaceous earth | Deep, minute pores 5μm width, densely distributed, | Variable size and shape | - | - | - |
| GAC | Rough surface with 3 dimensional pore distribution, pore size up to 250μm | Amorphous | 0.6 | 5469 | Henze & Harremoes, 1983 |
| Limestone | Highly porous structures, composed of crystalline unit 2-5μm length, densely distributed deep pores 10 μm width | Variable size and shape | 0.49 | 5,000 – 10,000 | Henze & Harremoes, 1983 |
| Sponge | Labyrinth of pores 200-500μm width, hexa or pentagonal in shape | Highly compressible variable size and shape | - | - | - |

(*) In this study, bivalve shell carrier used has the size of 0.15-0.22 mm

Source: Modified from Harendranath et al. (1996)

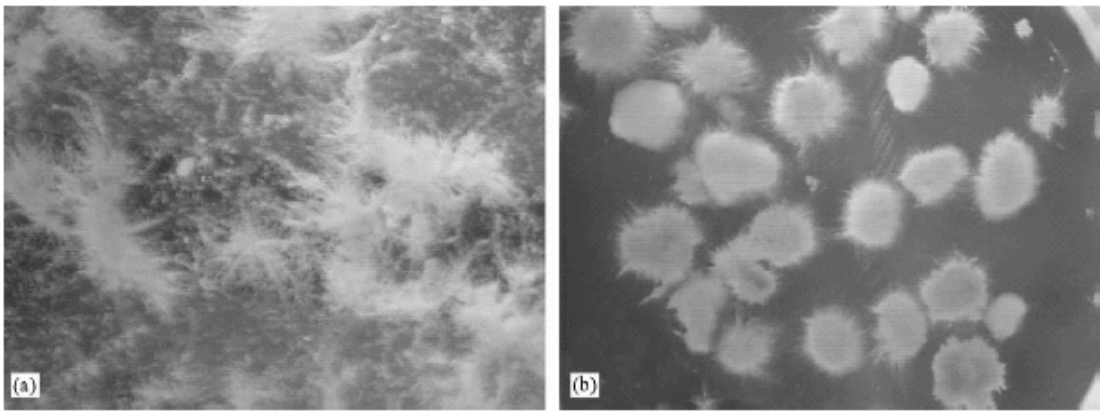



Figure 2.12 Bioflocs cultivated at a superficial air velocity of 0.008 m/s (a); and granules formed at a velocity of 0.025 m/s in USBR (b) (Tay et al., 2001).

The research by Beun et al. (1999) also had the observation that at low superficial air velocity there was no formation of granules in USBR. It was found that the specific gravity of aerobic granules was increased and SVI was decreased with the increase of hydrodynamic shear force (Figure 2.13). High granule density and low SVI ensure the good solid-liquid separation. This enhances the operation of the process and the production of high quality effluent in the wastewater treatment.

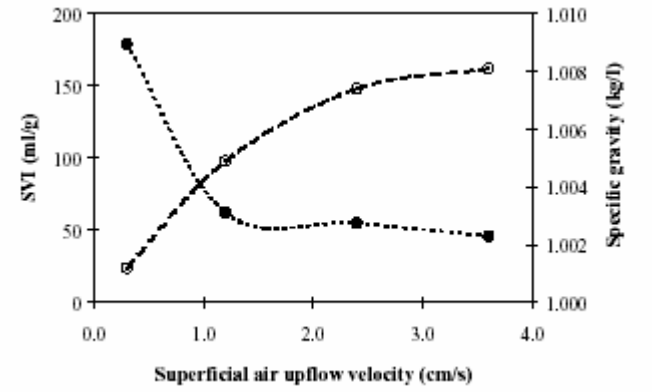



Figure 2.13 Effects of superficial air upflow velocity on the specific gravity and SVI of aerobic granules developed in USBR. (•): SVI; (■): specific gravity (Liu et al., 2002)

In addition to the above, the hydrophobicity and the polysaccharides of the granular sludge increase with increase in hydrodynamic shear stress (Tay et al., 2004). Hence, it could be concluded as the hydrodynamic shear force has significant effect on aerobic granulation and granule characteristics. Tay et al. (2001) state that the superficial air velocity had to be greater than 1.2 cm/s (43.2 m/h) to form aerobic granule in a reactor. Hence, this is one of the most important factors which influence the aerobic granulation process.

2.3.3.4 Settling time

At the end of each cycle of operation, the biomass in the reactor is allowed to settle before the effluent withdrawal. So, the fast settling granules are retained in the reactor while the slow settling granules are washed out from the reactor (Liu and Tay, 2004). Hence, the settling velocity is an important factor to maintain aerobic granules in the reactor. The

settling velocity of the sludge from the conventional system is usually less than 10 m/h while the settling velocity of the granular sludge is much higher than 10 m/h. In the aerobic granule cultivation process, the settling velocity of particles is chosen first to decide the settling time needed for the system (Beun et al., 2002).

Settling time (h) = [Settling height (m) / Chosen settling velocity (m/h)]

Table 2.6 Settling velocity, superficial air velocity and diameter of granule from different authors

| References | Beun et al., 2000 | Etterer and Wilderer, 2001 | Wang et al., 2004 | Liu & Tay, 2006 |
|---|---|---|---|---|
| Settling velocity (m/h) | 16.2 | 12.6-64.8 | > 32.7 | 17.6 |
| Superficial air velocity (m/h) | 86.4 | 72 | 63 | reduced from 60 – 19.8 |
| Granule size (mm) | 1 | 1.1-6.5 | 6-9 | 0.75 |
| Initial formation time (days) | 30 | 56 | 67 | 27 |

Source: Modified from Thanh (2005)

At short settling time, the production of extracellular polysaccharides and the cell surface hydrophobicity were improved (Tay et al., 2001). During another study by Liu and Tay (2006) it was found that the aerobic granules had stable operation with the reduced aeration rate in famine period. As such, settling time is an important factor for the cultivation of aerobic granules.

2.3.3.5 Different feeding strategy

The intermittent feeding of a system is more advantageous than that of the continuous feeding (Beun et al., 2002). The intermittent feeding favors the formation of compact and dense aerobic granules. Under starvation, microorganisms become more hydrophobic which facilitates microbial adhesion and aggregation in the reactor (Liu and Tay, 2004).

2.3.3.6 Extracellular Polymeric Substances (EPS)

The EPS promotes the cohesion and adhesion of cells and, maintain structural integrity of the biofilm where the proportion of EPS produced could be between 50-90% of the total organic substances present in the system (Wingender et al., 1999; Liu and Tay, 2002). Generally, the EPS includes bound EPS attached to cell wall and, soluble EPS suspended in bulk solution. The EPS contains various organic substances like Polysaccharide (PS), Protein (PN), DNA, humic acid and uronic acid which are used during the starvation condition of the micro organisms (Wang et al., 2006b).

The content of the polysaccharides was higher than the protein content present in the biofilm (Liu and Tay, 2002; Yang et al., 2004; Vandevivere and Kirchman, 1993). These in turn imply that the polysaccharides would highly play an important role in the attachment and self-immobilization processes of bacteria rather than the proteins (Wingender et al., 1999). The ratio of polysaccharides to proteins (PS/PN) depends on hydrodynamic shear force (Tay and Liu, 2002), inhibitor such as ammonia (Yang et al., 2004), and independent of surface charge (Wang et al., 2006b; Zhang et al., 2007).

Also, the intermittent feeding of the system favours the EPS production compared to the continuous feeding (Wang et al., 2006b).

2.3.3.7 Cell surface hydrophobicity

Cell self immobilization and attachment process mainly depend on the cell surface hydrophobicity in which hydrophobicity is induced by culture conditions (Liu et al., 2003). Cell hydrophobicity is determined by the contact angle (CA) measurement of microbial adhesion to hydrocarbon in form of liquid or solid (Liu et al., 2004). The cell hydrophobicity is classified into three categories as follows:

- $CA > 90^o$ : hydrophobic surface
- $50^o < CA < 60$ : medium hydrophobic surface
- $CA < 40^o$ : hydrophilic surface

The cell hydrophobicity for the glucose-fed and the acetate fed aerobic granules were 68% and 73% respectively while for the suspended seed sludge it was only about 39%. Hence, the cell hydrophobicity of aerobic granules was about two times higher than that of the suspended seed sludge (Tay et al., 2003). If a system is exposed to high free ammonia, the nitrifying bacteria can not form granules due to the low surface hydrophobicity. On the other hand some of the other studies found that the starvation conditions in aerobic granules could facilitate the cell surface hydrophobicity which could favor the microbial adhesion and the aggregation (Tay et al., 2001; Liu et al., 2004).

2.3.3.8 Organic loading rate

Too high or too low OLR appears to be unfavorable for the formation of a compact sludge bed, and to maintain the stability of performance of the reactor. Tay et al. (2003) found that the best aerobic granules were cultivated at 4 kg COD/ $m^3$.day with size of 5.4 mm, SVI of 50 mL/g and COD removal rate of 99%. At OLR of 1 kg COD/ $m^3$.day only the patchy flocs and at OLR of 8 kg COD/ $m^3$.day both granules and fluffy flocs were observed. Another recent study found that the SVI of the granular sludge was increased with increasing OLR but the mean diameter of the granules was reduced (Kim et al., 2008). This too shows that there is an optimum OLR for the granular sludge operation.

Another author Moy et al. (2002) investigated the effects of OLR with the physical characteristics of aerobic granular sludge and identified that the acetate fed system could create the compact spherical morphology of granules at OLR of 6 and 9 kg COD/ ($m^3$.day) and at low OLR loose fluffy morphology dominated by the filamentous bacteria.

2.3.3.9 Mineral cations

According to Liu and Fang (2003), the mineral cations could affect bioflocculation, settling and dewaterability of the granular sludge. Wang et al., 2004 found that most of the metal elements in the sludge change significantly during the start-up operation because of the different chemical composition of the influents. The amount of calcium and potassium increases in matured aerobic granules. Hence, calcium may play an important role in cultivation of aerobic granular sludge.

Table 2.7 Metal elements in the sludge (mg/g) (Wang et al., 2004)

| **Type** | K | Na | Ca | Mg | Fe | Cu | Mn | Co | Zn |
|---|---|---|---|---|---|---|---|---|---|
| **Seed sludge** | 9.60 | 9.16 | 30.20 | 5.93 | 26.40 | 0.23 | 0.37 | 0.024 | 1.12 |
| **Matured sludge** | 43.58 | 8.00 | 45.70 | 2.58 | 0.76 | 0.01 | 0.01 | 0.012 | 0.17 |

#### 2.3.3.10 Starvation conditions

The SBR system consists of four phases in a cycle of operation namely feeding, aeration, settling and supernatant withdrawal. During the aeration phase, the granules start to degrade the substrate, produce EPS and then starve due to depletion of substrate. Under this starvation condition, the microorganisms become more hydrophobic which facilitates microbial adhesion and aggregation due to usage of EPS produced during the feminine period (Liu and Tay, 2004; Li et al., 2006). Another study confirms that the reasonable starvation time was necessary to maintain the long-term stability of the aerobic granules (Liu and Tay, 2007). Hence, during the starvation period, the microorganisms could produce stronger and denser granules.

#### 2.3.3.11 Inhibition to aerobic granulation by free ammonia

For most of the microbial community the high concentration of free ammonia is an inhibitor. Yang et al., (2004) investigated the effect of free ammonia to the granule formation which is tabulated in Table 2.8.

Table 2.8 Effects of free ammonia to aerobic granular sludge (Yang et al., 2004)

| **Reactor** | **R1** | **R2** | **R3** | **R4** | **R5** |
|---|---|---|---|---|---|
| N/C ratio | 5/100 | 10/100 | 15/100 | 20/100 | 30/100 |
| Free ammonia (mg N/L) | 2.5 | 9.2 | 18.0 | 23.5 | 39.6 |
| Granular size (mm) after 4 weeks | 0.51 | 0.32 | 0.25 | - | - |
| Morphology | Smooth, regular shaped dense | Smooth, regular shaped dense | Less smooth than R1, R2 | - | - |

High free ammonia inhibits nitrification, cell hydrophobicity, production of extracellular polysaccharides and nitrifying activity. Particularly, it reduces the cell hydrophobicity and the EPS which in turn affects the granulation process (Yang et al., 2004). Another finding from Yang et al. (2004) is high free ammonia concentration reduces the activities of nitrifying bacteria and the energy metabolism of heterotrophs. Metabolic activities of the heterotrophic bacteria are quantified by the specific oxygen utilization rate (SOUR) which decreases with increase of free ammonia.

#### 2.3.3.12 Substrate composition

In the aerobic granule formation a wide variety of substrates are being used including glucose, acetate, ethanol, phenol and synthetic wastewater. Moy et al. (2002) found that the glucose fed granules become irregular with folds, crevices and depressions at high organic loading rate. On the other hand, acetate fed granules shows the spherical compact morphology (Figure 2.14).

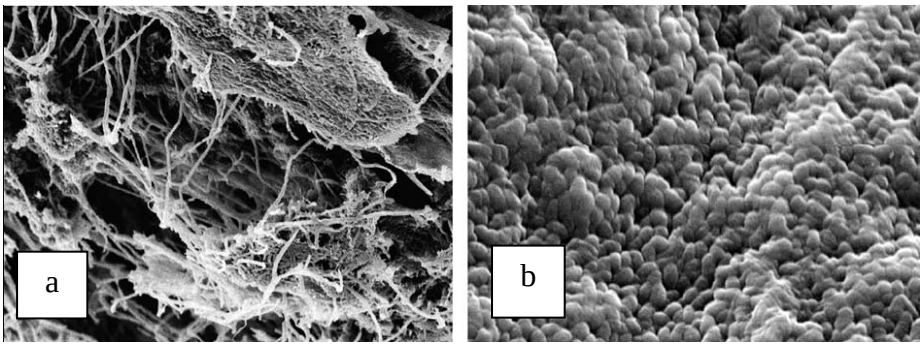



Figure 2.14 Aerobic granules grown on glucose (a) and acetate (b) (Tay et al., 2002)

#### 2.3.3.13 Volume exchange ratio

Volume exchange ratio or discharge depth is one of the important selected parameter which is the depth difference between influent and effluent point in the reactor. Wang et al. (2006a) reported that at the high volume exchange ratio the aerobic granules formation is faster than that of small volume exchange ratio. High ratio favors large size of granules with low SVI which leads to high settling ability. Moreover, the excessive production of EPS and, subsequent calcium accumulation at high volume exchange ratio was found to facilitate the formation and, further improvement of settleability of aerobic granules.

### 2.3.4 Application of aerobic granulation technology

The aerobic granulation technology is used for several applications such as organic and nitrogen removal, phosphorous removal, phenolic compound removal and heavy metal removal (Liu and Tay, 2004).

- Organic matter removal
  Aerobic granulation leads to high biomass retention in the reactor due to compact and dense structure of granules formed in the reactor. Initially at low loading fluffy loose filamentous bacteria was observed and at high loading it turn into irregular smooth shape granules in granulation process. These irregularities enhance the diffusion and penetration of nutrient and oxygen into the granules. Hence, high organic removal could be achieved.

- Simultaneous organic and nitrogen removal
  The aerobic granule consists of various microorganisms including heterotrophs, nitrifying and denitrifying bacteria. Due to the limitation of diffusivity of oxygen inside the granules both aerobic and anoxic zones exist (Pratt et al., 2007). Hence, simultaneous nitrification and denitrification is possible with the aerobic granulation technology.

- Phosphorus removal
  Environmental regulations in many countries limit the phosphorous concentration in the discharge wastewater to 0.5 – 2.0 mg/L. The common phosphorous removal process is the enhanced biological phosphorous removal (EBPR) process. To overcome the problems with conventional phosphorous removal process Lin et al. (2003) successfully developed phosphorous accumulating microbial granules.

- Recalcitrant removal in aerobic granular sludge (phenol)
  Phenol is not only a toxic substance but also the carbon source for bacteria. At the low concentration, phenol is biodegradable and at high concentration it could kill degrading bacteria. One of the advantages of granular sludge is that it could tolerate toxic loadings. Hence, the phenolic compounds can be treated with aerobic granules.

- Heavy metal removal
  Granules are ideal for absorption of heavy metals due to their physical characteristics including large surface area and high porosity for adsorption.

## 2.4 Aerobic Granulation Membrane Airlift Bioreactor

### 2.4.1 Development of membrane bioreactor

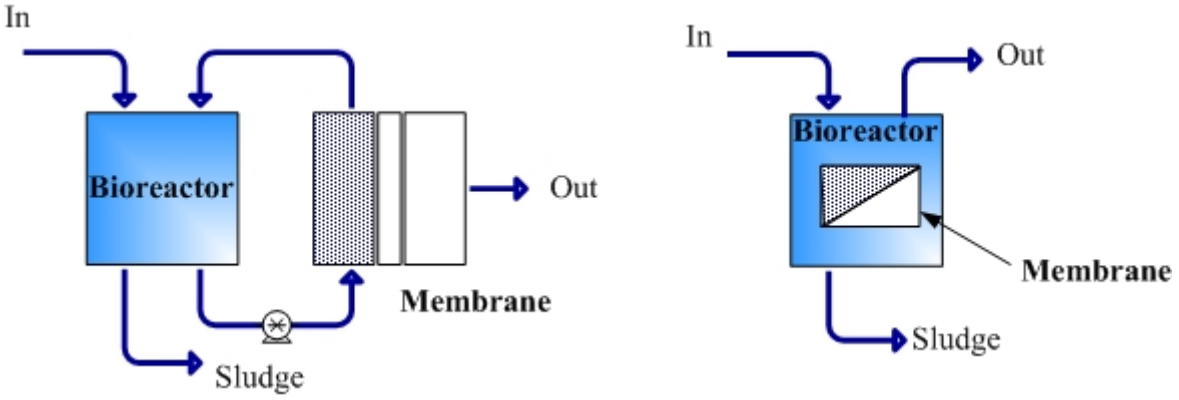
The conventional treatment process is robust and safe. At the same time the activated sludge process which is one of the mostly used conventional wastewater treatment processes, has the following major disadvantages.

- The treated water quality is dependant on the settling properties of the biological suspension. If the settling ability of the system is poor, it may result in presence of suspended solids in the treated water and a progressive washing out of the biomass from the bioreactor.
- The hydraulic retention time of the system is long. Hence, the volume of the tank has to be large which leads to large land requirement for the system.
- Insufficient germ removal or presence of persistent organic pollutants limits the reuse of treated waters.

Nowadays, due to the water scarcity the water reuse and recycling are becoming more and more popular. As such, an advanced treatment is required with the following properties (Wisniewski, 2007).

(i) Disinfection without any oxidation step that induces carcinogen molecule formation,
(ii) Possibility of compactness to optimize aesthetics, environmental impact,
(iii) Reliability notwithstanding the influent characteristic variation,
(iv) Standards regarding sustainability (energy, chemicals and waste production).

One such advanced treatment technique widely used nowadays is “Membrane Bioreactor” (MBR). The MBR process consists of suspended growth biological process combined with the membrane filtration which can be located either externally or submerged in the bioreactor (Figure 2.15). Even though the configuration is simple, the energy demand for this system is high. In general, permeate is extracted by suction or, less commonly, by pressurizing the bioreactor. In the external circuit, the membrane could be either outer- or inner skinned, and permeate is extracted by circulating the mixed liquor at high pressure along the membrane surface. On the other hand a submerged membrane system should be outer-skinned.




External Bioreactor Submerged Bioreactor

Figure 2.15 Solid/liquid separation MBR (Modified from Wisniewski, 2007)

### 2.4.2 Advantages of MBR process

With the conventional wastewater treatment it is difficult to achieve a good quality of effluent which could be used for appropriate purposes. In order to overcome this problem membrane technology is introduced, especially the membrane bioreactor (MBR). The MBR is a combination of the activated sludge process (ASP), and a membrane system. The membrane system replaces the traditional gravity sedimentation tank in the activated sludge process (ASP). This system carries several advantages as tabulated in Table 2.10.

Table 2.9 Advantages of MBR over conventional activated sludge process (Modified from Visvanathan et al., 2000)

| **Advantages** | **Details** |
|---|---|
| High rate decomposition | • Dissolved organic substances with low molecular weight can be removed by membrane filtration<br>• Treatment efficiency is improved due to prevention of leakage of un-decomposed polymer substances |
| Treated water quality | • The substrate conversion rate is 15-20 fold higher than that of CASP. Generally, MBR produce effluent with less than 5 mg/L $BOD_5$ (Stephenson et al., 2000; Visvanathan et al., 2000).<br>• Due to solid/liquid separation the suspended solid content in the effluent is very low. Hence, the effluent could be reused for cooling, toilet flushing, watering or process water. |
| Flexibility in operation | • SRT can be controlled independently. Hence the system can be run at long SRT which will provide favorable conditions for slow growing microorganisms. These microorganisms are capable of degrading bio-refractory compounds and controlling membrane fouling. |
| Compact plant size | • The system can withstand high volumetric loading due to high biomass concentration in the reactor (up to 40g/L). This will compact the size of the reactor.<br>• Also secondary settling tank, filter, sludge thickener or post treatment can be eliminated. |
| Low sludge production rate | • Low F/M ratio and longer SRT (from 50 to 100 days) causes low sludge production. |
| Disinfection | • The removal of bacterial and viruses can be achieved without any chemical addition according to membrane pore size. |

### 2.4.3 Aerobic granule membrane airlift bioreactor

To achieve further nitrogen removal in addition to the above mentioned advantages of MBR, a membrane airlift bioreactor (MABR) system could be used. MABR could treat nitrogenous substances through simultaneous nitrification and denitrification than that of MBR alone due to its configuration where both aerobic and anoxic zones exist.

Many researches have found that the thick membrane aerated biofilm can simultaneously provide favorable conditions for both nitrification (near the membrane) and denitrification (near the biofilm-liquid boundary) within a single biofilm (Gong et al., 2007). The microorganisms in the MLSS like Aspidisca, Vorticella, Suctoria, Rotifer, and Aeoloosma hemprichii, increase the removal efficiencies of nitrogen and organic matter (Fan et al., 2006 and Gang et al., 2007)

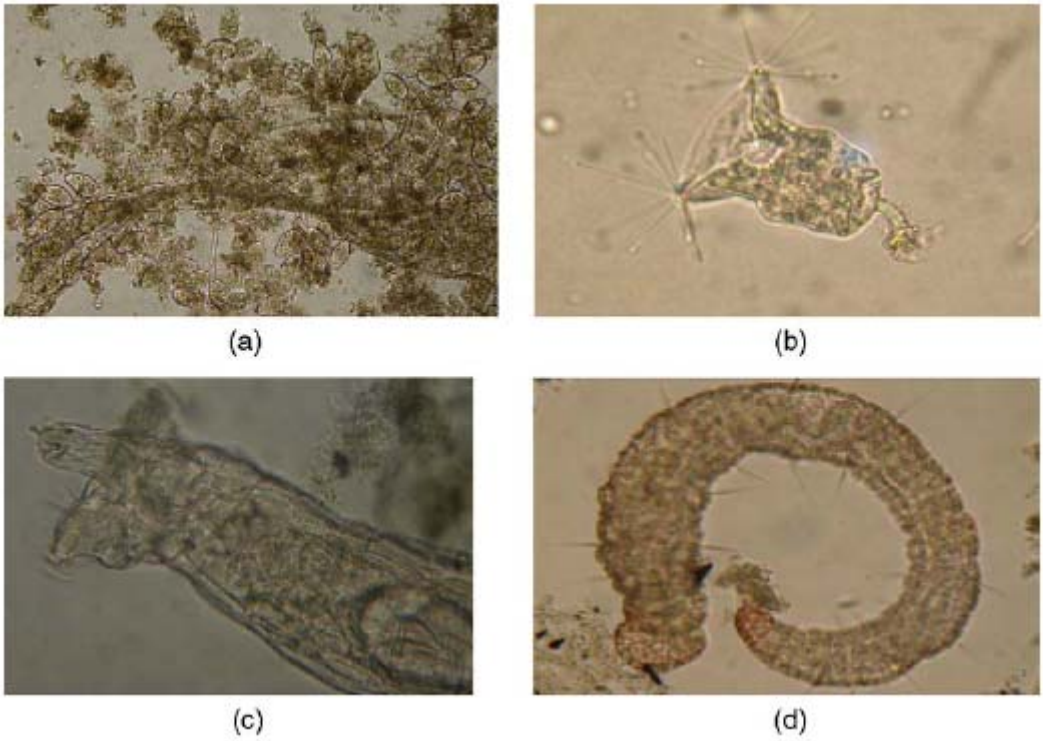



Figure 2.16 Microscope photographs of microorganisms (a) Voricella (b) Suctoria (c) Rotifier (d) Aeoosoma hemprichii

Even though the MABR system has several benefits it has disadvantages too; namely weak sludge settling characteristics due to fine size of sludge flocs and membrane fouling. To avoid the above mentioned drawbacks, MABR is coupled with aerobic granulation and developed a new technology called aerobic granule membrane airlift bioreactor. Since aerobic granules are denser and regular in structure, they have excellent settling ability, high biomass retention and ability to withstand high organic and nitrogen loading rate. Hence, the system is expected to reduce the power consumption needed to supply oxygen for the system, enhance nitrogen removal from wastewater without the need of expansion of facilities, and reduce supply of external carbon source for nitrification, operational expenses and space requirements (Jang et al., 2003).

The aerobic thermophilic bacterial process have several advantages including low waste biomass production, high degradation rates, reduced aeration basin volume, and elimination of cooling requirements for high temperature wastes. However the application of this process is limited due to poorly settled (by gravity) biomass characteristics. Further the aerobic thermophilic biomass showed good settling characteristics in sequencing batch reactors (SVI around 60 mL/g) (Zitomer et al., 2007).

The combination of aerobic granulation and membrane bioreactor could eliminate or lower the concentration of floc sludge which would reduce the membrane fouling. Furthermore, due to existence of anaerobic environment in aerobic granules, denitrification of nitrate nitrogen could be achieved (Li et al., 2005). When compared with MBR alone, aerobic granule MBR has several advantages including good filtration characteristics of mixed liquor, low permeability loss, and less frequent fouling (Tay et al., 2007).

2.4.4 Membrane Fouling

2.4.4.1 General

The membrane fouling that result in a decrease of the performance of a membrane, caused by the deposition of suspended or dissolved solids on the external membrane surface, on the membrane pores, or within the membrane pores, lead to flux decline. As the resistance increases the flux declines in the membrane system. This increase in resistance may be due to concentration polarization, adsorption, gel layer formation, plugging of pores, etc. Membrane fouling can result from scaling, adsorption of organic substances, and bio fouling. Membrane fouling could result from the formation of a polarization cake layer and the plugging of membrane pores (Figure 2.17).

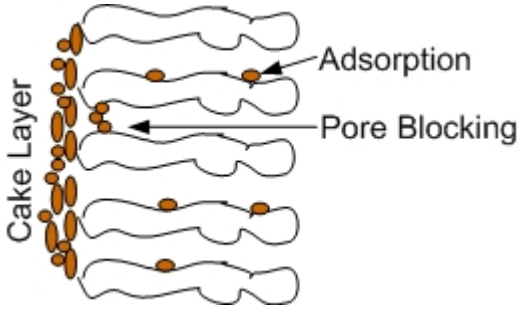



Figure 2.17 Schematic Diagram of Membrane fouling

Effect of membrane fouling on the decline of permeate flux could be explained by the resistance-in-series model. As per this model, the relationship between permeate flux and Trans membrane pressure (TMP) is described by the following equation 2.1.

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

Where,
J: Permeate flux ($m^3/m^2.s$)
$\Delta P$: Transmembrane pressure (Pa)
$\mu$: Viscosity of the permeate (Pa.s)
$R_t$: Total resistance for filtration (1/m)

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

Where,
$R_m$: Intrinsic membrane resistance
$R_c$: Cake layer resistance
$R_f$: Fouling resistance due to irreversible and pore plugging

Characteristics of the cake layer play an important role in membrane fouling. Effects of cake layer characteristics could be described by the Carman-Kozeny equation as follows (Liew et al., 1995):

$$P_h = \frac{d_p^2 * \varepsilon^3}{180(1-\varepsilon)} \qquad \text{Eq. 2.3}$$

Where,
$P_h$ : Hydraulic permeability through the cake layer
$d_p$: Particle diameter
ε: Porosity of the cake layer

Based on this model, it is evident that greater the particle size and porosity, the higher the permeability. Many attempts had been conducted to improve the permeability of the cake layer by the addition of filter aids such as metal-based coagulants into reactor (Visvanathan et al., 2000). These filter aids were expected to form a dynamic cake layer on the membrane surface. The permeability of the dynamic cake layer was thought to be higher due to larger particle size and porosity. The porous layer also acted as a filter layer to retain soluble organic compounds preventing them from contacting and plugging in the membrane pores.

According to Le-Clech et al. (2006) the fouling mechanism in MBR could be discussed based on two different conditions namely, constant TMP operation and constant flux operation. The constant TMP operation consists of three phases namely, (i) an irreversible fouling caused by soluble fraction of biomass (rapid flux decline), (ii) deposition of sludge particle on the membrane surface (slow flux decline) and (iii) severe fouling due to increase in cake resistance (stable flux). The constant flux operation has three stages of membrane fouling namely conditioning fouling, steady fouling, and TMP jump.

Le-Clech et al. (2006) and Rosenberger et al. (2006) had identified several factors which contributed to membrane fouling and mitigation measures to overcome this problem. They are described in the following diagram.

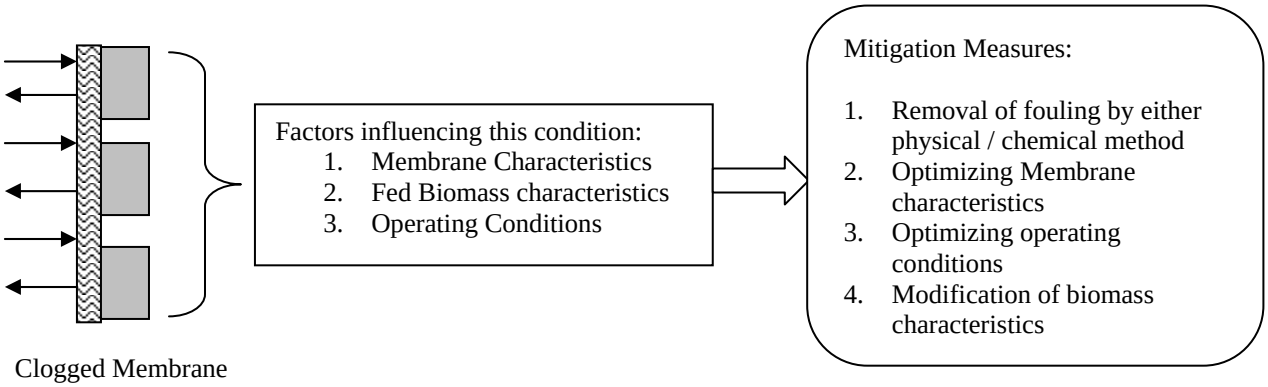



Figure 2.18 Factors influencing membrane fouling and mitigation measures

2.4.4.2 Membrane Characteristics

1. Physical parameters
   Membranes with small pores reject various ranges of materials which in turn result high cake layer resistance in membrane surface compared to membranes with large pores. However, due to deposition of organic and inorganic material inside the membrane pores, the large pore membranes shows poor long term performance. Further the rougher membranes are more prone to membrane fouling when compared to the smoother ones. Membrane configuration too plays an important role in fouling. The hollow fibres type has high possibility for fouling compared to the tubular type membrane which leads to frequent washing and cleaning of membrane (Le-Clech et al., 2006).

2. Chemical parameters
   Generally, the membrane fouling is severe in hydrophobic than the hydrophilic membranes. Type of membrane material also influences membrane fouling when polymeric based membranes are normally used in MBR application. Once the membrane is initially fouled the chemical characteristics become secondary (Le-Clech et al., 2006).

2.4.4.3 Fed-biomass characteristics

1. Feed composition
   The composition of feed water too influences the fouling rate. For example saline water (Tam et al., 2006) and synthetically fed MBR (Le-Clech et al., 2003) has resulted high fouling rate.

2. Biomass parameter
   The activated sludge biomass could be fractionated into three parts namely suspended solids, colloids and solutes. Each part of biomass fraction influence fouling in different rate. MLSS might not play a significant role in membrane fouling at low fluxes. Furthermore, MLSS alone is a poor indicator of biomass fouling propensity (Le-Clech et al., 2006).

   Viscosity is another important factor which affects biomass concentration. The increase in viscosity would lead to reduction of the mass transfer of oxygen which results in high fouling propensity (Germain and Stephenson, 2005). Hence, fouling is high at low dissolved oxygen concentration. At low temperature the deposition of materials on the membrane surface is high as the viscosity increases with decrease in temperature (Rosenberger et al., 2006).

3. Floc characteristics
   Several researches found that floc size distribution of MBR sludge is lower than that of conventional sludge. Larger size of floc could not directly block the pore entrance, while the biological flocs play major role in forming fouling cake on the membrane surface. Furthermore, the fouling resistance which is caused by microbial floc increases with the SRT, contact angle, and surface charge (Le-Clech et al., 2006).

   It was found by Jun et al. (2007) that the aerobic granular sludge could result in severe membrane pore-blocking, while the activated sludge could cause severe cake fouling. The major components of the foulants were identified as proteins and polysaccharide materials.

   Another study by Winsniewski and Grasmick (1998) concluded that intensive recirculation of biomass results floc breakage which causes poor settleability of suspension and increase in micro flocs in the reactor. This increases the potential for fouling of membrane.

4. Extracellular polymeric substances (EPS)
   EPS are the construction material for microbial aggregation. The main function of EPS is to aggregate bacterial cells, protect the bacteria and retain water and adhesion to surface. Many researches indicated that the EPS is the most significant factor which is affecting membrane fouling. With time, the thickness of biofilm increases, leading to

aerobic and anaerobic condition in the biofilm layer. The amount of EPS production is high at the transition location between aerobic to anaerobic which leads to membrane fouling. Especially, high concentration of polysaccharides induces high fouling in the submerged MBR system (Rosenberger et al., 2006)

5. Soluble microbial products (SMP)
   SMP are organic compounds consisting of proteins, polysaccharides and organic colloids which are produced during substrate utilization during biomass growth and then released during cell lysis. Due to hydraulic shock loads, low pH, nutrient deficiency and presence of toxic compounds the SMP was formed (Jarusutthirak and Amy, 2007; Rosenberger et al., 2006). SMP level in the MBR sludge is high due to retention of large amount of macromolecules on the membrane surface. So far, the effect of protein in SMP retained on to the membrane surface is reported rarely when compared to polysaccharides. However, it is presumed that it will play an important role in membrane fouling (Le-Clech et al., 2006).

   Another research by Liang et al. (2007) under took an experiment to observe the SMP effect on membrane fouling behavior for different SRTs. From this study, they had found that the accumulation of SMP is high when the SRT is low, majority of the SMPs are hydrophobic which increases with long SRT and the fouling potential increase when the SRT is shortened.

   Further, Winsniewski and Grasmick (1998) identified that the hydrodynamic shear force which is created in the reactor and biological conditions like pH, Nutrients, temperature could change the biological suspension. Hence, the soluble substances plays significant role in membrane fouling.

6. Fraction of Sludge
   Fraction of sludge could be classified into three such as solids, colloids and solutes. Several reaches had been done to observe the fouling potential of each fraction of sludge. Results from Bouhabila et al. (2001)'s study shows that the liquid fraction of sludge, i.e., solutes and colloids, plays a crucial role in membrane fouling and the specific resistance of liquid fraction is 10 times higher than that of total resistance.

Table 2.10 Fouling behavior of different sludge fractions

| **Reference** | **Fraction (%)** | | |
|---|---|---|---|
| | **Solids** | **Colloids** | **Solutes** |
| Wisniewski, & Grasmick, 1996 | 26 | 50 | 24 |
| Defrance, 1997 | 5 | 30 | 65 |
| Bouhabila et al. (2001) | 52 | 25 | 23 |

Source: Bouhabila et al. (2001)

From the results appearing in the above table, if is difficult to compare as it depends on the operating conditions and analytical methods.

As per to Rosenberger et al. (2006), the liquid portion (colloid and solute) of sludge, especially polysaccharides and proteins, have high fouling potential compared to solid portion of the sludge. Further, high polysaccharide concentration in sludge supernatant causes high degree of fouling while low concentration result low degree fouling.

2.4.4.4 Operating conditions

1. Aeration
   Aeration in Membrane system has several functions including providing oxygen to the biomass, maintaining the activated sludge in suspension and mitigating fouling. The aeration causes shear at the membrane surface which prevents large particle deposition. In hollow fibre membrane the aeration could help to overcome the high packing density of material on the membrane surface (Le-Clech et al., 2006). As mentioned above, the degree of aeration could affect the diffusivity of oxygen into the biofilm which leads to high EPS production. Hence, the membrane fouling is severe due to increase in EPS. Li et al. (2007) found that the strong aeration is less important in preventing membrane fouling. They further stated that low aeration increases the bio-granule diameter and reduces the energy consumption.

2. Solid retention time (SRT)
   The biomass characteristics are controlled by SRT which would be the most important parameter impacting on degree of membrane fouling. Long SRT favors high MLSS concentration which leads to membrane fouling (Chang et al., 2002). On the other hand Liang et al. (2007) found that increase in nitrogen and organic removal efficiencies (Han et al., 2005), results in decrease in specific utilization rate, SMP accumulation and fouling rate at high SRT where no effect was observed for reverse osmosis and nano filtration (Jarusutthirak and Amy, 2006).

   According to Han et al. (2005), SRT between 50 to 70 days was the best range to have high removal efficiencies in terms of organic and nitrogen species and high sludge activities.

2.4.4.5 Mitigation measures

Membrane fouling could be reversible or irreversible depending on the degree of fouling. The reversible fouling could be overcome with physical treatment such as membrane relaxation and backwashing. Backwashing could be done either by water or air where air backwashing is the efficient method for flux recovery. However, it may cause breakage of membrane. The irreversible fouling which is caused by adsorption of dissolved matter into membrane pores which could be removed by chemical cleaning (Chang et al., 2002). Further, the fouling could be controlled by optimizing the membrane characteristics; optimizing operational conditions namely aeration, flux; and modifying biomass characteristics (Le-Clech et al., 2006).

However, the development of MBR treatment is limited due to problems such as fouling, energy cost, cleaning cost, etc. Hence, the MBR is coupled with aerobic granulation to overcome these problems. It is noted that only few scientists (Tay et al., 2007 and Li et al., 2005) had done the research on the membrane bioreactor coupled with the aerobic granulation. Further, the nitrogen removal from wastewater is more challenging treatment process at the present. Hence, the research on this aspect was untaken to investigate the nitrogen removal and fouling of an aerobic granular membrane airlift bioreactor which will be an attractive solution for water reuse in near future.

# CHAPTER 3

# METHODOLOGY

In this chapter the materials and methods used to investigate the (i) simultaneous nitrification and denitrification in MABR, (ii) the organic removal and nitrogen removal patterns in the batch granulation MABR system, and (iii) the membrane fouling behavior of MABR at various nitrogen concentrations and granulation supernatant through MABR system are described. The lab scale experimental setup was installed at the environmental engineering ambient laboratory, to determine the performance of the aerobic granular MABR system.

## 3.1 Overall Experimental Process

The overall experimental work of this research was characterized into three parts namely,

(1) Performance evaluation of MABR
Different nitrogen concentrations were fed into the MABR to evaluate the performance based on nitrogen removal efficiency.

(2) Characterization of aerobic granules
The aerobic granules were characterized based on physical, chemical and biological characteristics such as settling velocity, sludge volume index, morphology, bound EPS, microbial observation and granule fractions for different feeding conditions.

(3) Determination of fouling behavior of MABR
Fouling behavior of MABR depends on several factors as presented in the Figure 3.1. In this study, as described in the Figure 3.1, some of the factors were fixed while some others were varied and measurements were taken accordingly to investigate the objectives of this research.

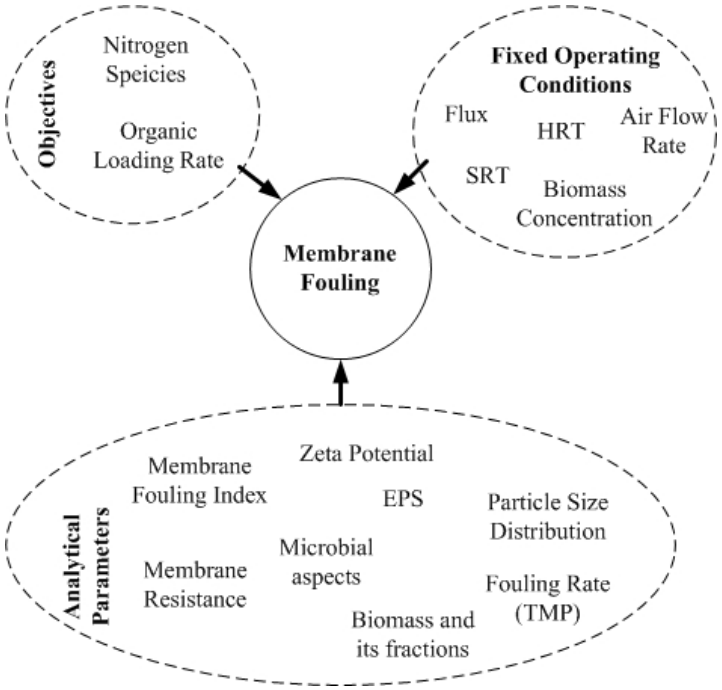


Figure 3.1 Factors effecting membrane fouling

The results obtained were used to determine the performance of the aerobic granular MABR system (Figure 3.2) based on organic and nitrogen removal efficiencies and membrane fouling pattern.

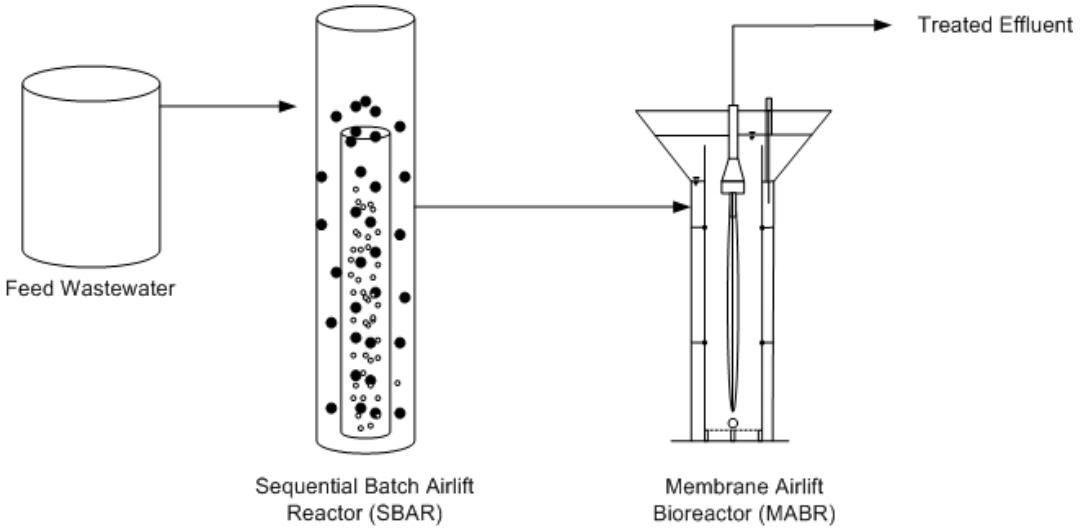



Figure 3.2 Overall Experimental Setup

## 3.2 Sequencing Batch Airlift Reactor (SBAR)

The SBAR was used to cultivate the aerobic granules due to its capability of thorough mixing and intermittent feeding of substrate which is more advantageous than that of biofilm airlift suspension reactor (BASR), which is a continuous feeding system (Beun et al., 2002). The aerobic granules were cultivated by synthetic wastewater with organic and nitrogenous sources in SBAR with initial OLR of 2 kg COD/$m^3$.d and NLR of 0.6 kg N/$m^3$.d. The organic loading rate was varied to 4 kgCOD/$m^3$.d with the NLR of 0.4 kgN/$m^3$.d (Figure 3.3).

The operation of SBAR consists of five cycles in 4 hours such as feeding of synthetic wastewater, high aeration, low aeration ("denitrification" stage), settling of granules and withdrawal of supernatant. High and low aeration rates of the cycle were 10.2 L/min (59 $m^3/m^2$/h) & 0.5 L/min (2.9 $m^3/m^2$/h) respectively. The low aeration was to achieve the sufficient mixing and denitrification in the granule core.

Table 3.1 Cycles of SBAR

| **Cycle (4 h)** | Feeding | High Aeration (10.2 L/min) | Low Aeration (0.5 L/min) | Settling | Withdrawal |
|---|---|---|---|---|---|
| **Time (min)** | 6 | 180 | 48 | 3 | 3 |

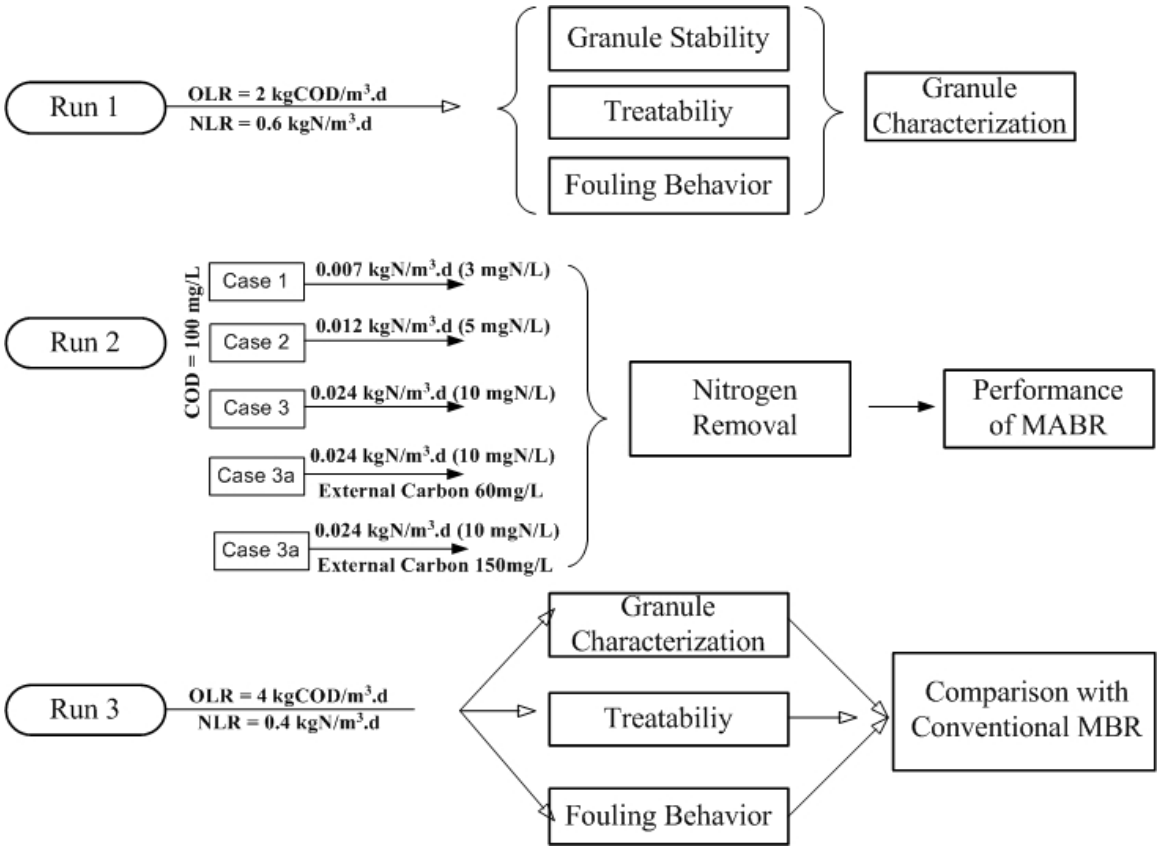



Figure 3.3 Experimental runs of the aerobic granule MABR

Table 3.2 Details of SBAR and MABR

| Reactor | Unit | SBAR | MABR |
|---|---|---|---|
| Size | mm x mm | Raiser: LxD = 1300 x 115<br>Down comer: lxd = 900 x 70 | Height = 620<br>Refer Figure 3.5 |
| Working volume | L | 9.7 | 13.0 |
| HRT | h | 7.3 | 10.4 |
| SRT | days | Depends on OLRs | 20 |
| Air flow rate | $m^3/m^2/h$ | Aeration: 59<br>Low aeration: 2.9 | 3.8 |
| Sludge removal | mL /day | Automatic removal with supernatant | 375 |
| Flow rate | L /day | 31.8 (5.0 L/batch, 4 h/batch, 6 batch/day) | 40.32 L/day<br>(28 mL/min, 7 On/ 3 Off) |
| Flux | $L/m^2/h$ | NA | 2.8 |

NA – Not Applicable

### 3.3 Membrane Airlift Bioreactor (MABR)

The detail design drawing of MABR is illustrated in Figure 3.5. Reactor was made up of transparent acrylic plastic material and the details of operational conditions are listed in Table 3.2. In the Run 2 (Refer Figure 3.3), the MABR was fed separately to evaluate the performance of the MABR based on nitrogen removal efficiency. Then in the Run 3, the supernatant of 5.3 L from SBAR was sent to the MABR in every 4 hours cycle. The influent for MABR was pumped from the SBAR which was operated with 7 minutes on / 3 minutes off filtration cycle. In MABR, the remaining substrate was consumed to treat unsettled colloids and biomass from the SBAR. SRT of MABR was fixed at 40 days by

withdrawing 375 mL of mixed liquor daily. The hollow fiber micro filtration membrane module was used in this experiment. The characteristic of the membrane module is tabulated in Table 3.3. The membrane is STRERAPORESUR Series of hollow fibre membrane units from Mitsubishi Rayon, Japan.

Table 3.3 Characteristics of membrane module

| Specification | Characteristics |
|---|---|
| Membrane material | Poly Ethylene |
| Membrane type | Submerged hollow fibre |
| Pore size | 0.1 μm |
| Surface area | 0.42 $m^2$ |
| Dimension of membrane (D x L) | 4.5 cm x38 cm |

Source: Manufacturer, Mitsubishi Rayon Co. Ltd.

## 3.4 Food and Microorganisms

### 3.4.1 Feed Wastewater

The feed wastewater composition for SBAR and MABR for different runs is as listed below.

a. Sequencing Batch Airlift Reactor

The feed wastewater in this experiment was synthetic wastewater with the components of glucose, ammonium chloride, sodium bicarbonate, potassium phosphate and trace elements. The detail of these components indicating the concentration is listed in the Table 3.4.

Table 3.4 Composition of Feed Wastewater

| Medium | Component | Concentration (mg/L) |
|---|---|---|
| A | Glucose | 775 |
| B | $NaHCO_3$ | 2640 |
| C | $NH_4Cl$ | 745 |
| D | $KH_2PO_4$ | 50 |
| E | $CaCl_2.2H_2O$ | 30 |
| | $MgSO_4.7H_2O$ | 12 |
| | $FeCl_3$ | 4 |
| F | Trace Elements | |
| | $H_3BO_3$ | 150 |
| | $CoCl_2.6H_2O$ | 150 |
| | $CuSO_4.5H_2O$ | 30 |
| | $FeCl_3.6H_2O$ | 1500 |
| | $MnCl_2.2H_2O$ | 120 |
| | $Na_2Mo_4O_{24}.2H_2O$ | 60 |
| | $ZnSO_4.7H_2O$ | 120 |
| | KI | 30 |

The above values of the components are for OLR of 2 kg COD/$m^3$.d (700 mg/L) and NLR of 0.6 kg $NH_4^+$-N /$m^3$.d (195 mg/L). When increasing the loading rate to 4 kgCOD/$m^3$.d, concentration of Mediums A and D were proportionate to the organic matter except for Medium E, F and C. Being the nitrogen source, concentration of Medium C was kept constant at all organic loading to observe its removal efficiency in each loading rate. Medium B was varied with different loading rate to adjust the pH of the feed in the range of 7.6 ± 0.2.

b. Membrane Airlift Bioreactor

The feed wastewater for MABR during Run 2 was synthetic wastewater with the same feed components as in the feed wastewater of SBAR except $NH_4Cl$. The $NaNO_2$ and $NaNO_3$ were used instead of $NH_4Cl$ with the same concentration. The Concentration of $NaNO_2$ and $NaNO_3$ were varied for three different cases (3mgN/L, 5mgN/L and 10mgN/L) with constant COD of 100 mg/L to evaluate the performance of the MABR. Medium B was varied with different loading rate to adjust the pH of the feed in the range of 7.6 ± 0.2, similar to the feed of SBAR.

### 3.4.2 Carrier/Support Media

The carrier/support media for cultivation of aerobic granules was Bivalve Shell Carrier. This media was produced in Asian Institute of Technology (AIT) with bivalve shell of white rose cockle. Shell carrier is a good support media which assits microbial adhesion and granulation. The physical characteristics of bivalve shell carrier media is as follows:

- Density = 1.45 g/cm$^3$
- Settling Velocity = 55-300 m/h
- Color = White
- Size = 0.15-0.30 mm
- Components = Ca, Fe, & Mg
- Weight Loss (550$^o$C, 20 mins) = 2 %

The production process of bivalve shell carrier is illustrated in the Figure 3.4 below.

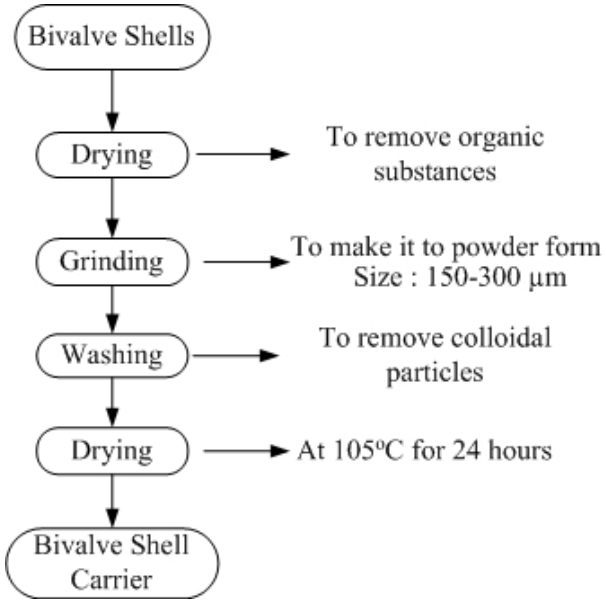



Figure 3.4 Production of Bivalve Shell Carrier Media

### 3.4.3 Microbial Seed

Seed sludge for the aerobic granulation was taken from the conventional activated sludge process of Thammasat University's wastewater treatment plant which is situated adjacent to AIT.

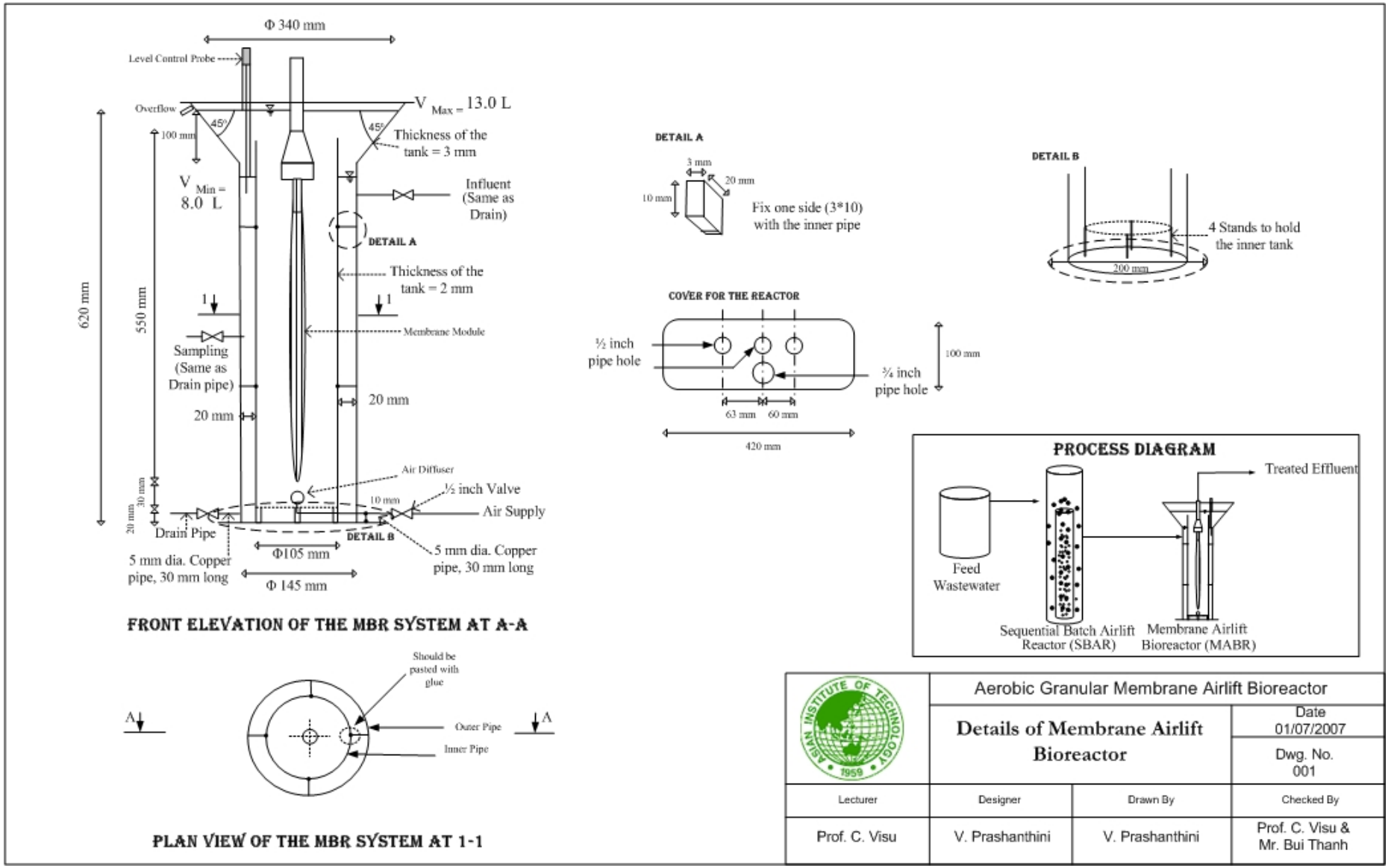
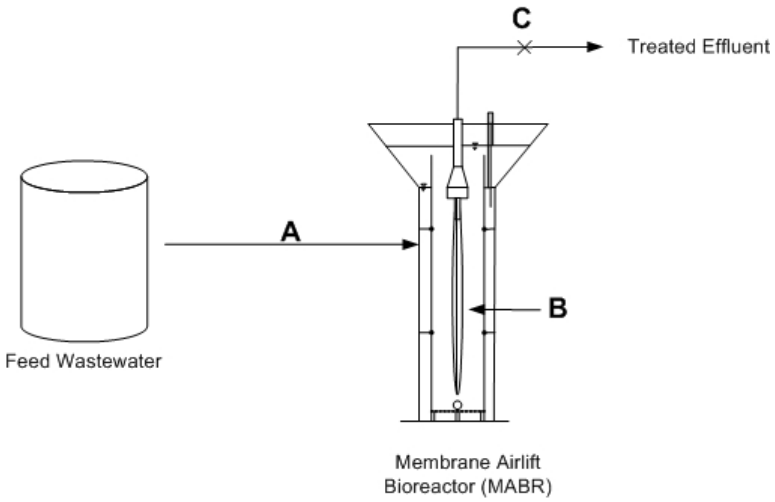



Figure 3.5 Design Details of MABR

### 3.5 Analytical Methods

The analyzed parameters are listed in the Table 3.5 for the sampling points indicated in Figure 3.6.

Run 2: Case 1, Case 2 & Case 3




Run1 and Run 3:

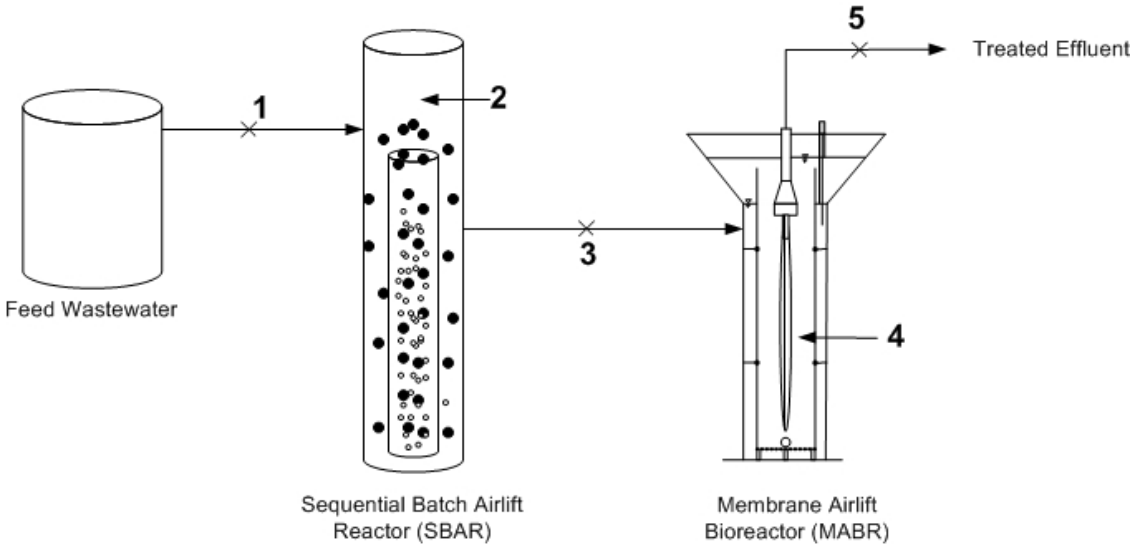



Figure 3.6 Sampling locations of the system

Table 3.5 Analytical Parameters based on Locations

| Location | Parameters |
|---|---|
| A | Total Organic Carbon (TOC), $NO_2$-N, $NO_3$-N |
| B | TOC, Bound PS & PN, SVI, MLSS, CST, Microbial Observation,Trans Membrane Pressure (TMP) |
| C | TOC, $NO_2$-N, $NO_3$-N |
| | |
| 1 | TOC, $NH_4$-N, $NO_2$-N, $NO_3$-N |
| 2 | Bound PS & PN, Solid Volume Index (SVI), MLSS, Settling Velocity, Ratio of $VSS_{granule}/VSS_{total}$, Microbial Observation |
| 3 | TOC, $NH_4$-N, $NO_2$-N, $NO_3$-N, Soluable PS & PN, Particle size distribution |
| 4 | TOC, Bound PS & PN, SVI, MLSS, CST, Microbial Observation, Trans Membrane Pressure (TMP), Particle size distribution |
| 5 | TOC, $NH_4$-N, $NO_2$-N, $NO_3$-N, Soluable PS & PN |

### 3.5.1 Membrane Cleaning and Membrane Resistance

Before starting the next run, the membrane was taken out of the reactor and cleaned. The simplified membrane cleaning procedure is shown in Figure 3.7.

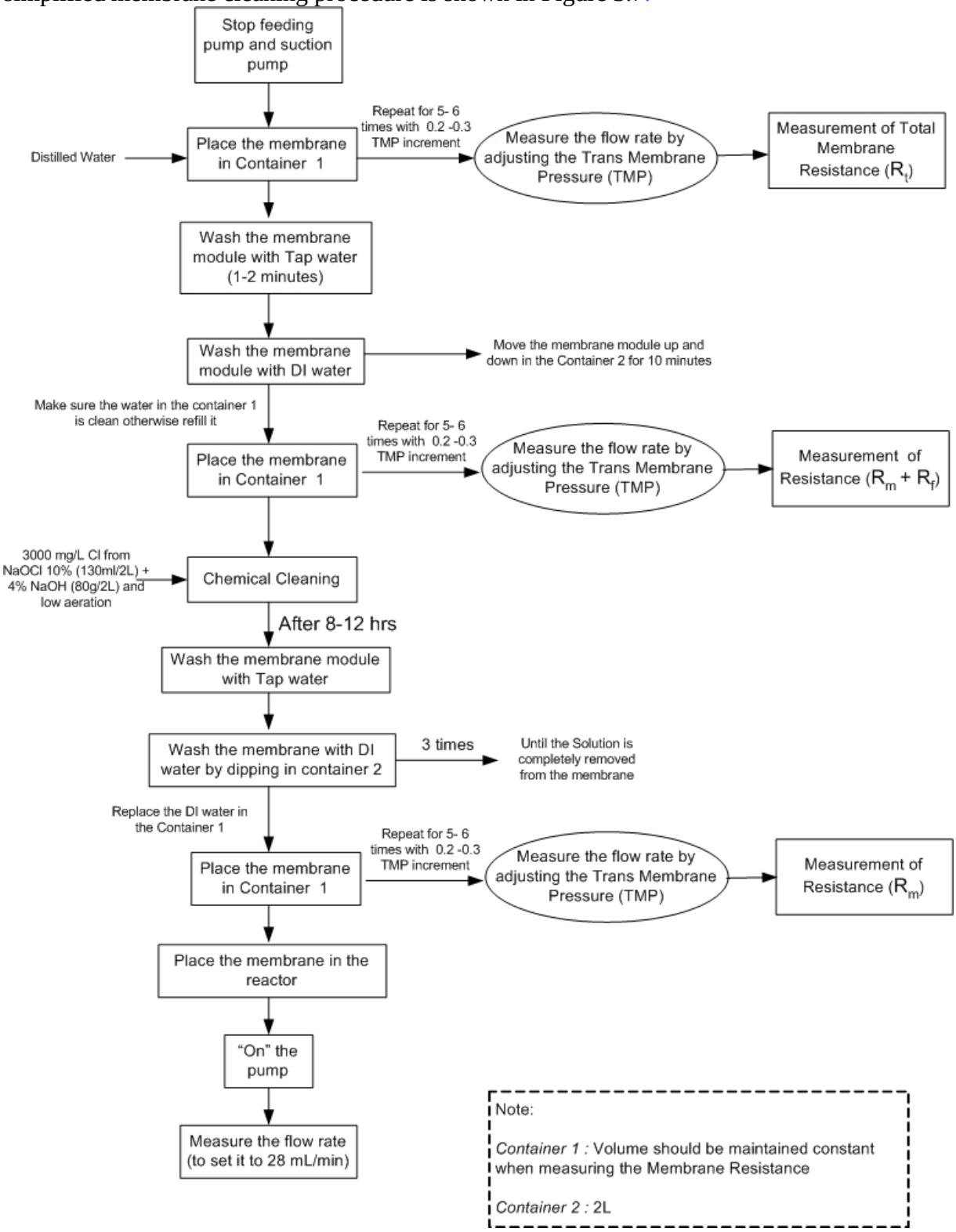



Figure 3.7 Procedure for Membrane Cleaning and Membrane Resistance Measurement Process

Membrane resistance was measured by using the resistance –in-series model (Choo and Lee, 1996 and Thanh, 2005). The membrane resistance was calculated from the slope of linear curve of ΔP versus permeate flux (J) from the following equation.

$$J = \frac{\Delta P}{\mu * R_t} \quad \text{Eq 3.1}$$

$$\Delta P = J * \mu * R_t \quad \text{Eq 3.2}$$

Where,

J : Permeate Flux ($L/m^2.h$)

ΔP : Trans Membrane Pressure (kPa)

μ : Viscosity of the Permeate (Pa.s)

$R_t$ : Total Resistance ($m^{-1}$); $R_t = R_m + R_c + R_f$

$R_c$ : Cake Resistance form by the Cake Layer ($m^{-1}$)

$R_f$ : Fouling Resistance caused by Solute Adsorption into the membrane Pores ($m^{-1}$)

### 3.5.2 Settling velocity

A plastic cylinder (6 cm in diameter and 90 cm in height) was filled with clear liquid phase of the reactor for free-settling test. Single granule was put into the cylinder and allowed to reach its final settling velocity at the upper 30 cm of the water column. Then the settling time for the distance of 50 cm was taken manually with accuracy of ± 0.5 s (Etterer and Wilderer, 2001).

### 3.5.3 Extracellular Polymeric Substances (EPS)

EPS are the necessary materials for microbial aggregation which has two forms namely soluble EPS and bound EPS. Soluble EPS was determined directly from filtered bulk liquor in term of mg/L. and on the other hand Bound EPS was determined in terms of polysaccharides (PS) and protein (PN) per mg VSS. Bound EPS was extracted by cation exchange resin (CER) named DOWEX 50 x 8, 20-50 mesh (sodium form) (Frølund et al., 1996). The detailed EPS extraction procedure is as Figure 3.8 and the CER resin specifications are listed in Table 3.6 and 3.7.

Table 3.6 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°C |
| pH range | 0-14 |

Table 3.7 Cation exchange resin buffer solution constituents

| **Chemical name** | **Concentration (mM)** | **Amount in 1 L DI water (g)** |
|---|---|---|
| $Na_3PO_4$ | 2 | 0.3280 |
| $NaH_2PO_4$ | 4 | 0.4800 |
| NaCl | 9 | 0.5265 |
| KCl | 1 | 0.0746 |

*Calculation Procedure:*

For PS:

| | |
|---|---|
| Polysaccharides concentration in sample | = A mg/L |
| PS from EPS extracted solution X litre | = AX mg |
| MLVSS of the sample | = B mg/L |
| MLVSS if the mixed liquor volume is C litre | = BC mg |

$$PS(\frac{mg}{gVSS}) = \frac{PS(mg)}{MLVSS(mg)} * 1000 = \frac{AX}{BC} * 1000$$

For PN:

| | |
|---|---|
| Protein concentration in sample | = A mg/L |
| PN from EPS extracted solution X litre | = AX mg |
| MLVSS of the sample | = B mg/L |
| MLVSS if the mixed liquor volume is C litre | = BC mg |

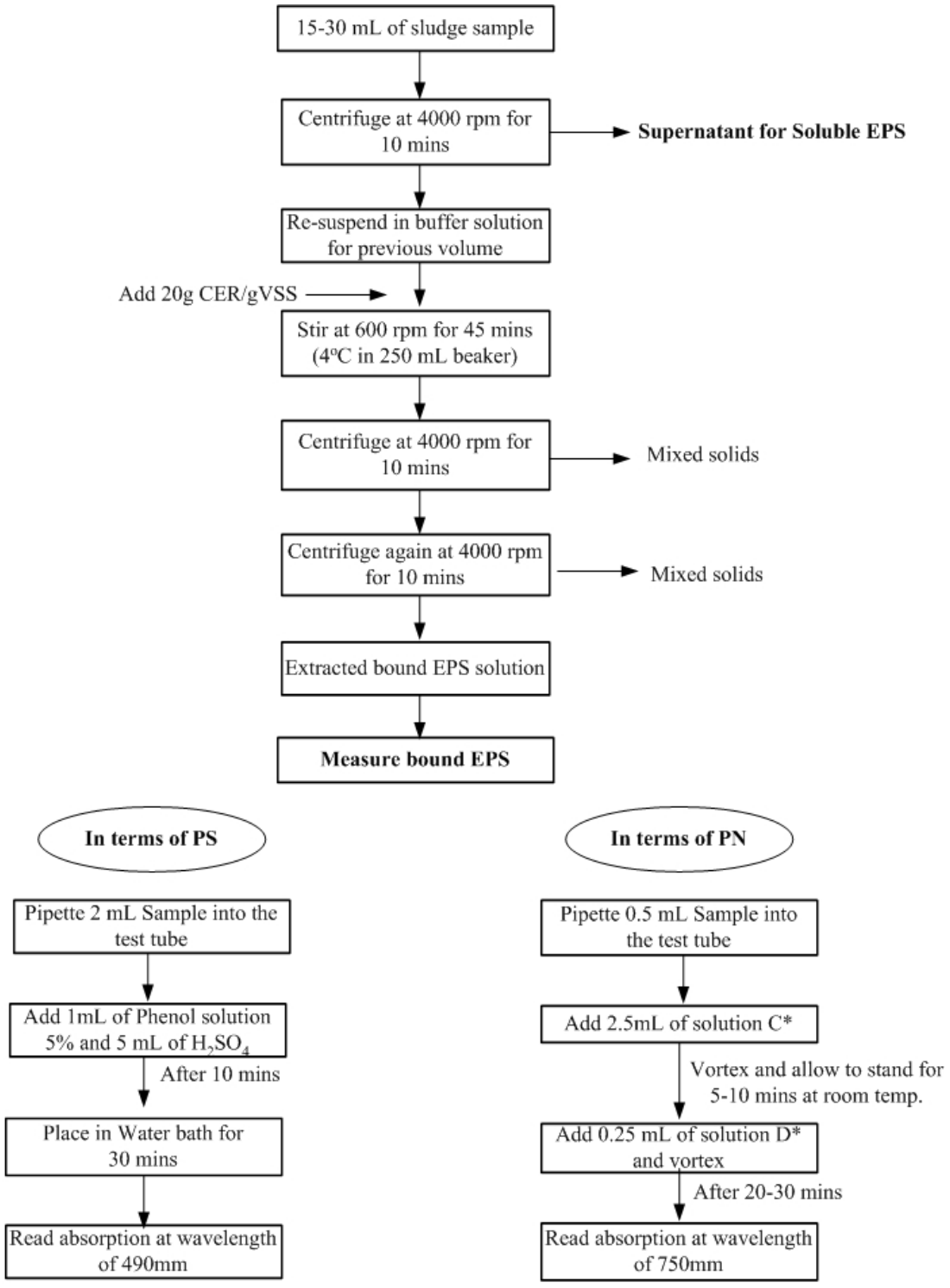
$$PN(\frac{mg}{gVSS}) = \frac{PN(mg)}{MLVSS(mg)} * 1000 = \frac{AX}{BC} * 1000$$

3.5.4 Measurement of bound EPS in fouling

During the cleaning process, the sludge which was attached to membrane surface was collected to measure the bound EPS in the cake layer. The procedure that was followed is described in Figure 3.8.

3.5.5 Granule Morphology

Different types of microbes were observed by biological microscope by Olympus CX40RF200 with maximum 100 X zoom and camera Moticam 1000, 1.3M Pixel USB 2.0 at the AIT Environmental Engineering laboratory.




Note: Before preparing for PS measurement Sulfurmic Acid (SFA) will be added for samples to avoid nitrite interference

(*) Solution A: 100 mL of (0.5 g $CuSO_4.5H_2O$ + 1 g $Na_3C_6H_5O_7.2H_2O$);
Solution B: 1000 mL of (20 g $Na_2CO_3$ + 4 g NaOH);
Solution C: 1 mL of solution A + 50 mL of solution B;
Solution D: 10 mL of Folin-Ciocalteu phenol reagent + 10 mL of deionized water.

Figure 3.8 Procedure for bound EPS extraction

### 3.5.6 Cell Lysis Test in MABR

The procedure for cell lysis test is explained in the Figure 3.9.

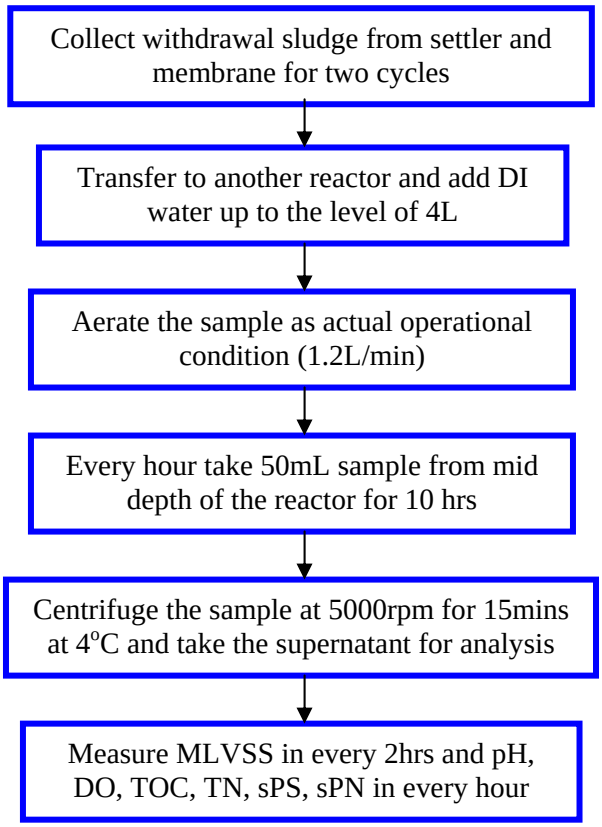



Figure 3.9 Procedure for Cell lysis test (Modified from He et al., 2006)

Note:
The first MLVSS of the sample was analyzed immediately to determine the biomass concentration in the experiment to compare with the original MLVSS. If the biomass concentration is not same (approximately) it needs to be increased / decreased.

Table 3.8 Additional Parameters and Analytical Methods

| **Parameters** | **Analytical Method** | **Analytical Equipment** | **Unit** | **Range of measurement** | **References** | **Frequency of Measurement** |
|---|---|---|---|---|---|---|
| TOC | TOC = Total Carbon (TC) – Incorganic Carbon (IC) | TOC $V_{CSN}$ & TOC 5000A, Total Organic Carbon Analyser, Shimadzu, Japan | mg/L | TC: 0-1000<br>IC: 0-200 | APHA, 1998 | 2-3 times a week |
| $NH_4^+$ | Colorimetric method | Spectrophotometer U 2001, Hitachi | Abs | | APHA, 1998 | 2-3 times a week |
| $NO_2^-$ | Colorimetric method | Spectrophotometer U 2001, Hitachi | Abs | 0 – 25 µg/L | APHA, 1998 | 2-3 times a week |
| $NO_3^-$ | Colorimetric method | Spectrophotometer U 2001, Hitachi | Abs | 0 – 5 mg/L | APHA, 1998 | 2-3 times a week |
| pH | pH measurement | pH meter, Cyberscan pH 30, Eutech instruments | | | APHA, 1998 | Every day |
| DO | DO measurement | DO meter, HACH, HQ10 LDO | mg/L | | APHA, 1998 | Every day |
| SVI | $SVI_{15}$ for granules and $SVI_{30}$ for activated sludge | | ml/min | | APHA, 1998 | Once a week |
| CST | Capillary suction method | Triton Electronics Limited, England | s | | APHA, 1998 | Once a week |
| Granule morphology | Microscope | Olympus CX40RF200 with maximum 100 X zoom & camera Moticam 1000, 1.3M Pixel USB 2.0 | | | - | Once the system is stable |
| Granule settling velocity | Free settling test | | m/h | | APHA, 1998 | Once a week |
| Soluble & bound EPS | Cation exchange resin extraction, Dubois and Lowry method | | mg/L | | Frolund et al, 1996<br>Dubois et al., 1956<br>Lowry et al., 1951 | 2 times a week |
| Membrane resistance | Resistance-in-series model | | $m^{-1}$ | | Choo and Lee, 1996 | Once membrane fouled |
| Particle size distribution | Mastersizer | Mastersizer S (Malvem, UK) | µm | 0.1 – 900 | - | One time for each loading |
| MLSS | Gravimetric method | | mg/L | | APHA, 1998 | Once a week |
| MLVSS | TOC method | TOC $V_{CSN}$ , Total Organic Carbon Analyser, Shimadzu, Japan | | | Tijhuis et al, 1994; & Beun et al., 2002 | Twice a week |

| **Parameters** | **Analytical Method** | **Analytical Equipment** | **Unit** | **Range of measurement** | **References** | **Frequency of Measurement** |
|---|---|---|---|---|---|---|
| Trans-membrane pressure | Digital Pressure gauge | PG 30, Copal Electronics, Japan | kPa | 0 – 30 | | Every day |
| Nitrogen removal pattern of SBAR & MABR | $NH_4$-N, $NO_2$-N, $NO_3$-N, TOC, TN, pH, DO at every 30 mins for one cycle of operation (4 hrs) | | | | | Once per different Run |
| Cell lysis test | TOC, TN, sPS, sPN at every 1 hr for 20 hrs | | | | | Once per different Run |

# CHAPTER 4

# RESULTS AND DISCUSSION

This chapter comprises of three parts namely granule stability, performance of membrane airlift bioreactor (MABR) based on nitrogen removal and, treatability of the aerobic granular MABR system and membrane fouling. The first part of this chapter focuses on the investigation of granule stability based on MLSS, size, settling velocity, morphology, and organic and nitrogen removal efficiencies. The second part deals with the performance evaluation of the MABR based on treatability with simultaneous nitrification and denitrification. At the later part of this chapter, the fouling pattern, and organic and nitrogen removal efficiencies of aerobic granular MABR system are compared between OLR 4 kgCOD/$m^3$.d and conventional MBR. All three parts of this chapter are compiled to conclude the suitability of the system for water reuse and reclamation.

## 4.1 Granule Stability and its effect at OLR 2 kgCOD/$m^3$.d (Run 1)

The granules in the SBAR commenced to disintegrate when the OLR was changed from 4 to 2 kgCOD/$m^3$.d mainly due to the long sludge retention time (SRT) of the granular sludge. The granules were settled and retained in the reactor for more than 300 days. The long SRT of the granules resulted in disintegration due to lack of substrate and nutrient diffusion into the core of the granules. This led to cell lysis in the core of the granules which caused breakage of granules. Further, the sudden change in OLR from 2 to 4 kgCOD/$m^3$.d and then 4 to 2 kgCOD/$m^3$.d had extended the granule disintegration since the SBAR was operated at OLR 2 kgCOD/$m^3$.d for more than 300 days. The raw results obtained for this run is tabulated in Appendix B.

### 4.1.1 Granule Characteristics

### A. Granule Size, Morphology and Settling Velocity

The pH of SBAR varied in the range of 7.9±0.1 at the beginning of each batch during the 160 days of operation. Also, the dissolved oxygen concentration at high aeration (Organic removal & Nitrification) and denitrification stages were 7.4±0.2 mg/L and 4.0±0.2 mg/L respectively. The pH of the feed was maintained at 7.8±0.3 by adjusting with $NaHCO_3$ or 50% HCl whenever required.

The granule size, settling velocity and the morphology of the granules are some of the main measures to characterize the granules. The average granule size and settling velocity were found to be in the range of 0.2 – 5.0 mm and 10 – 130 m/h respectively in the previous research works (Beun et al., 1998, Zheng et al., 2005, Wang el al., 2007, Kim et al., 2008).

The average granule size and the settling velocity in this run were 5.8±1.3 mm and 5.2±1.3 mm and 135±17 m/h for OLR 2 kgCOD/$m^3$.d and 125±22 m/h for OLR 4 kgCOD/$m^3$.d respectively (Appendix B, Table B.5). The granule size reduced from 5.8 to 5 mm (Figure 4.1). Hence, it could be concluded that the matured and large granules got disintegrated during this run. Similarly, the granule settling velocity too reduced from 142 to 125 m/h due to the broken granules and flocs in the reactor.

Once, the granules become matured and big in future, there will be oxygen and/or substrate limitation in the core of the granules which will favor the simultaneous nitrification and denitrification process in the granular sludge. On the other hand, if the sizes of the granules are small there can not be simultaneous nitrification and denitrification (SND) since the substrate and oxygen can penetrate up to the core of the granules.

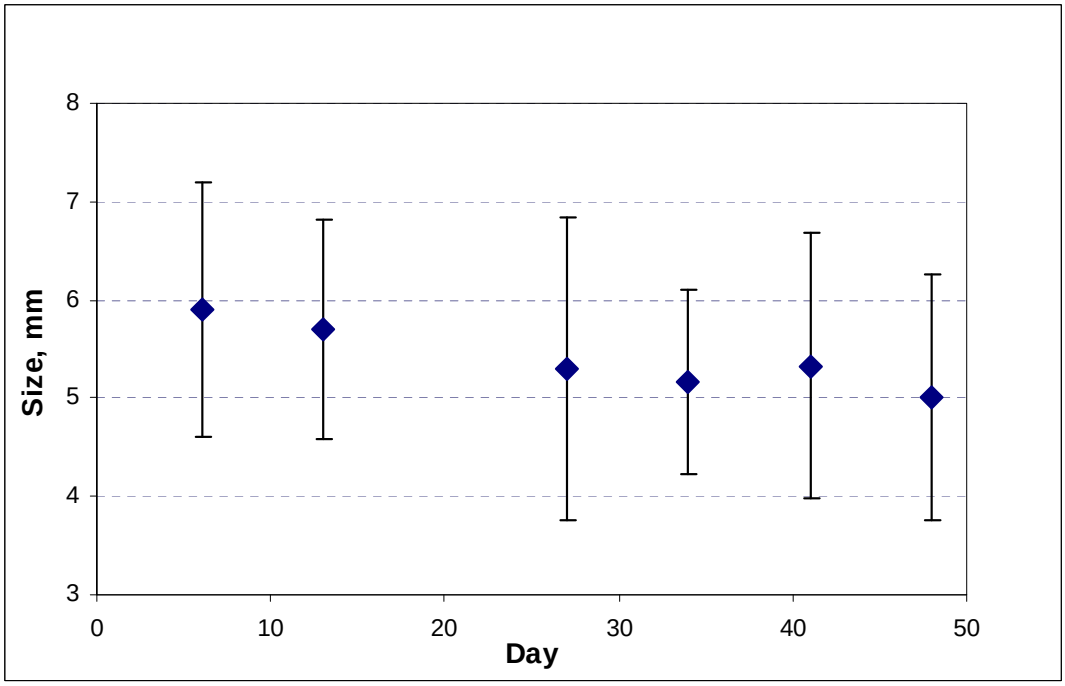



Figure 4.1 Weekly granule size variations at OLR 2 kgCOD/$m^3$.d

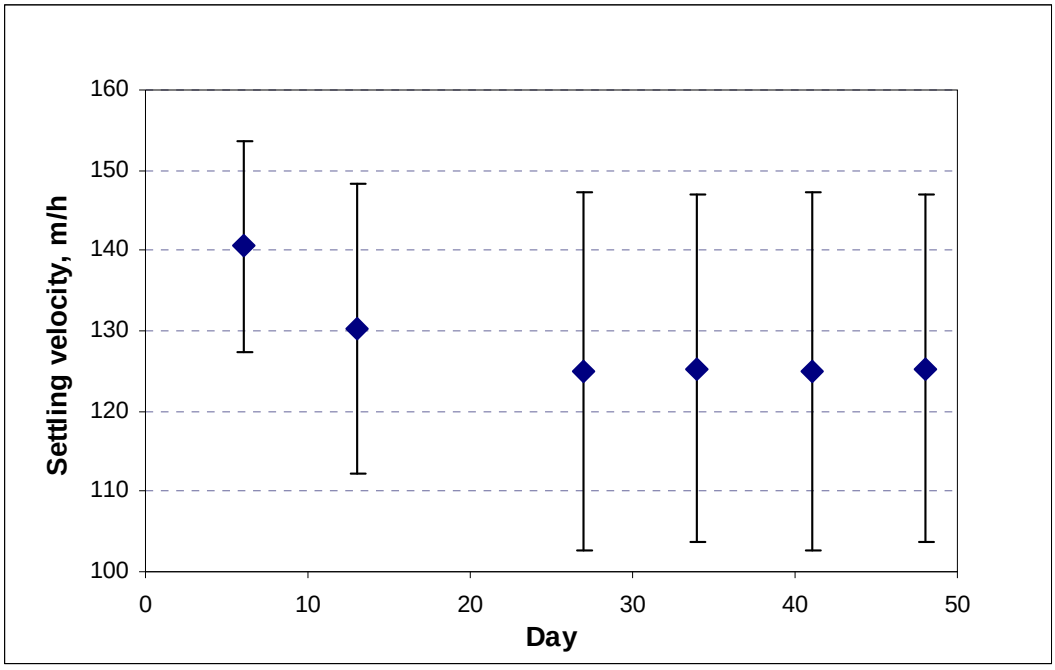
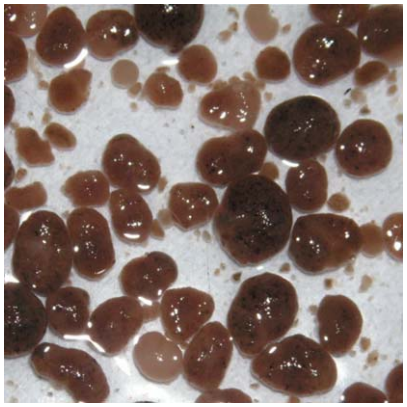
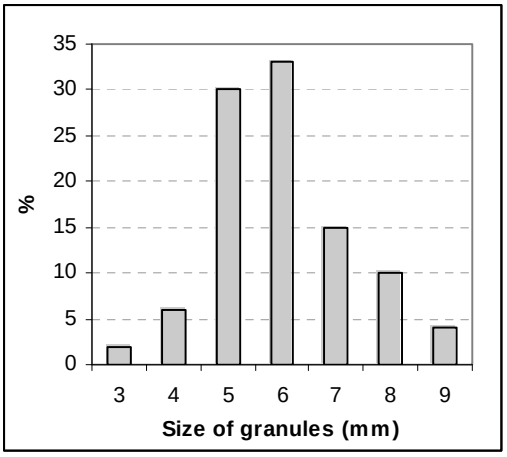



Figure 4.2 Weekly granule size variations at OLR 2 kgCOD/$m^3$.d

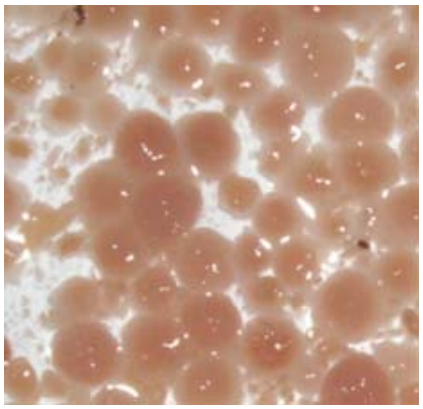
In the Figure 4.3, some of the big and matured granules have black spots which imply that there exists the anoxic zone due to limited diffusion of substrate and oxygen in the core of the granules. Hence, simultaneous nitrification in the surface and denitrification in the core of the granules would have been achieved at the beginning of the research. However, at later stages, due to granule disintegration the big and matured granules disappeared and small granules were dominant in the reactor. From the Figure 4.3, for the day 6 and 34, it is seen that the percentage of small granules (size < 5) has increased by 20%. Also, at day 34, the white granules were dominant in the reactor which showed that there were less number of nitrifiers and denitrifiers present in the reactor. Hence, it is evident the nitrogen removal of the SBAR was reduced after 34 days of operation.

*Day 6*






*Day 34*



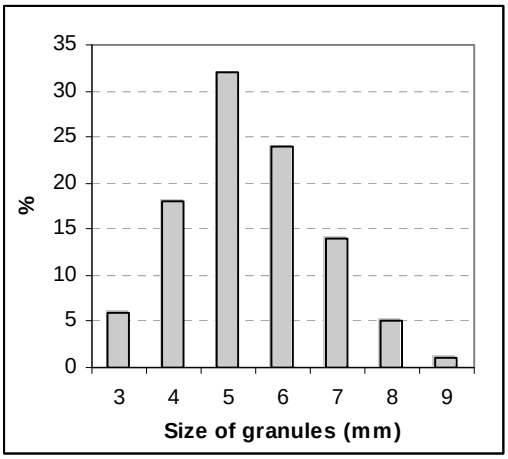



Figure 4.3 Granule Morphology and Size distribution in Day 6 & 34 at OLR 2 kgCOD/$m^3$.d

**B. MLSS**

The MLSS of the granular sludge in the SBAR was 12000 mg/L at the initial stages of the research and it started decreasing to 7500 mg/L and then to 4500 mg/L at $40^{th}$ and $80^{th}$ day of operation respectively (Figure 4.4). This is due to the detachment phenomena of granules.

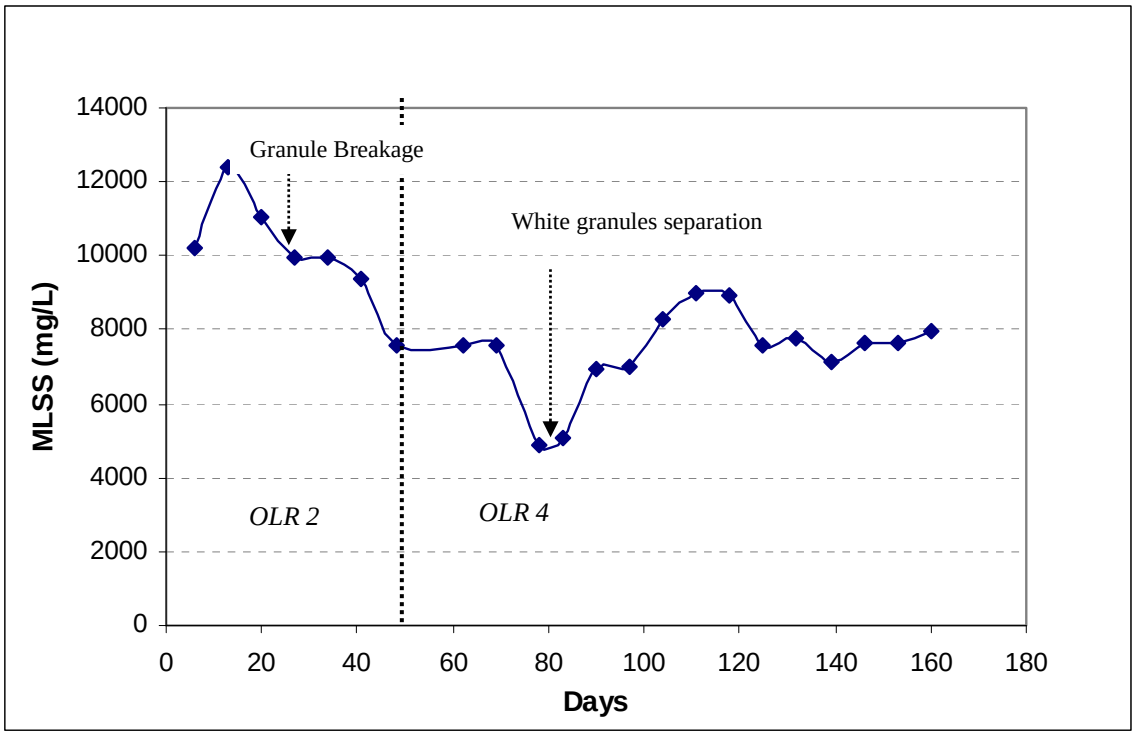



Figure 4.4 Variation of MLSS at OLR 2 & 4 kgCOD/$m^3$.d in SBAR

The following Figure 4.5 shows the granule appearance during the granule detachment and formation process.

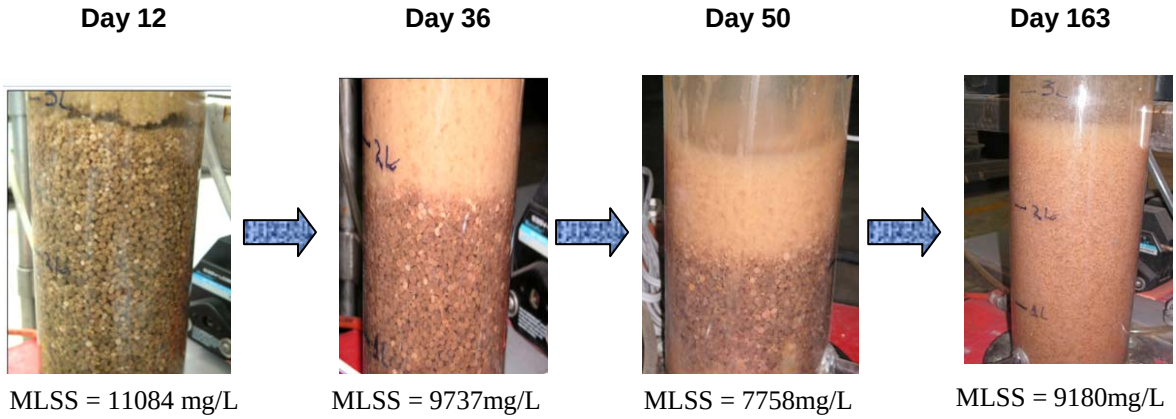



Figure 4.5 Granular sludge appearance at various MLSS

The reduction of MLSS to 4500 mg/L at day 80 was due to the removal of white granules present in the SBAR. This caused sudden increase in $SVI_{15}$ of the granular sludge. The average $SVI_{15}$ and CST of the granular sludge were maintained at 29±4 mL/g and 12±1 sec respectively in the reactor. According to other researchers like Jang et al (2003), Qin et al (2004), Tay et al (2004), Thanh (2005), Li et al (2006) and Kim et al (2008), the SVI was maintained in between 10 – 140 mL/g. Hence, the SVI of the granular sludge in this run was not affected very much by the granule detachment phenomena.

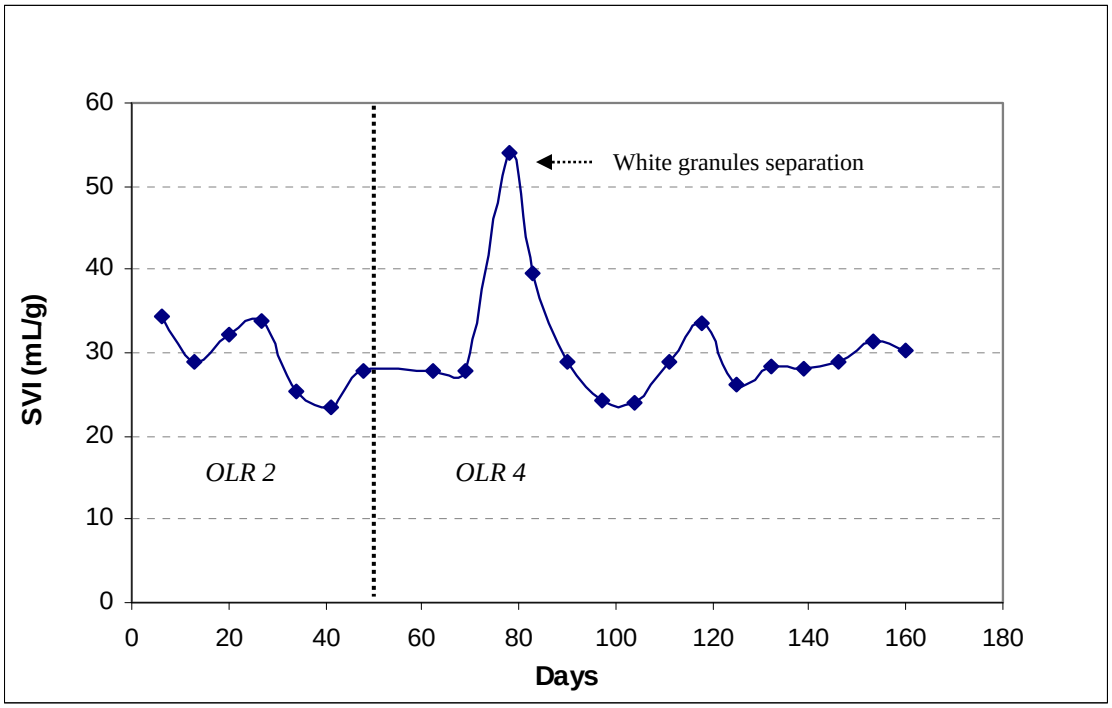



Figure 4.6 SVI of Granular sludge at OLR 2 & 4 kgCOD/$m^3$.d

### 4.1.2 Nitrogen and Organic Removal in SBAR and MABR

**A. SBAR**

The organic loading was increased from 2 to 4 kgCOD/$m^3$.d after 50 days of operation to facilitate the granule formation in SBAR as the granules started to disintegrate after 10 days of operation. The organic removal in SBAR at both OLRs 2 and 4 kgCOD/$m^3$.d was more than 94% of the total TOC supplied. The effluent TOC concentration was less than 10 mg/L (COD 30mg/L) during the initial 60 days of operation and then due to granule disintegration it was raised to 30 mg/L (COD 90mg/L). At day 100, the new granules started to form in the reactor and the performance based on organic removal was recovered back to previous condition. This shows that the aerobic granular sludge has the excellent treatability in terms of organic matter removal (Appendix B, Table B.1).

In this research the TOC was measured instead of COD measurement to avoid some interference. COD measurement is commonly used to measure the organic strength of wastewaters as the measurement method takes shorter time than that of BOD measurement method. During the COD experiment the chloride ($Cl^-$) ions can be oxidized and can result in high COD values.

$6Cl^- + Cr_2O_7^{2-} + 14H^+ \rightarrow 3Cl_2 + 2Cr^3+ + 7H_2O$

Therefore, by addition of mercuric sulphate prior to the analysis, the interference of $Cl^-$ ions can be eliminated. Similarly, the nitrite ($NO_2^-$) interference also can be eliminated by addition of sulfamic acid which oxidizes the nitrite to nitrate.

In this research, the feed wastewater contained $NH_4Cl$ as a nitrogen source which had contributed to the residue of $Cl^-$ ions in the samples and $NO_2^-$ due to denitrification process in the system. Due to above mentioned interferences by $Cl^-$ and $NO_2^-$, the COD measurement for some samples could not give reliable results in this research and consume extra time and chemicals. Hence, total organic carbon measurement (TOC) was used to evaluate the organic removal efficiency of the system using TOC $V_{CSN}$ & TOC 5000A, Total Organic Carbon Analyzer, Shimadzu, Japan.

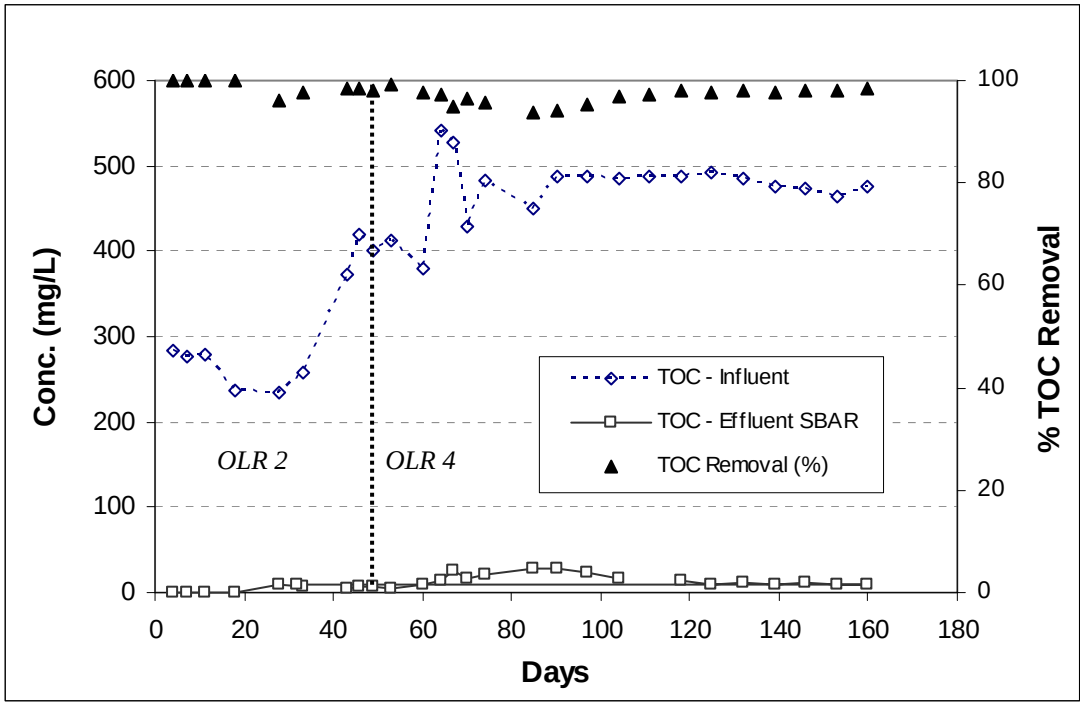



Figure 4.7 Organic Removal Efficiency at OLR 2 & 4 kgCOD/$m^3$.d of SBAR

The nitrogen removal efficiency of the aerobic granular sludge for the 160 days of operation is described in Figure 4.8. The SBAR performance based on nitrogen removal was not stable during this period due to granule disintegration phenomena. The first 10 days of operation, the nitrogen removal in SBAR was 40% of total nitrogen supplied (0.6kgN/$m^3$.d) which includes the nitrogen used for assimilation.

Once the granules started to disintegrate the nitrate level started to increase and nitrite level started to decrease. This was due to the sudden change in OLR from 4 to 2 kgCOD/$m^3$.d. This change of OLR favored washout of nitrifying and denitrifying micro organisms from the reactor. Hence, the nitrogen removal of the reactor was reduced. Also, the denitrification in the system was reduced to breakage of big and matured granules (Refer section 4.1.1 A). After 40days of operation at OLR 2 kgCOD/$m^3$.d the organic loading was gradually increased to 4 kgCOD/$m^3$.d to enhance the granule formation. However, due to low biomass concentration in the reactor, the nitrogen removal was further reduced based on nitrification. The complete nitrification in the reactor was reduced and formation of free ammonia started to increase which restrained the granule formation (Yang et al, 2004). Eventually, due to less nitrification in the reactor the pH started to boost up to 8.8 and was difficult to control. This too favored the free ammonia formation more and more in the reactor. Therefore, the nitrogen loading was reduced to 0.4 from 0.6 kgN/$m^3$.d to avoid free ammonia production in the granular reactor.

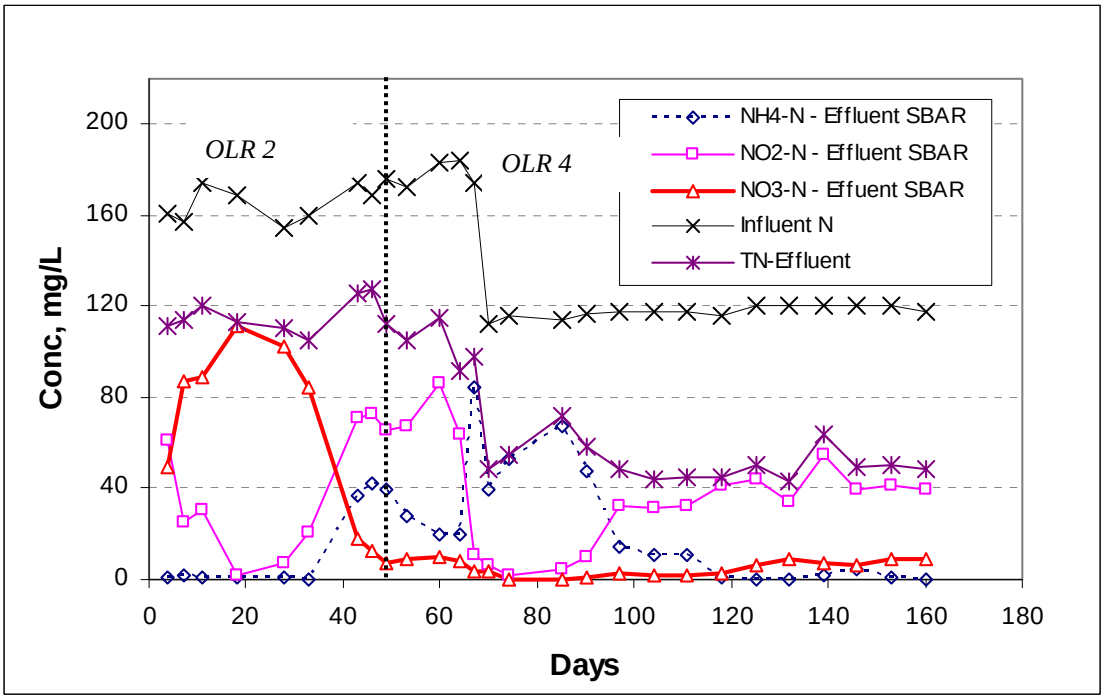



Figure 4.8 Nitrogen Removal Efficiency at OLR 2 & 4 kgCOD/$m^3$.d of SBAR

**B. MABR**

The organic removal in MABR at both OLRs 2 & 4 kgCOD/$m^3$.d was fluctuating in the range of 20 – 35 % of the TOC from effluent of SBAR. Due to unstable operation of granular reactor, the MABR performance could not be evaluated in this run. Figure 4.9 shows the TOC produced due to cell lysis in the MABR reactor, TOC of effluent of SBAR and TOC of permeate. High biomass concentration and low substrate availability caused the cell lysis in the MABR reactor. Hence, the operation of the aerobic granule membrane airlift reactor was stopped and both reactors (SBAR and MABR) were separately fed with synthetic wastewater. The wastewater characteristics are tabulated in section 3.4.

The electron donor (or COD) is necessary to achieve denitrification process in any system. In this run the TOC fed into the MABR was very low (varied between 30 – 90 mg/L) which was not adequate for complete denitrification process. In addition to the TOC of effluent of SBAR, the TOC produced due to cell lysis varied between 0 – 70 mgTOC/L (Figure 4.9) which was used for denitrification process. Hence, TN removal in MBAR was not high as expected (Theoretically, the nitrogen removal in the system could be 30 mgN/L for 160 mgTOC/L which is around 25% of TN supplied to MABR). Figure 4.10 shows that the accumulation of the total nitrogen in the reactor is not significant. Also, due to the unstable operation of SBAR, the actual performance of the MABR could not be evaluated.

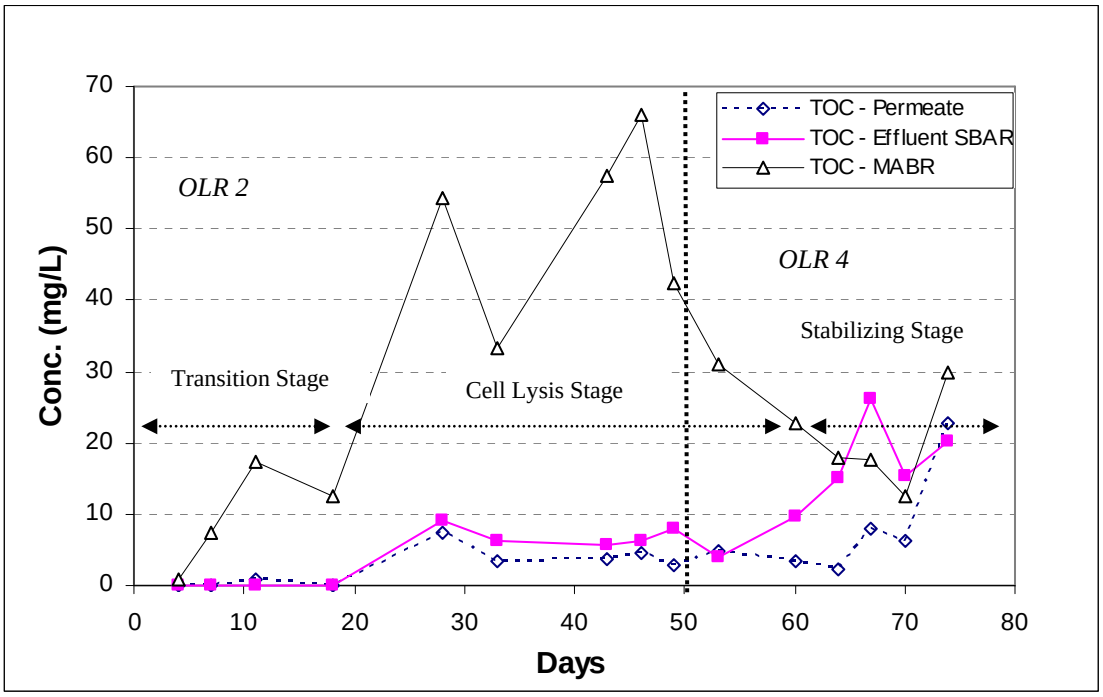



Figure 4.9 Organic Removal Efficiency at OLR 2 & 4 kgCOD/$m^3$.d of MABR

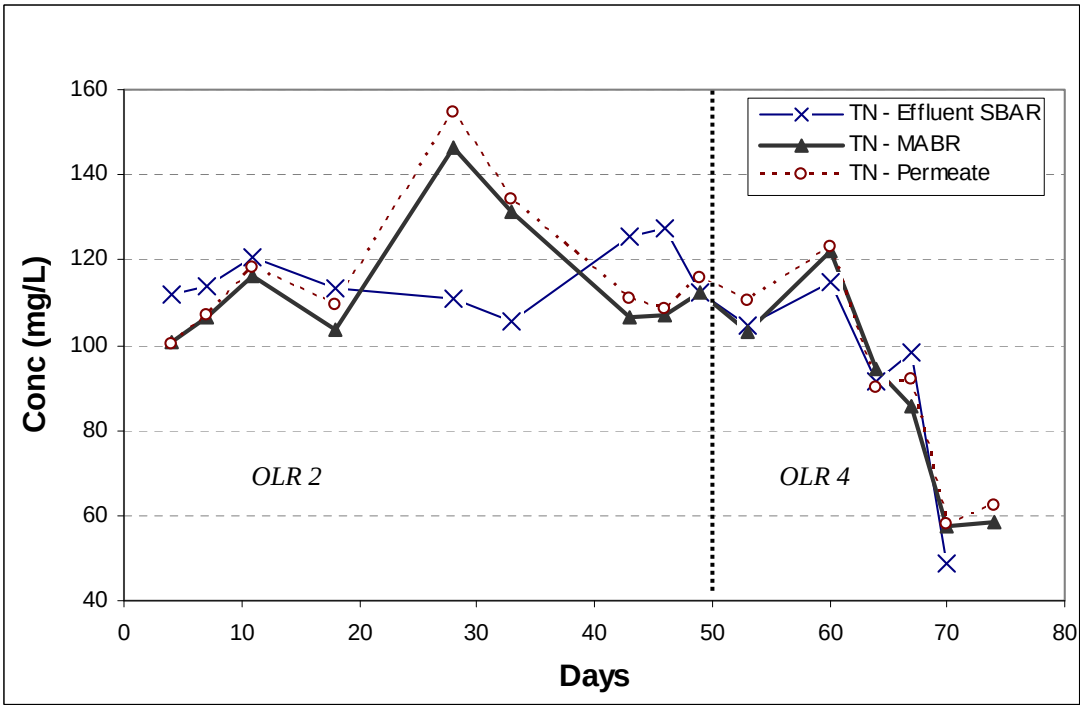



Figure 4.10 Nitrogen Removal Efficiency at OLR 2 & 4 kgCOD/$m^3$.d of MABR

The Figure 4.11 shows the intensive monitoring results of MABR (Appendix B, Table B.2). At the end of the batch operation $NH_4$-N and $NO_2$-N were almost completely nitrified to $NO_3$-N. The TOC in the MABR shows an increasing trend and TN does not show any large variation during the batch. Hence, it can be concluded that there exists cell lysis in the system. As such, it was planned to do the cell lysis test (Section 3.3) in the next run.

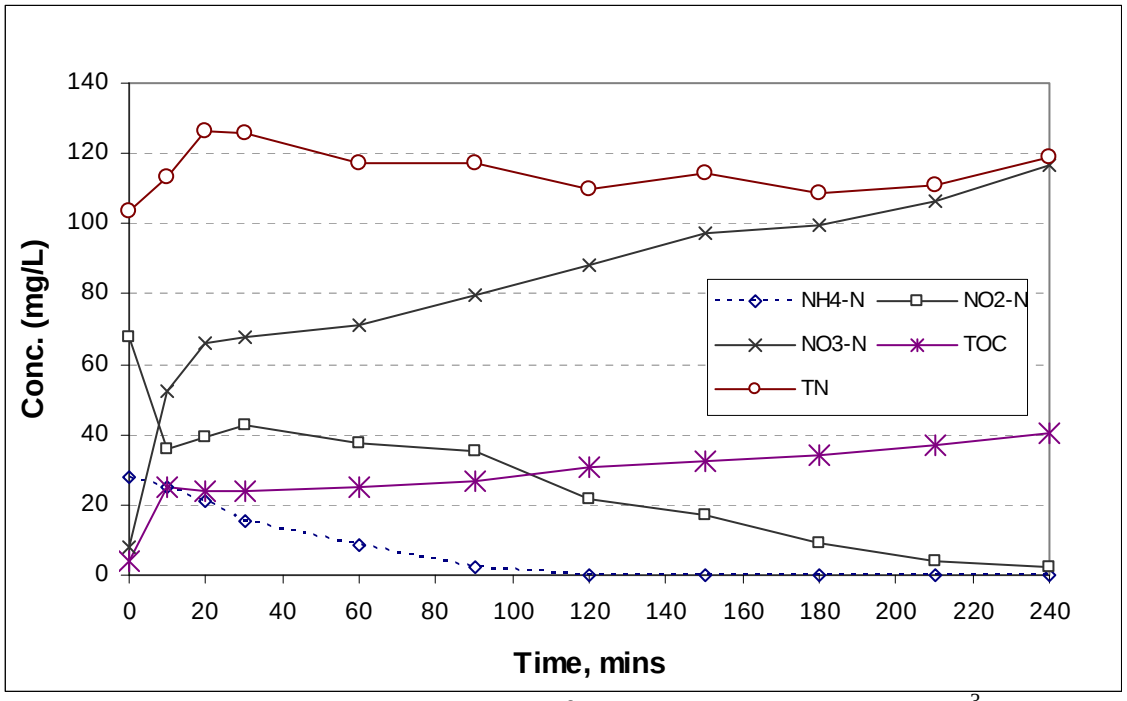


Figure 4.11 Intensive Monitoring for MABR at OLR 2 kgCOD/$m^3$.d

### 4.1.3 Fouling Behavior of MABR

### A. Sludge Characteristics

The pH of MABR varied in the range of 8.1±0.1 and 7.8±0.2 at OLR 2 and 4 kgCOD/$m^3$.d respectively. The pH in the SABR rose up to 8.8 due to reduction in nitrification. Hence, the pH was brought down to the range 7.8-8.2 to avoid high pH in MABR and SBAR.

In addition, the dissolved oxygen concentration at outer and inner tube of the MABR was 6.0±0.2 mg/L and 1.7±0.1 mg/L at both OLRs respectively. The pH in the MABR was maintained in between 7.8 – 8.2 with the support of automatic pH controller. Further the flow rate of the membrane was always kept constant at 29 mL/min.

The MLSS content of the granular sludge had reached around 3000 – 4000 mg/L gradually in 50 days of operation at OLR 2 kgCOD/$m^3$.d. At the beginning of the research, due to granule disintegration, the broken granular sludge was fed into the MABR with the SBAR supernatant. This caused increase in MLSS up to 5000 mg/L at the initial stage (Figure 4.12).

After the 70 days of operation of MABR, the average $SVI_{30}$ and CST were 80±10 mL/g and 39±18 s respectively. When compared with the granular sludge the SVI of MABR is 2.5 fold higher (Figure 4.13) which is similar to the conventional activated sludge. Hence, it could be concluded that the granular sludge has excellent settling ability than that of the MABR sludge. In addition, the dewaterability of MABR sludge is difficult when compared to granular sludge. The sludge wastage of MABR and granular reactor was 1.5 g/d and 10 g/d respectively. Hence, less amount of sludge is produced in the MABR.

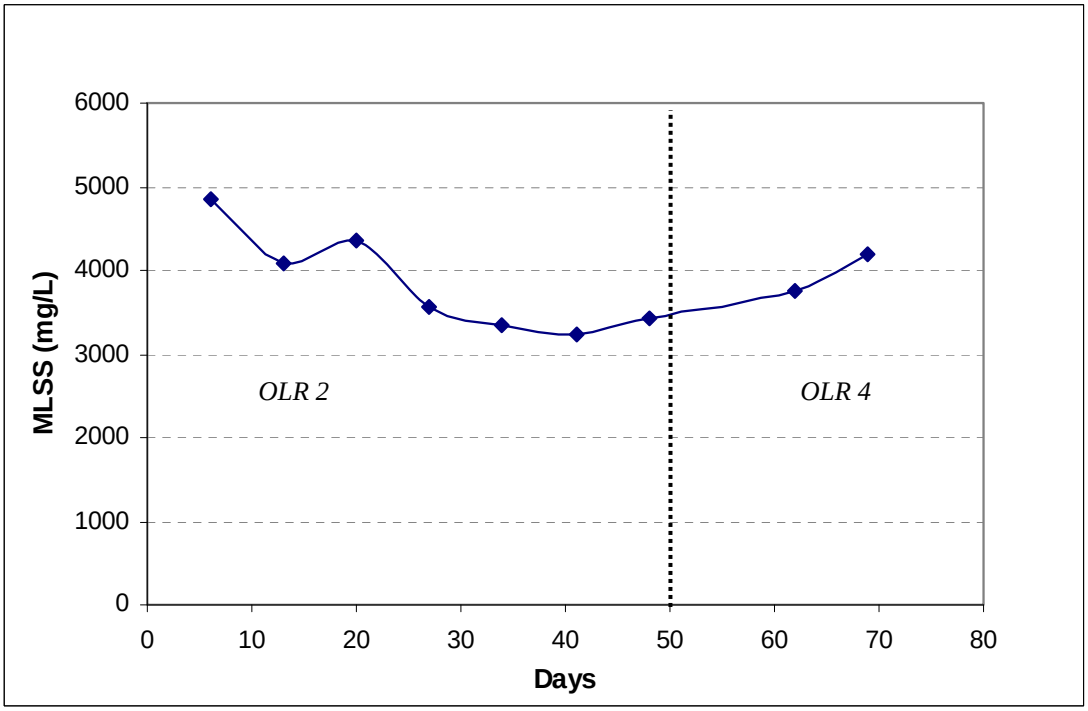



Figure 4.12 Variation of MLSS at OLR 2 & 4 kgCOD/$m^3$.d of MABR Sludge

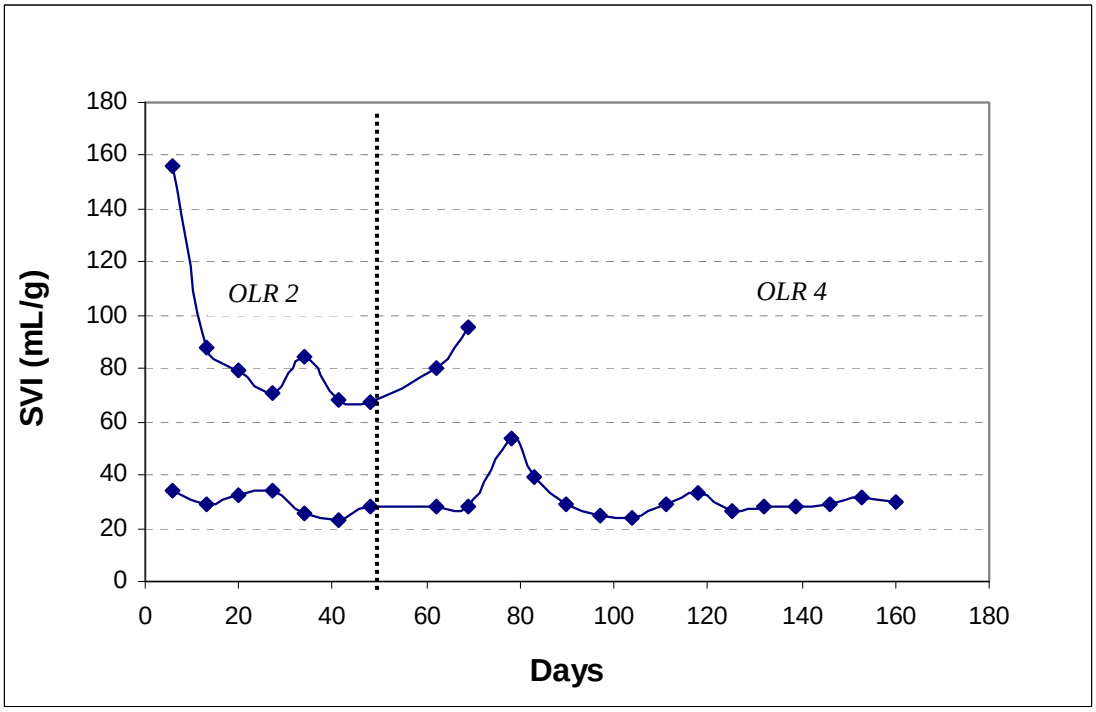



Figure 4.13 Variation of SVI at OLR 2 & 4 kgCOD/$m^3$.d of MABR and Granular Sludge

**B. Fouling Behavior**

The TMP profiles for the two runs are plotted in the Figure 4.13. The first and second cycles at OLR 2 kgCOD/$m^3$.d shows the fouling control by the granular sludge. In the second cycle, the fouling was very rapid when compared to previous cycle as the SBAR effluent mostly contains flocs. This caused increment in MLSS in the reactor and resulted in rapid fouling in the MABR. The fouling rate of membrane for cycle 1 and cycle 2 at OLR 2 kgCOD/$m^3$.d are 0.105 and 0.475 kPa/d respectively (Figure 4.14).

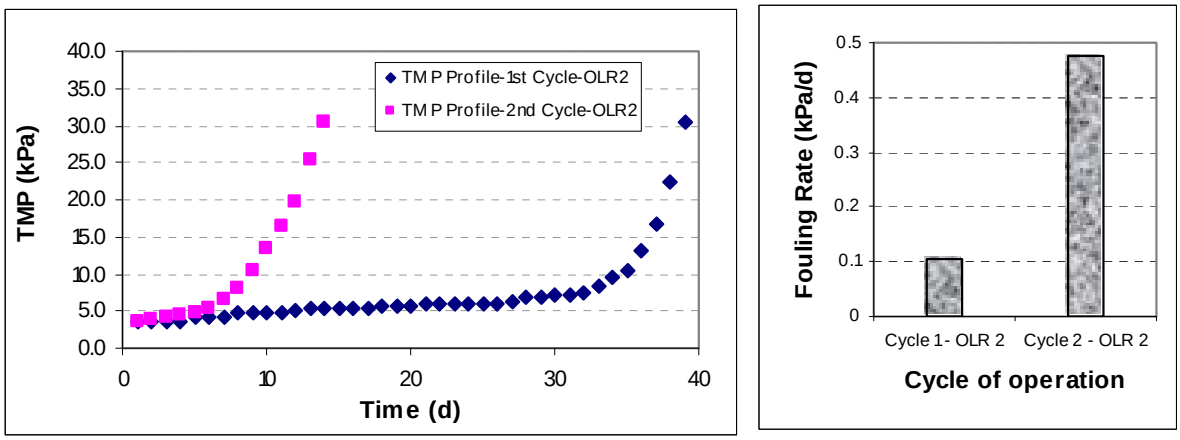



Figure 4.14 TMP Profile and Fouling rate at OLR 2 kgCOD/$m^3$.d

According to Tay et al. (2007), the fouling frequency of an aerobic granule membrane bioreactor (AGMBR) was 57 days (Figure 4.15) which is three fold higher than that of traditional submerged membrane bioreactor (SMBR) at flux 12 LMH. Hence, it could be concluded that if the SBAR system performs well, it is possible to prolong the fouling frequency in MABR when compared to conventional MBR.

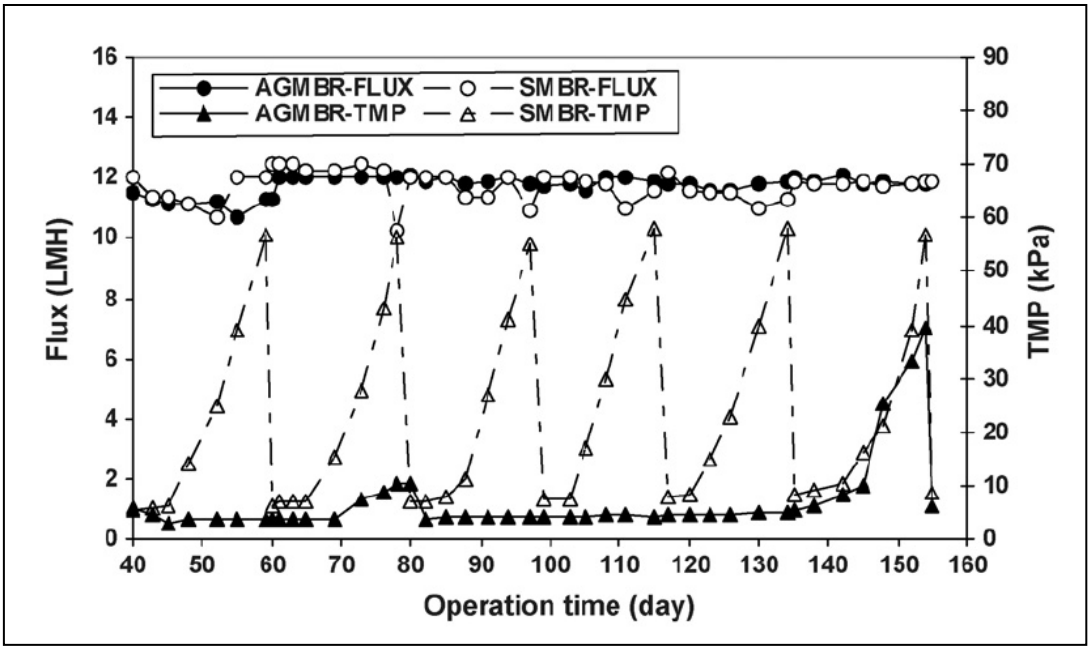



Figure 4.15 TMP Profile and Permeate Flux (Tay et al., 2007)

**C. Soluble Extra Cellular Polymeric Substance**

Soluble EPS is one of the important factors which contributes to membrane fouling. The soluble EPS consists of various substances where polysaccharides and proteins are mainly retained on the membrane surface. The increase in PS & PN in MABR confirms that cell lysis is occurring in the MABR. Permeate from the MABR contains less amount of PS which could be concluded that the remaining PS is deposited on pores and surface of the membrane. The deposition rate of sPS and sPN per membrane surface areas were 29 and 22 mg/L.$m^2$ respectively. In this run the PS/EPS is greater than 0.8 and it could be concluded that the polysaccharides are the major cause for membrane fouling in MABR than that of protein (Le Clech et al., 2006).

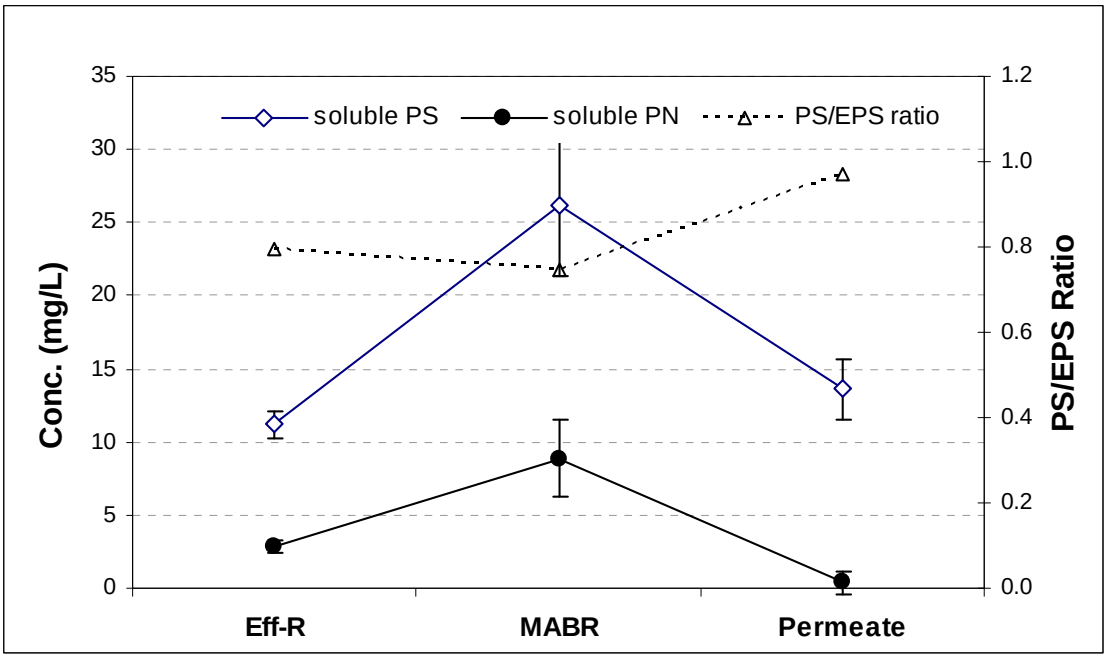



Figure 4.16 Fouling rate of membrane at OLR 2 kgCOD/$m^3$.d

It is to be note that the EPS measurement was done only at OLR 2 kgCOD/$m^3$.d due to loss of excessive granular sludge during this period (Appendix B, Table B.3).

Therefore, the granule breakage phenomena had caused the unstable operation of SBAR which in turn affected the performance of the MABR. Fen et al. (2008) have found that very high aeration and long SRT could cause excessive production of EPS and this may suppress the bio granulation process. The granule breakage has occurred due to two reasons mainly (i) Long SRT of granular sludge and (ii) Sudden change in OLR within a short period where the SBAR was operated for more than 300 days at 2 kgCOD/$m^3$.d. Furthermore, the granule formation and long term stability of granules depend on the starvation time (Liu and Tay, 2008). Hence, after 300 days of operation, the granules have lost their stability. To reduce granule breakage, the sludge in the reactor should be removed periodically where the new sludge was washed out with supernatant while the accumulation of aged sludge in the reactor was occurring in every batch of operation.

Due to granule breakage, the SBAR and MABR were separated after 70 days of operation to evaluate the performance of the MABR based on nitrogen removal efficiency. Meanwhile the granules were cultivated in the SBAR. The next section 4.2 describes the performance evaluation of the MABR.

## 4.2 Performance of MABR at Different Nitrogen Loading (Run 2)

This section describes the performance evaluation of the MABR based on nitrogen removal through simultaneous nitrification and denitrification. In this run the COD supply was maintained at 100 mg/L and the nitrogen concentration was varied to 3, 5, and 10 mg/L to observe the simultaneous nitrification and denitrification in the MABR. Further, the external carbon was added at concentration of 60 and 150 mg/L COD for the last two runs to assess the nitrogen removal through denitrification process.

### 4.2.1 Monitoring Data

The pH of MABR was 8.0±0.1 at the beginning of each cycle and, 8.3±0.1 and 8.1±0.1 at inside and outside tubes respectively after two hours of operation. In addition, the dissolved oxygen concentration at inner and outer tube of the MABR was 6.9±0.3 mg/L and 4.8±0.1 mg/L at three different nitrogen loadings. The pH in the MABR was maintained in between 7.8 – 8.2 with the support of automatic pH controller. Further the gross flow rate through the membrane was maintained at 4.14 $L/m^2.h$ (29 mL/min) throughout the experiment.

### 4.2.2 MABR Sludge Characteristics

The average MLSS, $SVI_{30}$ and CST, during the operation from 83$^{rd}$ to 153$^{rd}$ day of MABR are tabulated in Table 4.1 (Appendix C, Table C.5) for different nitrogen concentrations. The MLSS in the MABR was 800 – 900 mg/L and the SVI was improved from 56.6. ± 2.2 to 36.8 ± 2.0 mL/g at the end of the experiment. Due to low food supply (100 mg/L COD) the biomass concentration in MABR was very low for the all three cases.

Table 4.1 MLSS, SVI and CST of MABR Sludge at Different C/N Ratio

| **Parameter** | **Unit** | **Case 1: C/N = 7.5 (Equal Nitrogen)** | **Case 2 : C/N = 4.0 (Low Nitrogen)** | **Case 3 : C/N = 12.5 (High Nitrogen)** |
|---|---|---|---|---|
| MLSS | mg/L | 900 | 887 | 843 |
| SVI | mL/g | 57 | 56 | 37 |
| CST | s | 9.9 | 8.9 | 7.8 |

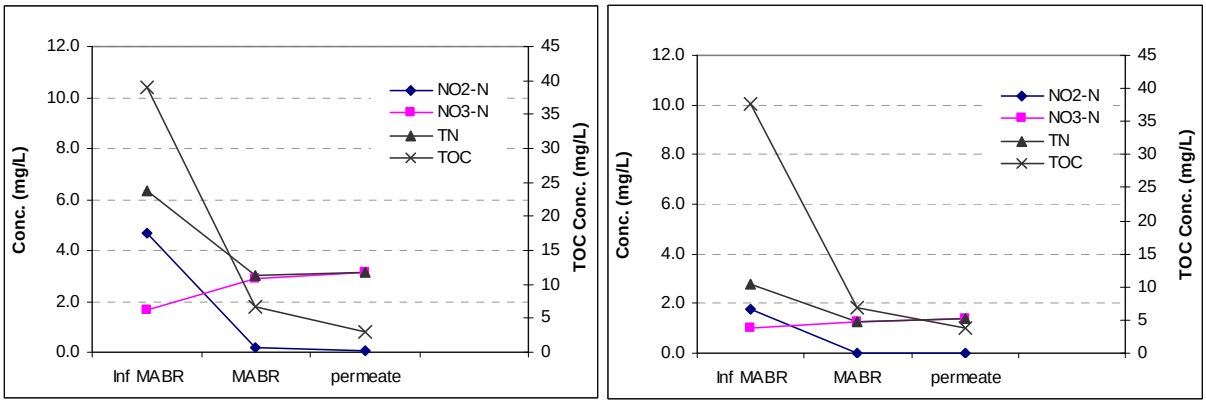
### 4.2.3 Organic and Nitrogen Removal in MABR

The organic and nitrogen removal of the system was investigated at different nitrogen loading with fixed organic loading. The removal efficiencies at different cases are tabulated in Table 4.2 (Appendix C, Table C.1). Also, the Figure 4.17 shows the $NO_2$-N, $NO_3$-N, Total Nitrogen and TOC concentration at various sampling points which was used to evaluate the removal efficiencies of the system at different cases.

Further, the external carbon was added to assess the denitrification in the system as electron donor is an important parameter to achieve the complete denitrification in any system. In this run (case 1, 2 and 3), there are two different carbon sources available namely COD supplied as feed and EPS produced during cell lysis which was not adequate to have the complete denitrification. Hence, the external carbon was added to assess the performance of the MABR based on denitrification.

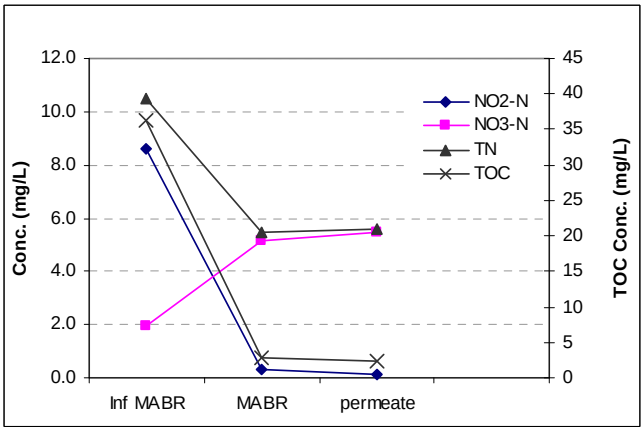
Table 4.2 Removal Efficiencies in MABR at Different Nitrogen Concentration

| **Parameter** | **Unit** | **Case 1 : Equal Nitrogen** | **Case 2 : Low Nitrogen** | **Case 3: High Nitrogen** | **Case 3a : 60 mg/L Carbon Addition** | **Case 3b: 150 mg/L Carbon Addition** |
|---|---|---|---|---|---|---|
| Organic Removal (TOC) | % | 89 | 90 | 94 | 82 | 88 |
| Organic removal Rate | mgTOC/ gVSS.hr | 20.0 | 19.2 | 20.2 | 17.8 | 18.6 |
| Nitrogen Removal by Denitrification | % | 24 | 4 | 30 | 42 | 47 |
| Denitrification Rate | mgDN/ gVSS.hr | 1.1 | 0.1 | 2.1 | 3.1 | 3.4 |
| Total N removal | % | 62 | 71 | 54 | 64 | 70 |
| Total Nitrogen removal Rate | mgTN/ gVSS.hr | 2.8 | 1.8 | 3.9 | 4.6 | 5.1 |




(a)

(b)




(c)

Figure 4.17 Nitrogen Species and Total organic carbon concentration for (a) Case 1: Equal Nitrogen (b) Case 2: Low Nitrogen (c) Case 3: High Nitrogen at different sampling points

The organic removal and nitrification based on total organic carbon (TOC) and total nitrogen (TN) were 89% and 100% respectively in all three cases after two hours of the first batch of operation. But the nitrogen removal through denitrification process at case 1, 2 and 3 was 24%, 4% and 30% respectively. The nitrogen needed for assimilation of

biomass in this run was around 3mgN/L and the remaining nitrogen was expected to be removed by denitrification process.

$$10\ NO_3^- + 12.625\ C_6H_{12}O_6 \rightarrow 13.25\ CO_2 + 4.5\ N_2 + C_5H_7NO_2 + 25.25\ H_2O + 14OH^- \qquad \text{Eq 4.1}$$

The electron donor or COD requirement for denitrification process in any system could be calculated from the above equation (Eq 4.1). Around 16.232g of glucose ($C_6H_{12}O_6$) is required to denitrify one gram of $NO_3^-$. However, in the MABR system major part of the 100 mg/L COD was used for assimilation and the remaining COD is not sufficient to achieve the denitrification in the system. This shows that the electron donor is the limiting factor for nitrogen removal by denitrification in the system. Hence, the external carbon was added when there was no circulation of biomass in the system and the performance of the system is tabulated in Table 4.2 and illustrated in the Figure 4.18 (Appendix C, Table C.2).

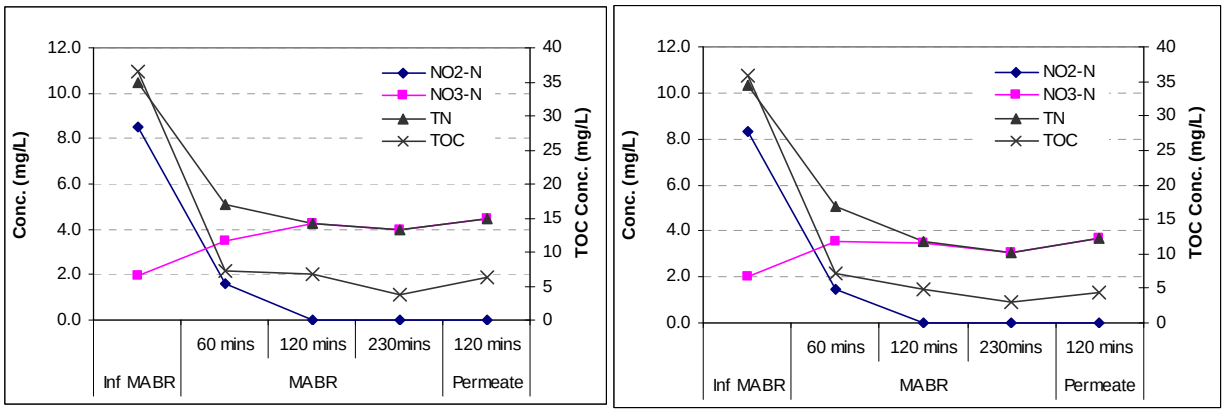
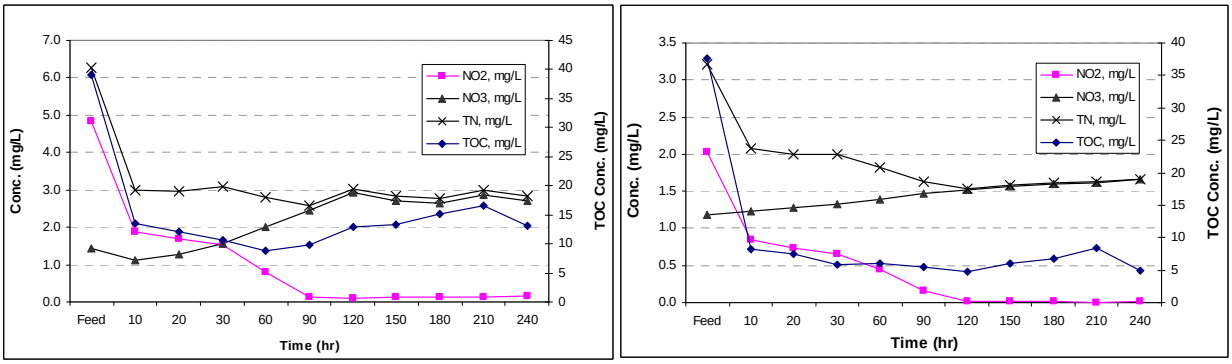


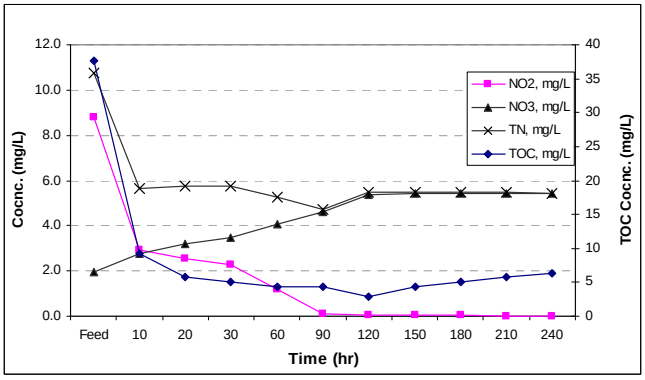

Figure 4.18 Nitrogen Species and Total organic carbon concentration for (a) Case 3a: External Carbon 60mg/L (b) Case 3b External Carbon 150mg/L at different sampling points

After addition of external carbon into the system the nitrogen removal efficiency was increased by 10 – 20% approximately. In the case of 60mg/L and 150mg/L external carbon addition the system achieved 42% (Theoretically 60%) and 47% (100%) of nitrogen removal through denitrification. Hence, from this run it could be concluded that, this system could achieve maximum 70% of nitrogen removal including 50% of denitrification.

The intensive monitoring for all three cases except external carbon addition was illustrated in the Figure 4.19 (Appendix C, Table C.4). All the three cases show the complete nitrification in the system and 70% TOC removal at the end of the batch. Also, the graphs show the increment in TOC after two hours of operation due to cell lysis in the MABR. The cell lysis in the system increases the TOC and TN in the MABR which is identified by cell lysis test proposed in section 4.1.2 B. The cell lysis test was carried out in this run to evaluate the real performance of the system based on nitrogen removal. The Figure 4.20 shows the cell lysis result in MABR. The rate of nitrogen produced to cell lysis was calculated and added to influent TN to calculate the actual performance of the MABR system (Appendix C, Table C.6).




(a) (b)




(c)

Figure 4.19 Intensive Monitoring for (a) Case 1: Equal Nitrogen (b) Case 2: Low Nitrogen (c) Case 3: High Nitrogen

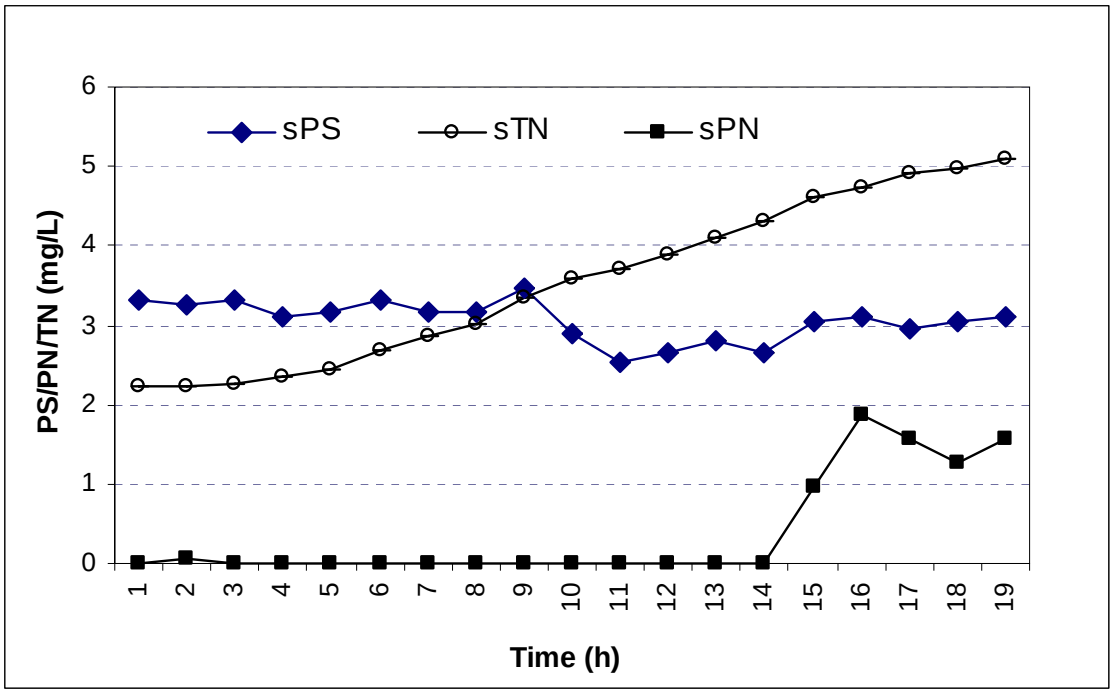



Figure 4.20 Cell Lysis Test Results in Run 2

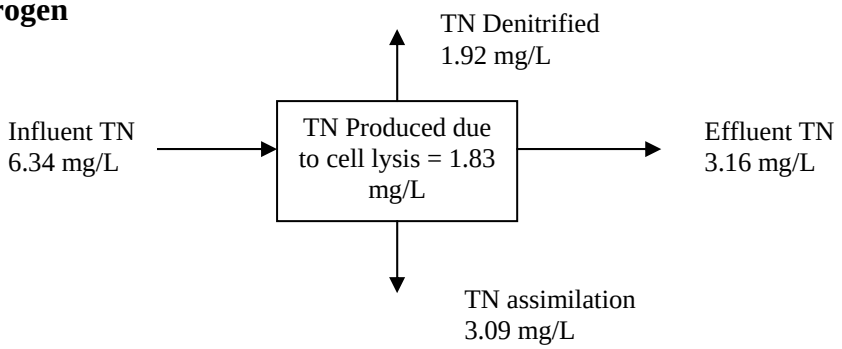
This test was conducted to study the cell lysis in the reactor which changes the characteristics of the supernatant under starvation condition. The mixed liquor biomass concentration was 350 mg VSS/L where the MLVSS showed little fluctuation at different times. This was due to the lysis and synthesis of cells in the reactor during the experimental duration. The pH in the MABR varied from 7.6-7.8 and the DO concentration was about 6.5 mg/L during this experiment.

The increment in sTN is the evidence for release of soluble microbial products (SMP) from biomass in the MABR. The sPS in the reactor was dominating species when compared to sPN as it si easily degradable compared than sPS. Hence, sPS was accumulated in the reactor and contributed 100% of soluble EPS at the beginning of the test. The Figure 4.20 explains that the sPN consumable rate is faster than the release rate. Therefore, during the first 14 h of operation the sPN was not present in the reactor. After 14hrs, the sPN release rate increased due to excessive cell lysis which was contributed by anoxic zonehi in the MABR and as a result the sTN rate of production was increased.

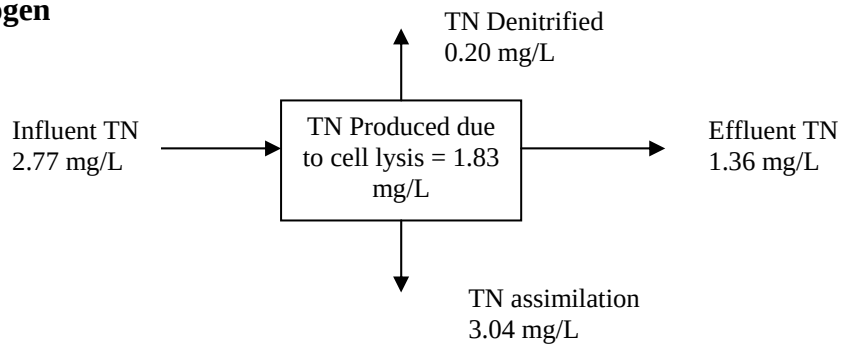
It can be concluded that the HRT of 2-5 h is the optimum condition for filtering the supernatant of granulation reactor. At this HRT range it can achieve better quality of permeate and less fouling due to low sPS, sPN, sTN and TOC. However, further investigation should be done to evaluate fouling potential with different HRTs.

The detailed material balance shown in Figure 4.21 describes the calculation of denitrified nitrogen from the MABR. The carbon source for the denitrification process includes part of feed COD and EPS produced from cell lysis.

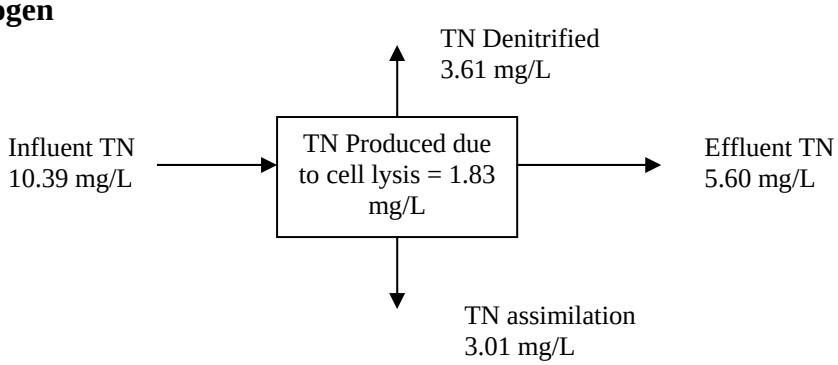
**Case 1: Equal Nitrogen**




**Case 2: Low Nitrogen**



**Case 3: High Nitrogen**




TN Assimilation = (COD in – COD out) x 5/150 (Chiu et al., 2007 and Choi et al., 2008)
TN Denitrified = TN in + TN produced by cell lysis – TN Assimilation – Effluent TN

Figure 4.21 Mass Balance of Total Nitrogen in MABR

### 4.2.4 Soluble and Bound Extra Cellular Polymeric Substance (EPS)

Many researches indicated that the soluble and bound EPS are the most significant factor in membrane fouling. Especially, high concentration of polysaccharides extends fouling in submerged MBR system (Rosenberger et al., 2006). In this run the soluble and bound EPS were measured to support the above statement and the results are listed in Table 4.3 (Appendix C, Table C.3).

Table 4.3 Soluble and Bound EPS Concentrations at Different Sampling Points

| **Parameter** | | **Unit** | **Case 1: Equal Nitrogen** | **Case 2 : Low Nitrogen** | **Case 3 : High Nitrogen** |
|---|---|---|---|---|---|
| Bound PS | | mg/gVSS | 19.6 ± 1.6 | 29.8 ± 3.4 | 21.3 ± 0.4 |
| Bound PN | | mg/gVSS | 22.3 ± 3.3 | 35.8 ± 3.0 | 17.8 ± 3.4 |
| Soluble PS | MABR | mg/L | 3.1 ± 1.1 | 3.4 ± 0.1 | 3.2 ± 0.5 |
| | Permeate | | 1.8 ± 0.4 | 2.0 ± 0.2 | 2.0 ± 0.2 |

The soluble PS is one of the main factors which could cause fouling in MABR since 50% of the soluble PS was retained by the membrane in all three cases while the PN produced was nil during this run. The soluble PS and PN, and bound PS and PN in case 2 were higher than the other two cases due to nutrient deficiency in the system (Jarusutthurak and Amy, 2007).

### 4.2.5 Fouling Behavior of MABR

The fouling rate was found to be very low due to low biomass concentration in MABR. The membrane was operated for 88 days and the TMP increment was observed during external carbon addition phase in this run. This is due to increase in biomass concentration in MABR from 870 mg/L to 1870 mg/L. According to Le-Clech et al. (2006), the biomass concentration alone is not a suitable indicator to prove the membrane fouling in MBR.

Hence, from this run it can be concluded that the MABR system could treat nitrogenous substances through simultaneous nitrification and denitrification due to its configuration where both aerobic and anoxic zones exist.

During this run, the performance of SBAR reached to stable condition. Hence, the SBAR and MABR were recombined to evaluate the performance of the aerobic granular membrane airlift bioreactor based on removal efficiencies and fouling behavior of membrane. The results obtained for the third run is discussed in the section 4.3.

### 4.3 Performance of Aerobic Granular Membrane Airlift Bioreactor (Run 3)

This section describes the performance evaluation of the aerobic granular MABR based on organic and nitrogen removal and, fouling behavior of membrane. During this run, the OLR and NLR were maintained at 4 kgCOD/$m^3$.d and 0.4 kgN/$m^3$.d respectively. The results obtained from this run is compared with the conventional MBR which was run during the same period by another student for his thesis (Munasinghe, 2008)

#### 4.3.1 MABR and Granular Sludge Characteristics

The pH measurement in SBAR at the beginning of the cycle was 7.9±0.1 while the influent pH was maintained at 7.7±0.1. The DO measurement during high aeration and low aeration (denitrification stage) were 7.1±0.1 mg/L and 3.8±0.1 mg/L respectively. The pH of MABR was 7.9±0.1 at the beginning of each cycle and after two hours of operation 8.0±0.1 and 7.9±0.1 at inside and outside tubes respectively. In addition, the dissolved oxygen concentrations at inner and outer tube of the MABR were 6.8±0.1 mg/L and 1.7±0.1 mg/L during this run. The pH in the MABR was maintained in between 7.8 – 8.2 with the support of automatic pH controller. Further the flow rate through the membrane was 4.14 L/m2.h (29 mL/min) throughout the experiment.

The average MLSS, $SVI_{30}$ and CST, during the operation from $167^{th}$ to $230^{th}$ day of MABR and Granular sludge are tabulated in Table 4.4. The SVI of MABR sludge is 2.3 fold higher than that of granular Sludge which shows that the granular sludge has excellent settling ability when compared to MABR sludge (Appendix D, Table D.3). Similar results were obtained during the first run of this research which is mentioned in section 4.1.3A.

The conventional MBR was operated with OLR 2.4 kgCOD/$m^3$.d, NLR 0.4 kgN/$m^3$.d, HRT of 10 h, SRT of 30 days and MLSS of 10 g/L during this period. Surprisingly, it was observed that the CST of the MABR and conventional MBR were same at 13.4 s. Therefore, the dewaterability of the MABR and conventional MBR were the same and higher than that of granular sludge. Further, relatively a large amount of flocs in the SBAR were washed out to MABR during each batch of operation which contributed to high MLSS content in MABR.

Table 4.4 Characteristics of MABR and Granular Sludge at 4kgCOD/$m^3$.d & 0.4 kgN/$m^3$.d

| Parameter | Unit | MABR Sludge | Granular Sludge | Conventional MBR Sludge * |
|---|---|---|---|---|
| MLSS | mg/L | 5500 | 9900 | 10000 |
| SVI | mL/g | 50.6 | 21.9 | - |
| CST | s | 13.4 | 10.8 | 13.4 |
| Settling Velocity | m/s | < 10 | 140 | <10 |
| Size | mm | 0.3 | 1.7 | 0.2 |

* Source: Munasinghe (2008)

The average granule size was 1.7±0.1 mm and the weekly granule size variation is presented in Figure 4.22 (Appendix D, table D.5). The average granule size was found to be in the range of 0.2 – 5.0 mm by other researches like Beun et al. (1998), Wang el al. (2007), Kim et al. (2008) and etc. Once, the granules become matured and big, the flocs will be less and nitrogen removal through denitrification will be more in the system. As a result the fouling in MABR would also be reduced.

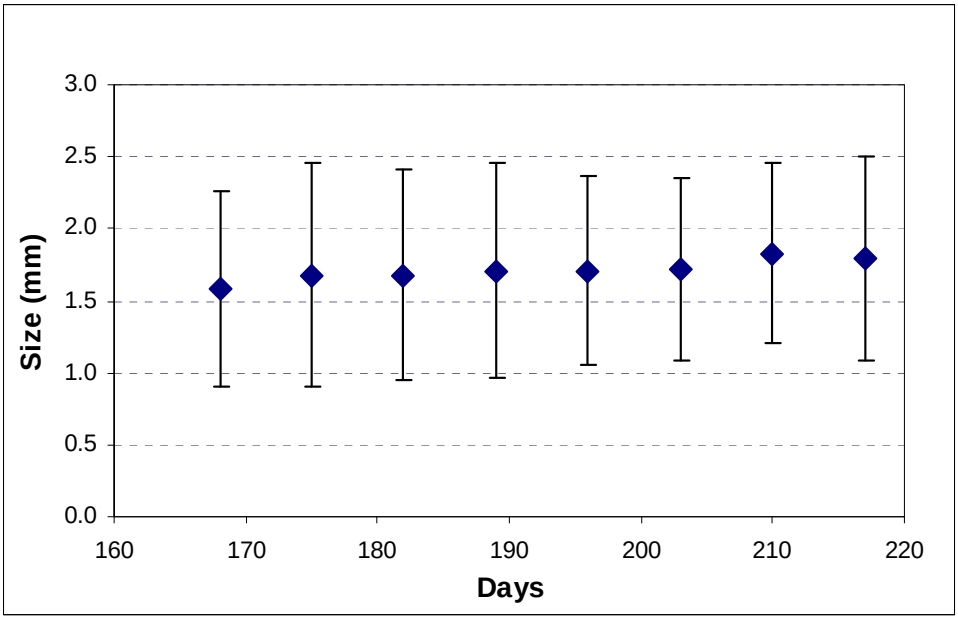



Figure 4.22 Weekly Granule Size Variation at 4 kgCOD/$m^3$.d & 0.4 kgN/$m^3$.d

The microorganisms in the MLSS like Aspidisca, Vorticella, Suctoria, Rotifer and Aeoloosma hemprichi increase the removal efficiencies of nitrogen and organic matter (Gang et al., 2007)**.** The Figures 4.23 and 4.24 show some of the microscopic photographs taken for MABR and granular sludge. Large amount Aeoloosma hemprochii and nematodes and few Rotifers were found in the MABR sludge. The worm Aeoloosma hemprochii might reduce the sludge production in MABR through predation process and the anoxic conditions in the MABR might have favored the growth of worms. However, in the granular sludge Rotifers were dominating species which improved the settling ability of the granular sludge (Fan et al., 2006 and Gang et al., 2007).

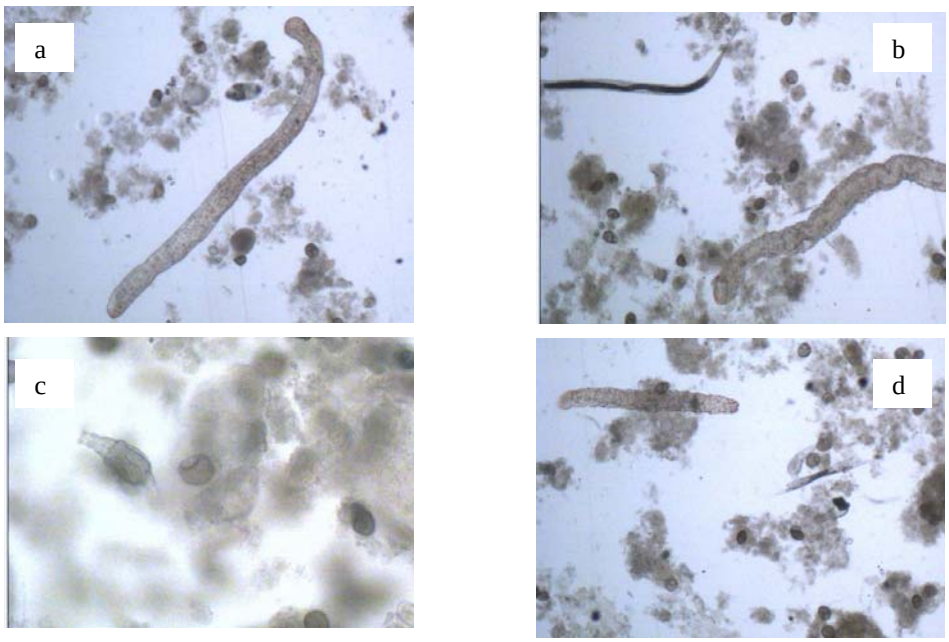



Figure 4.23 Microbial Community in MABR Sludge (a) Aeoloosma hemprochii (b) Aeoloosma hemprochii & Nematodes (c) Rotifer (d) Combined community (Magnification x10)

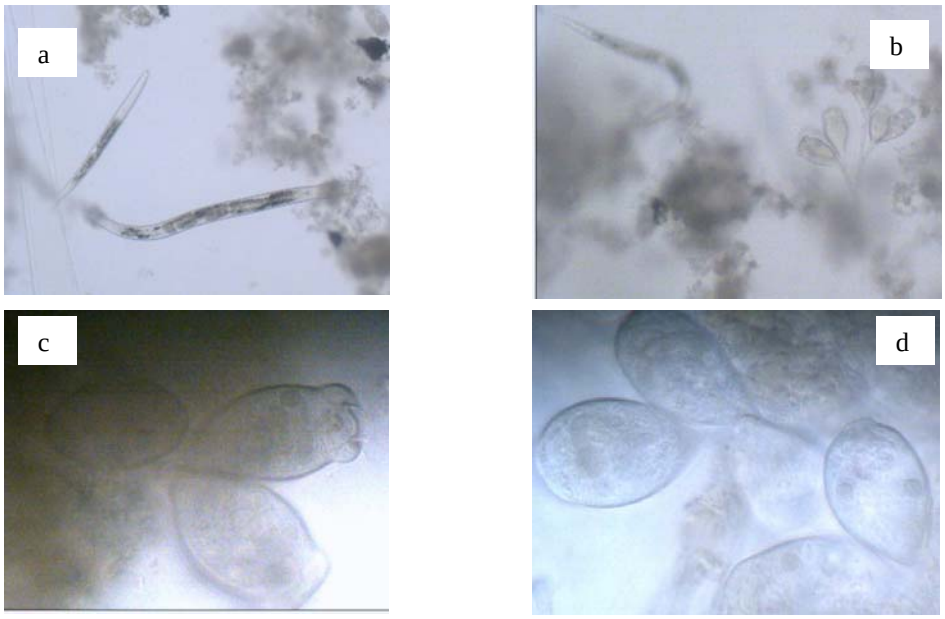



Figure 4.24 Microbial Community in Granular Sludge (a) Nematodes (b) Rotifiers & Nematodes (Magnification x10) (c) & (d) Rotifer (Magnification x40)

### 4.3.2 Nitrogen and Organic Removal in the Combined System

The performance of combined system, aerobic granular membrane airlift bioreactor (AGMABR), based on organic and nitrogen removal was not evaluated during Run 1 due to unstable operation of SBAR. Hence, in this run the removal efficiencies were compared with the conventional MBR. The organic removal in SBAR, MABR and AGMABR were 98%, 67% and 99% respectively (Figure 4.25). Further, the nitrogen removal in SBAR,

MABR and AGMABR were 56%, 26% and 61% including 27%, 25% and 35% denitrification respectively (Appendix D, Table D.1). The organic and nitrogen removal in conventional MBR is 98% and 27% respectively which is tabulated in Table 4.5.

Table 4.5 Organic and Nitrogen Removal in AGMABR and Conventional MBR

| **Parameter** | **Unit** | **SBAR** | **MABR** | **AGMABR** | **Conventional MBR*** |
|---|---|---|---|---|---|
| TOC removal | % | 98 | 67 | 99 | 98 |
| TOC removal rate | mgTOC/gVSS.h | 26.3 | 0.7 | 27.0 | 16.3 |
| TN removal | % | 56 | 26 | 61 | 27 |
| TN removal rate | mgTN/gVSS.h | 4.3 | 2.5 | 6.8 | 3.0 |
| Denitrification | % | 27 | 25 | 35 | 10 |
| Denitrification rate | mgDN/gVSS.h | 2.0 | 2.5 | 4.5 | 1.3 |
| MLVSS | mgVSS/L | 7600 | 3900 | - | 9050 |

Source: Munasinghe (2008)

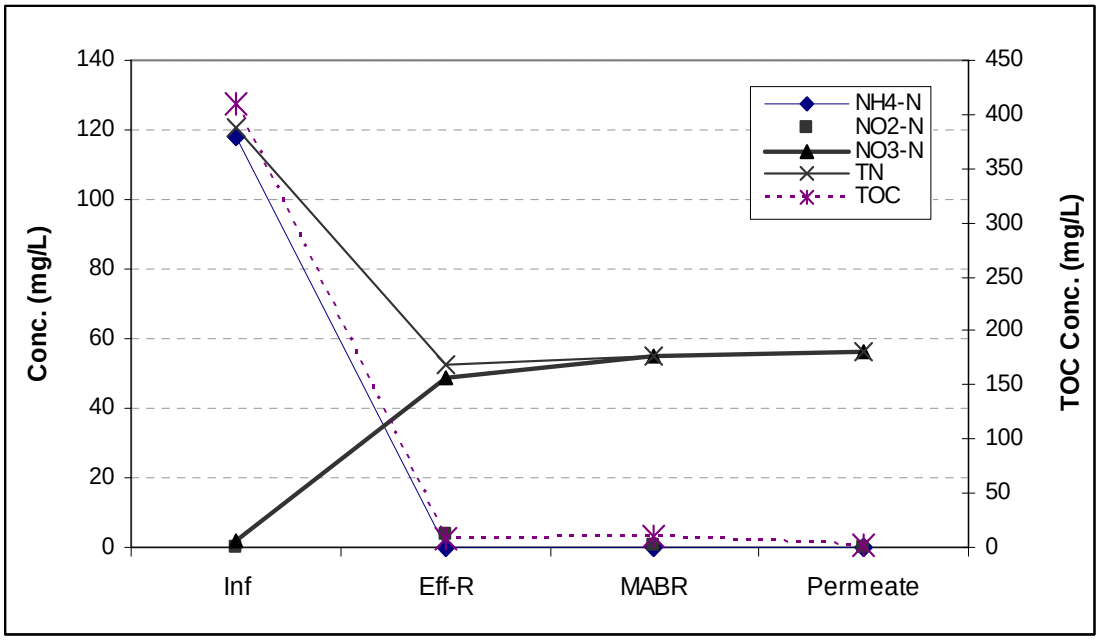
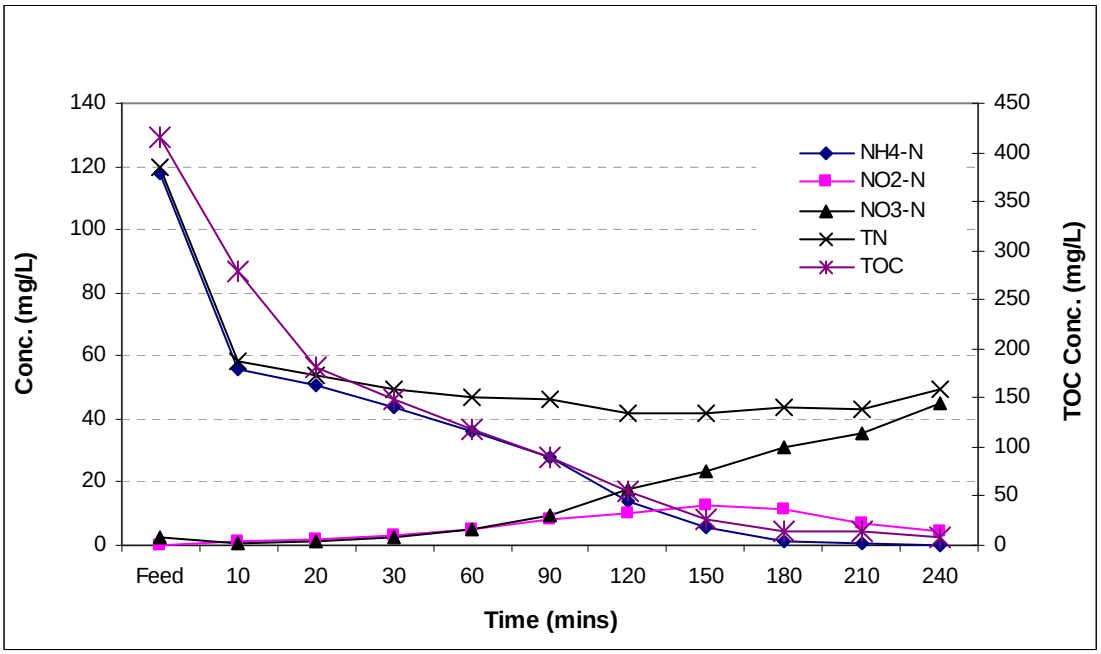



Figure 4.25 Ammonium Nitrogen, Nitrite nitrogen, Nitrate nitrogen and Total Organic Carbon Concentrations at 4 kgCOD/$m^3$.d & 0.4 kgN/$m^3$.d

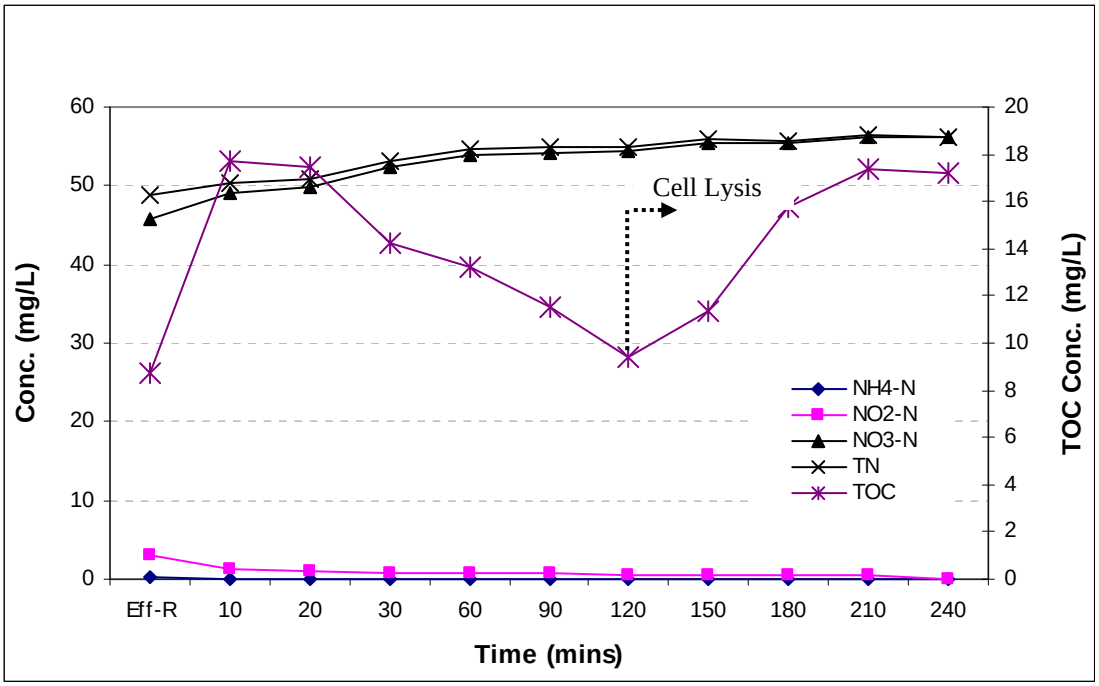
This shows that the AGMABR system could remove both organic and nitrogen more when compared to the conventional MBR. The limiting parameter for denitrification process in MABR is electron donor (external carbon source) which is clearly described in section 4.2. Therefore, if the external carbon source is added to MABR it could be achieved more denitrification in the system. Hence the AGMABR has better performance than MBR based on nitrogen removal.

The intensive monitoring results for SBAR and MABR are shown in the Figure 4.26 (Appendix D, Table D.2). In SBAR, after 3h of operation, the ammonium nitrogen was completely nitrified to nitrate nitrogen and as a result the nitrite nitrogen in the reactor was very low. The major part of the TOC was removed within the first hour of operation in a

batch. Similarly in MABR, TN shows increasing trend due to cell lysis in the reactor. Further, the TOC has fluctuated during the 4h batch which extends the evidence for cell lysis in the system.




(a)




(b)

Figure 4.26 Intensive Monitoring for (a) SBAR and (b) MABR at 4 kgCOD/$m^3$.d & 0.4 kgN/$m^3$.d

### 4.3.3 Fouling Behavior of MABR

### A. TMP Profile

The TMP profile for conventional MBR and MABR are shown in the Figure 4.27.

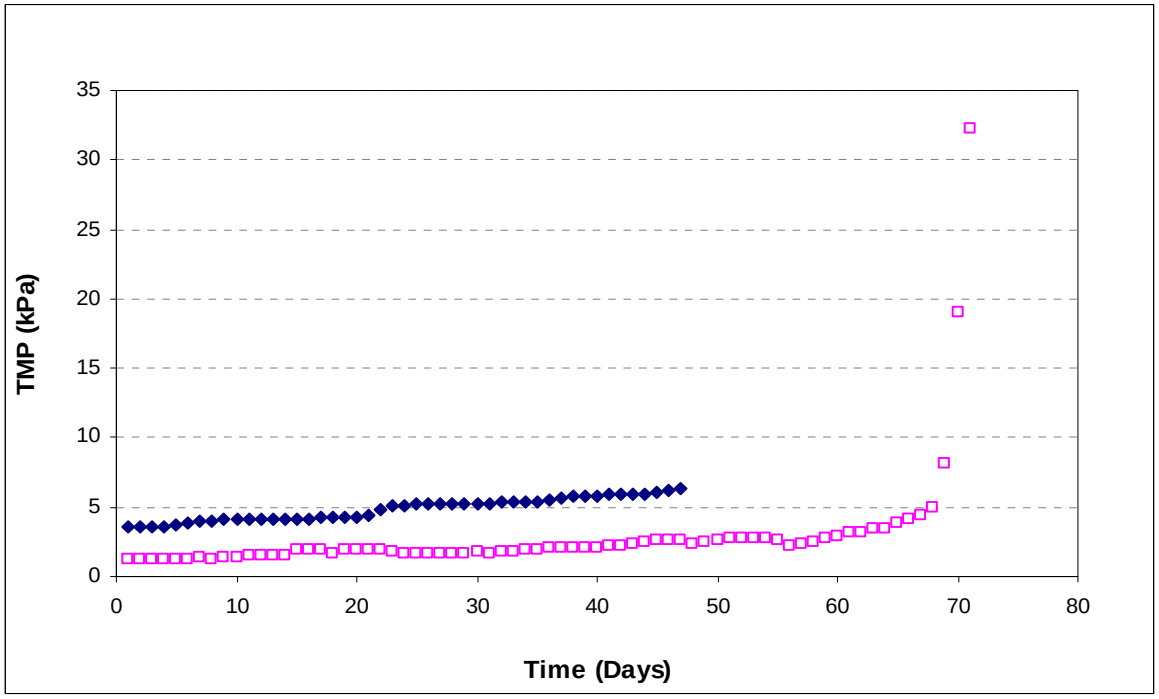



Figure 4.27 TMP Profile of MABR and Conventional MBR

The fouling rate in MABR and conventional MBR were 0.060 and 0.029 kPa/d respectively which might be due to different mode of operation. The conventional MBR was in continuous operation while the MABR was operated in batches where anoxic and aerobic conditions exist. The TMP profiles show similar fouling trend for both membrane bioreactors. However the OLR in AGMABR is higher when compared to conventional MABR. Further, the air supplied in the conventional MBR (9.6 $m^3/m^2.h$) was 2.2 fold higher than the air supplied in MABR (4.4 $m^3/m^2.h$). Hence, it could be concluded that with low aeration and high organic loading the AGMABR showed less fouling (Figure 4.27)

### B. Bound and Soluble Extra Cellular Polymeric Substance (EPS)

Many researchers have found that the soluble and bound EPS extend the fouling in a membrane. It is assumed that the soluble and bound EPS consist of polysaccharides and proteins which are retained on the membrane surface during filtration. The increase in soluble PS & PN in MABR showed the existence of cell lysis in the MABR (Appendix D, Table D.4). Further, 30% and 50% of the soluble PS and PN were retained by the membrane respectively which showed that the remaining PS and PN were deposited on pores and surface of the membrane (Figure 4.28).

The bound PS and PN concentrations for different sludge are tabulated in Table 4.5. The bound PS of flocs from SBAR was much higher than any other sludge and relatively a large amount of flocs in the SBAR was washed out to MABR during each batch of operation. Hence, it could be concluded that the bound PS of flocs would have contributed

for fouling in MABR. If the granules in SBAR reactor become big and matured, the flocs could not be seen in the reactor which would further reduce the membrane fouling.

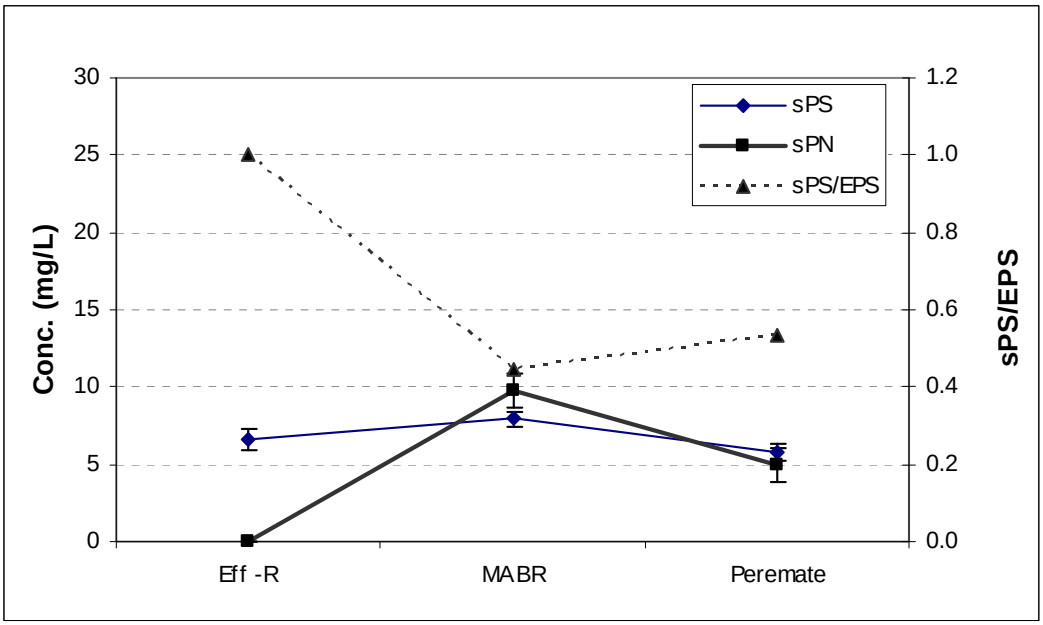



Figure 4.28 Soluble Polysaccharides and Protein at 4 kgCOD/$m^3$.d & 0.4 kgN/$m^3$.d

Due to high MLVSS maintained in conventional MBR, the bound EPS was less when compared to MABR. Also, from the research by Munasinghe (2008), the soluble PS in the conventional MBR was 2 fold higher than that in MABR which shows that the cell lysis in the conventional MBR is higher. Further, 45% and 71% of the soluble EPS consist of sPS in MABR and conventional MBR shows that in MABR, the sPS and sPN have equal contribution on fouling while in conventional MBR, major contributor is sPS. During another research (Liang et al., 2007) it was found that 60% of the soluble EPS contains sPS. Several researchers have identified that the sPS is the major contributor for membrane fouling (Jarusutthirak and Amy, 2007; Rosenberger et al., 2006, Le-Clech et al., 2006). Hence, it could be concluded that in MABR the production of sPS is less when compared to conventional MBR which would result in lesser fouling in membrane.

Table 4.6 Polysaccharides and Protein contents of different sludge

| **Parameter** | **Unit** | **MABR Sludge** | **SBAR Sludge** | | **Conventional MBR Sludge** | | **MABR OLR 2** kgCOD/$m^3$.d |
|---|---|---|---|---|---|---|---|
| | | | **Granule** | **Floc** | * | + | |
| Bound PS | mgPS/mgVSS | 13.7 | 6.4 | 19.1 | 5.2 | - | - |
| Bound PN | mgPN/mgVSS | 11.1 | 2.3 | 0.0 | 2.8 | - | - |
| MLVSS | mgVSS/L | 3900 | 7600 | 360 | 9050 | 8000 | 3500 |
| Soluble PS | mg/L | 8.0 | - | - | 17.7 | 8.0 | 26.0 |
| Soluble PN | mg/L | 9.8 | - | - | 7.4 | 5.6 | 9.0 |

* Source: Munasinghe (2008) + Liang et al. (2007)

The Figure 4.29 shows the TMP profiles of MABR at 2 (Run1) and 4 (Run 3) kgCOD/$m^3$.d. During Run 1 of this research the soluble PS presence in the system was 3.3 fold higher than that of Run 3 which might have increased the potential for rapid fouling in MABR during Run1. Hence, it could be concluded that the sPS is one of the major factor

which contribute for fouling. Furthermore, less sPS was reported at high organic loading which is one of the advantages in MABR system.

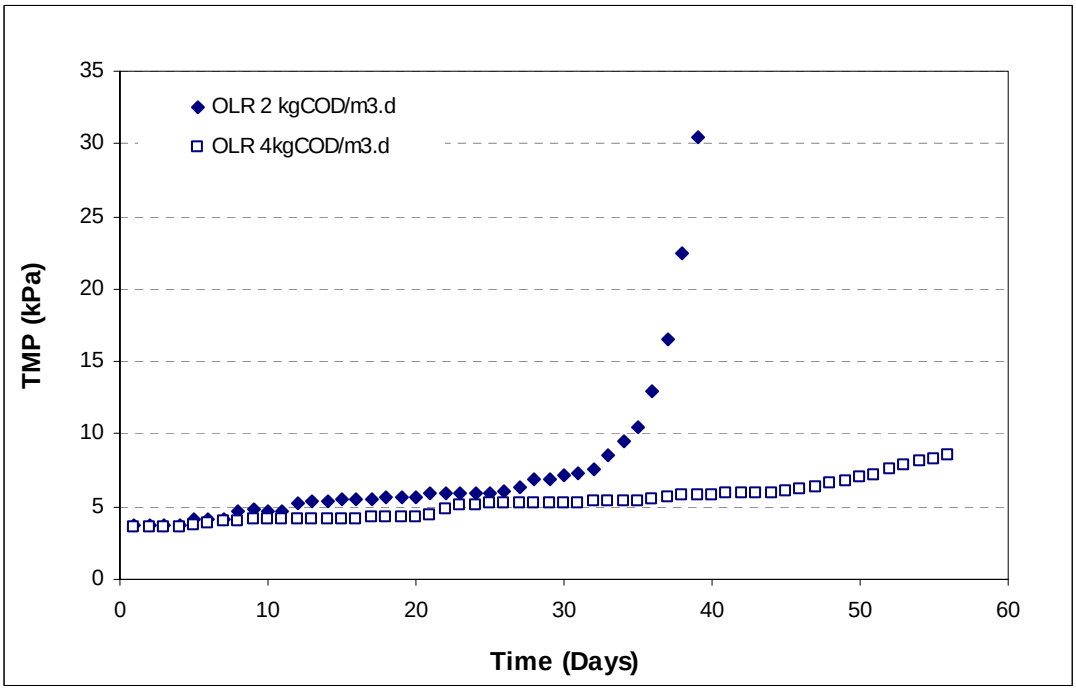



Figure 4.29 TMP Profile at 2 and 4 kgCOD/$m^3$.d

**C. Particle size distribution**

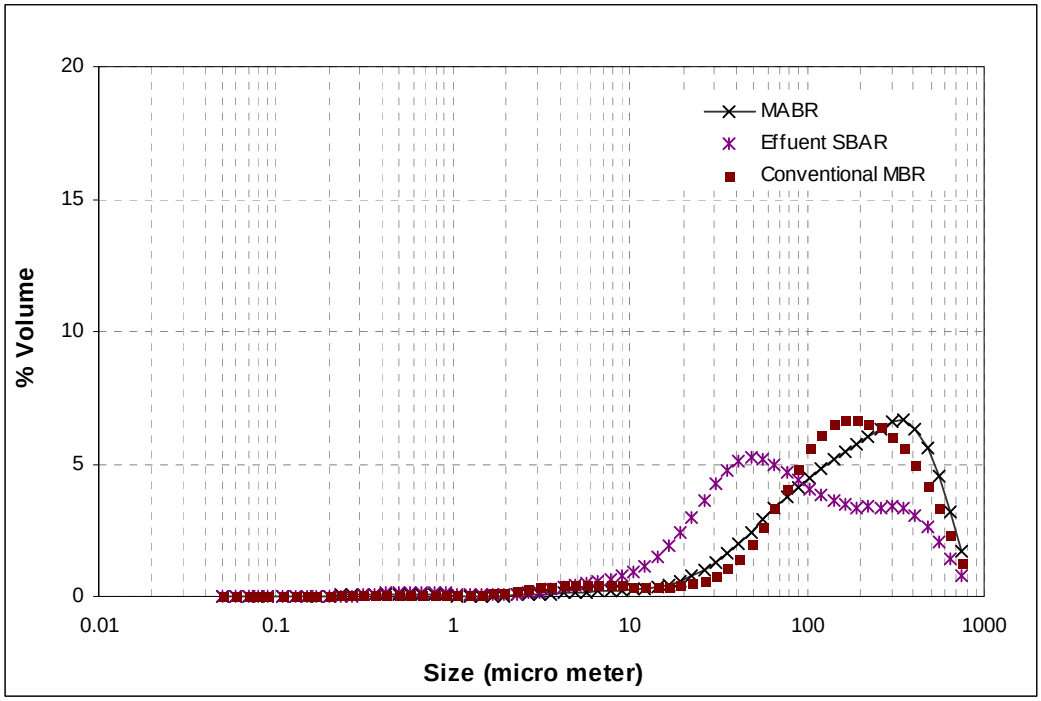



Figure 4.30 Particle Size Distribution of Different Sludge in terms of % volume

The particle size distribution of MABR, Effluent SBAR and conventional MBR sludge are shown in Figure 4.30. The mean diameter of the particles of MABR, Effluent SBAR and conventional MBR sludge were 256 μm, 150 μm and 229 μm respectively based on %

volume. The mean size of particles in MABR and conventional MBR were comparable which could be assumed that the fouling induced by particles is similar in both reactors. Further, by % volume almost all the particles were more than 0.1 μm and the no significant effect on pore clogging by MABR, Eff-R and conventional MBR sludge.

The AGMABR system has several advantages when compared to conventional MBR. The biomass in the MABR is much less than the conventional MBR due to granular reactor and cell lysis in the system. Also, the system can remove nitrogen through denitrification process and if the external electron donor is supplied the high denitrification rate could be achieved in the system. In both the systems, the complete nitrification could be achieved which would overcome the problem of free ammonia discharge to the environment. Further, the nitrogen loading in this study is very much higher when compared to others (Jun et al., 2007). On top of the above mentioned benefits the MABR has several advantages when compared to conventional MBR, such as no direct contact with substrate supply, low biomass concentration maintained in the reactor, low aeration requirement and presence of aerobic and anoxic zones within the reactor. Hence, the AGMABR system will be an attractive alternative option for water reuse and recycling in the near future.

# CHAPTER 5

# CONCLUSIONS AND RECOMMENDATIONS

During this study, the SBAR was operated at organic and nitrogen loadings of 4 kg COD/$m^3$.d and 0.4 kg N/$m^3$.d. Subsequently, the supernatant from the batch granulation reactor was discharged into a membrane airlift bioreactor (MABR) for membrane filtration. In the MABR system, the remaining organic matters and nitrogen species were removed through assimilation, simultaneous nitrification and denitrification as per the configuration where both aerobic and anoxic conditions exist. This research resulted in three major aspects namely, (a) Granular sludge stability, (b) Denitrification in MABR and (c) Performance of AGMABR. Conclusions and recommendations drawn from this research are summarized below.

## 5.1 Conclusions

### A. Granule Stability and its effect at OLR 2 kgCOD/$m^3$.d (Run 1)

1. Due to long SRT (more than 300 days) and sudden changes in OLR, the stability of the granular sludge was disturbed which affected the performance of the system. To reduce the granule breakage, the sludge in the reactor to be removed periodically where the new sludge was washed out with supernatant while accumulation of aged sludge in the reactor was occurring in every batch operation.

2. At the start up stage of the granular reactor, the NLR need not be high as 0.6 kgN/$m^3$.day which had produced free ammonia in the system. Hence, the granule formation was restrained. In addition, the incomplete nitrification in the granular reactor increased the pH and as a result, the free ammonia production was also favored.

3. The SVI of MABR was 2.5 fold higher than that of granular sludge which concluded that the granular sludge has excellent settling ability. The presence of large amount of *Rotifer sp.* in the granular sludge was evident for excellent settleability.

### B. Performance of MABR at Different Nitrogen Loading (Run 2)

4. The nitrogen removal through denitrification process at case 1, 2 and 3 was 24%, 4% and 30% respectively which was limited by lack of electron donor in the MABR (Case 1: 5 mgN/L, Case 2: 3 mgN/L and Case 3: 10 mgN/L). Further, with the external carbon addition, the MABR could achieve maximum 70% of nitrogen removal including 50% of denitrification and 80% organic removal.

5. After 2 hrs of operation, the TOC and TN in the MABR showed increment in their values during intensive monitoring. This was due to cell lysis in the reactor and the TN production rate was found to be 0.6 mg TN/gVSS.h. Further, from the cell lysis test in MABR, it could be concluded that the HRT of 2-5 h is the optimum condition for filtering the supernatant of granulation reactor. At this HRT range it can achieve better quality of permeate and less fouling due to low sPS, sPN, sTN and TOC. However, further investigation should be done to evaluate the fouling potential with different HRTs.

6. Approximately 50% of the soluble PS was retained by the membrane in all three cases while the PN produced was nil during this run. The soluble PS and PN, and bound PS and PN in case 2 were higher than the other two cases due to nutrient deficiency in the system.

**C. Performance of Aerobic Granular Membrane Airlift Bioreactor (Run 3)**

7. The organic and nitrogen removal in AGMABR were 99% and 61% respectively where 35% of the total nitrogen was removed by denitrification process. On the other hand in conventional MBR the organic and nitrogen removal achieved were 98% and 27% respectively. Hence, the AGMABR system could remove more organic and nitrogen when compared to conventional MBR. However, the limiting parameter for denitrification process in MABR is the electron donor (external carbon source) and if the external carbon source is added to MABR it could achieve more nitrogen removal through denitrification in the system.

8. The soluble PS in MABR was less when compared to conventional MBR which showed that the MABR configuration could reduce the membrane fouling as the sPS was the major contributor for fouling. In addition at OLR 4 kgCOD/$m^3$.d the sPS in the MABR was 3.3 fold lower than that of OLR 2 kgCOD/$m^3$.d and as a result the potential for rapid fouling at high OLR might be less.

9. Flocs in the SBAR had less settling ability and they were washed out to MABR every 4 hrs of operation. The EPS of flocs had contributed for rapid fouling in membrane. During this run the granule size was 1.7±0.1 mm and flocs were seen in the SBAR. Once, the granules become matured and big in future, the flocs would be less and nitrogen removal through denitrification would be more in the system. As a result, the fouling in MABR also could be reduced.

10. The TMP profiles show that the fouling trend for conventional MBR and MABR are similar. However, the OLR treated in AGMABR and conventional MBR were 4 and 2.4 kgCOD/$m^3$.d respectively which proves the better performance of MABR at high OLR.

11. Even though the nitrogen loading in this study was very much higher when compared to other researches at OLR 4 kg COD/$m^3$.d and NLR 0.4 kg N/$m^3$.d the AGMABR shows a good performance. Hence, the AGMABR system would be an attractive alternative option for water reuse and recycling in the near future.

## 5.2 Recommendations for future research

1. Due to long sludge retention, the SBAR was not operated at various organic or nitrogen loading to optimize the loading conditions based on removal efficiencies and membrane fouling in this research. This optimization to be considered in the future research work.

2. Cultivation of aerobic granules to be done with the different types of wastewater such as domestic or industrial wastewater having high organic and nitrogen contents. For synthetic wastewater it is difficult to conclude the stability of granules since, industrial or domestic wastewaters do not have the same loading at all the time.

3. In this research the aerobic granules were cultivated with batch operation. Hence, cultivation of granules with continuous system like biofilm airlift suspension reactor instead of sequencing batch airlift reactor to be evaluated.

4. EPS is one of the major factors which support the fouling in membrane. The C/N ratio maintained during this experiment was 10. Hence, the effect of EPS production in membrane fouling to be studied for different C/N ratios such as 100:5, 100:10, 100:15 and so on. In addition, the effect of humic substances, which is one of the components of EPS, to be focused based on fouling potential in the MABR system.

5. From the cell lysis test in MABR, it was found that the HRT of 2-5 h was the optimum condition for filtering the supernatant of granulation reactor. On this HRT range it could achieve better quality of permeate and less fouling due to low sPS, sPN, sTN and TOC. During this research the HRT of the MABR was 11 hrs which could favor the cell lysis in the reactor. Hence, further investigation to be done to evaluate the fouling potential with different HRTs of MABR or MBR treating supernatant of granulation reactor.

6. Feeding in MABR in this study was a batch operation which could be changed in to an intermittent operation. As per the results achieved during the intensive monitoring of MABR, it could be concluded as after 2 hrs of operation, the TN removal was not significant and the cell lysis was severe in the reactor. Hence, it is proposed that the MABR feeding to be changed to intermittent feeding to evaluate the performance in terms of removal efficiencies and fouling. Furthermore, the proposed design of MABR would reduce the volume of the reactor by 35% and ultimately the HRT of the MABR would be reduced to 7 hrs which might reduce the cell lysis in the system. The proposed design by self with the above concept for the MABR with intermittent feeding is shown in Figure 5.1.

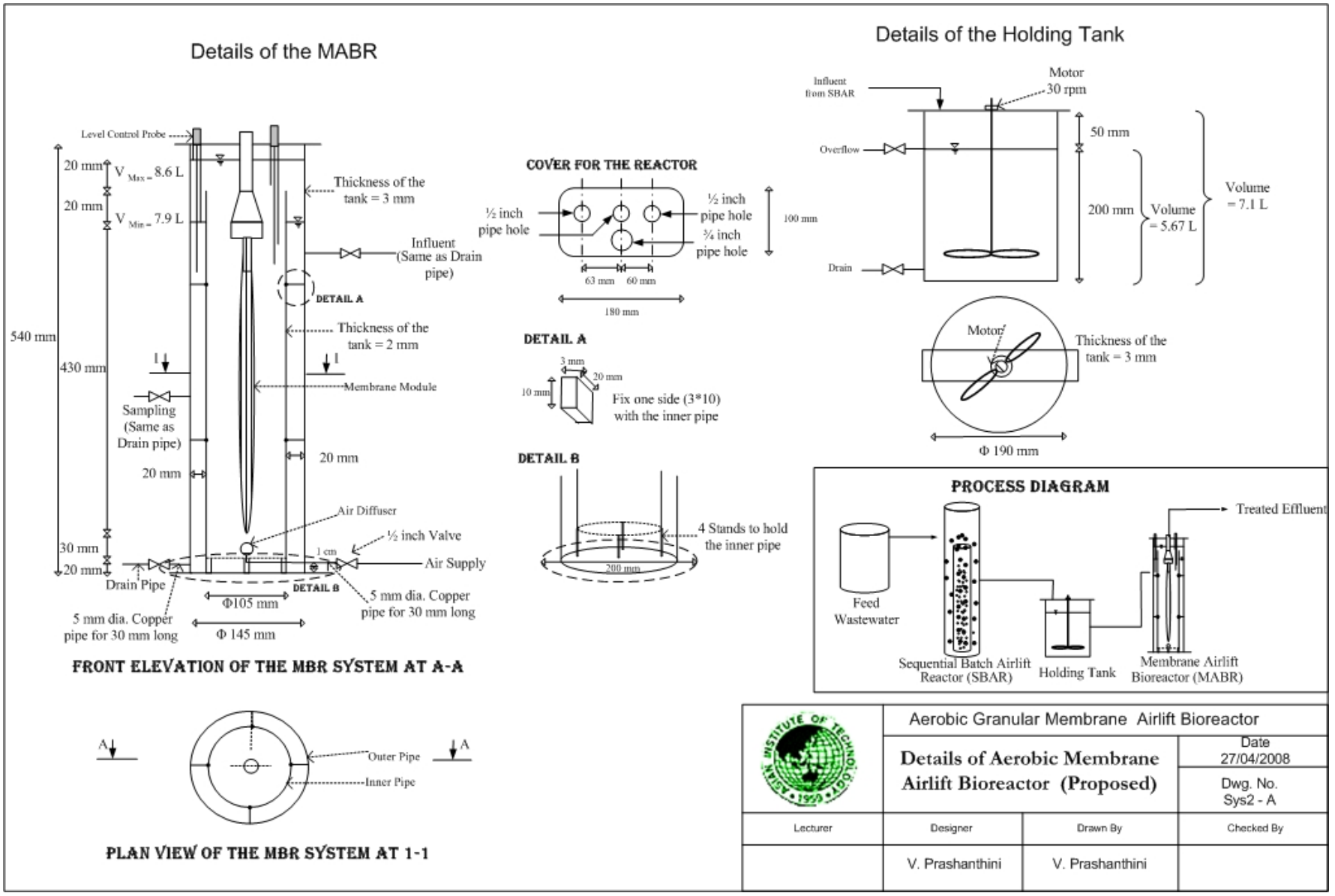



Figure 5.1 Design Details of Proposed MABR for future study

## References


APHA, AWWA, WPCF (1992). Standard methods for examination of water and wastewater, 18th Edition, Washington DC:APHA

Beun, J.J., Hendriks, A., Van Loosdrechat, M.C.M., Morgenroth, E. P. A. & Heijnen, J.J., (1998). Aerobic Granulation in a Sequencing Batch Reactor. *Water Research, 33* (10), 2283-2290.

Beun, J.J., Hendriks, A., Van Loosdrecht, M.C.M., Morgenroth, E.P.A. & Heijnen, J.J. (1999). Aerobic Granulation in a Sequencing Batch Reactor. *Water Research, 33*, 2283-2290.

Beun, J.J., van Loosdrecht, M.C.M. & Heijnen, J.J. (2000). Aerobic Granulation. *Water Science and Technology, 41*(4-5), 41-48.

Bouhabila, E. H., Ben Aim, R. & Buisson, H. (2001). Fouling Characterization in Membrane Bioreactors. *Separation Purification Technology, 22-23*, 123-132.

Cai, C., Xu, F., Zhu, N. & Cai, W. (2004). Cultivation of Aerobic Granules in a Sequencing Batch Shaking Reactor. *Environmental Technology, 25*, 937-944.

Cassidy, D.P. & Belia, E. (2005). Nitrogen and Phosphorus Removal From an Abattoir Wastewater in a SBR With Aerobic Granular Sludge. *Water Research, 39*, 4817-4823.

Cech, J.S., Chudoba, J. & Grau, P. (1984). Determination of Kinetic Constants of Activated Sludge Microorganisms. *Water Science and Technology, 17*, 259-272.

Chang, I-S., Clech, P.L., Jefferson, B. & Judd, S. (2002). Membrane Foulign in Membrane bioreactors for Wastewater Treatment. *Journal of Environmental Engineering*, 1018-1029.

Chiu, Y-C., Lee, L-L., Chang, C-N. & Chao, A. C. (2007). Control of carbon and ammonium ratio for simultaneous nitrification and denitrification in a sequencing batch bioreactor, *International Biodeterioration & Biodegradation, 59*, 1-7.

Cho, B.D. & Fane, A.G. (2002). Fouling transients in nominally sub-critical flux operation of a membrane bioreactor. *Journal of Membrane Science, 209*, 391–403.

Choi, C., Lee, J., Lee, K. & Kim, M. (2008). The effects on operation conditions of sludge retention time and carbon/nitrogen ratio in an intermittently aerated membrane bioreactor (IAMBR), *Bioresource Technology*, In Press, Corrected Proof.

Chudoba, P., Capdeville, B. & Chudoba, J. (1992). Explanation of Biological Meaning of the So/Xo Ratio in Batch Cultivation. *Water Science and Technology, 26*, 743-751.

De Kreuk, M.K., Pronk, M. & Van Loosdrecht, M.C.M. (2005). Formation of Aerobic Granules and Conversion Processes In An Aerobic Granular Sludge Reactor At Moderate Temperature. *Water Research, 39,* 4476-4484.

Dubois M, Gilles K.A., Hamilton J.K, Rebers P.A. & Smith F. (1956). Calorimetric method for determination of sugars and related substances. *Analytical Chemistry*, *28*, 350–356.

Etterer, T. & Wilderer, P.A. (2001). Generation and Properties of Aerobic Granular Sludge. *Water Science and Technology*, *43*(3), 19-26.

Fan, Y., Li, G., Wu, L., Yang, W., Dong, C., Xu, H. & Fan, W. (2006). Treatment and reuse of toilet wastewater by an airlift external circulation membrane bioreactor. *Process Biochemistry, 41,* 1364-1370.

Frolund, B., Palmgren, R., Keiding, K. & Neilsen, P.H. (1996). Extraction of Extracellular Polymer from Activated Sludge using a Cation Exchange Resin. *Water Research*, *30*, 1749-1758.

Gang, WU-L., Chun-song, D., Guang-xia, WU. & Yao-bo, F. (2007). Inorganic nitrogen removal of toilet wastewater with an airlift external circulation membrane bioreactor. *Journal of Environmental Science, 19*, 12-17.

Gong, Z., Yang, F., Liu, S., Bao, H., Hu, S. & Furukawa, K. (2007). Feasibility of a membrane-aerated biofilm reactor to achieve single-stage. *Chemosphere,* doi:10.1016/j.chemosphere.2007.05.023.

Han, S-S., Bae, T-H., Jang, G-G. & Tak, T-M. (2005). Influence of sludge retention time on membrane fouling and bioactivities in membrane bioreactor system. *Process Biotechnology, 40*, 2393-2400.

Harendranath, K., Anju, S., Gunaseelan, A., Satish, K. & Lala, K. (1996). Immobilization in fixed film reactors: An ultra structural approach. *Water Science and Technology, 33*(8), 7-15.

He, S-B., Xue, G. & Wang B-Z. (2006). Activated sludge ozonation to reduce sludge production. *Journal of Hazardous Material, B135,* 406-411.

Jang, A., Yoon, Y.H., Kim, I.S. & Bishop, P.L. (2003). Characterization and Evaluation of Aerobic Granules in Sequencing Batch Reactor. *Journal of Bio Technology*, *105*, 71-82.

Jarusutthirak, C. & Amy, G. (2007). Understanding Soluble Microbial Products (SMP) as a Component of Effluent Organic Matter (EfOM). *Water Research*, *41*, 2787-2793.

Jarusutthirak, C. & Amy, G. (2006). Role of soluble microbial products (SMP) in membrane fouling and flux decline. *Environmental Science Technology, 40*, 969-974.

Jun, Z., Feng-lin, Y., Fan-gang, M., Peng, AN. & Di, W. (2007). Comparison of membrane fouling during short-term filtration of aerobic granular sludge and activated sludge. *Journal of Environmental Science, 19*, 1281-1286.

Kim, S., Kim, S-M. & Jang, A. (2008). Characterization of aerobic granules by microbial density at different COD loading rates. *Bio resource Technology, 99*, 18-25.

Kim, J. & DiGiano, F.A. (2006). A two-fibre, bench-scale test of ultra filtration (UF) for investigation of fouling rate and characteristics. *Journal of Membrane Science, 271*, 196-204.

Le-Clech, P., Jefferson, B., Chang, I. S. & Judd, S. J. (2003). Critical flux determination by flux step method in a submerged membrane bioreactor. *Journal of Membrane Science, 227*, 81-93.

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

Le-Clech, P., Jefferson, B. & Judd, S.J. (2003). Impact of Aeration, Solids Concentration and Membrane Characteristics on the Hydraulic Performance of a Membrane Bioreactor. *Journal of Membrane Science, 218*, 117–129.

Li, X., Li, Y., Hua, Z., Du, G. & Chen, J. (2007). Characteristics of Aerobic Biogranules from Membrane Bioreactor System. *Journal of Membrane Science*, 294-299.

Li, Z.H., Kuba, T. & Kusuda, T. (2006). The Influence of Starvation Phase on the Properties and the Development of Aerobic Granules. *Enzyme and Microbial Technology, 38*, 670-674.

Li, X., Gao, F., Hua, Z., Du, G. & Chen, J. (2005). Treatment of Synthetic Wastewater by a Novel MBR With Granular Sludge Developed For Controlling Membrane Fouling. *Separation and Purification Technology, 46*, 19-25.

Liang, S., Liu, C. & Song, L. (2007). Soluble Microbial Products in Membrane Bioreactor Operation: Behaviors, Characteristics, and Fouling Potential. *Water Research*, *41*, 95-101.

Linlin, H., Jianlong, W., Xianghua, W. & Yi, Q. (2005). The Formation and Characteristics of Aerobic Granules in Sequencing Batch Reactor (SBR) by Seeding Anaerobic Granules. *Process Biochemistry, 40*, 1-7.

Lin, Y.-M., Liu, Y. & Tay, J.-H. (2003). Development and Characteristics of Phosphorus-Accumulating Microbial Granules in Sequencing Batch Reactors. *Applied Microbial and Cell Physiology, 62*, 430–435.

Liu, Y & Liu, Q.-S. (2006). Cause and Control of Filamentous Growth in Aerobic Granular Sludge Sequencing Batch Reactors. *Biotechnology Advances*, *24*, 115-127.

Liu, L., Wang, Z., Yao, J., Sun, X. & Cai, W. (2005). Investigation on the properties and kinetics of glucose-fed aerobic granular sludge. *Enzyme and Microbial Technology, 36*,307-313.

Liu, Y., Yang, S.F. & Tay, J-H. (2004). Improved Stability of Aerobic Granules by Selecting Slow Growing Nitrifying Bacteria. *Journal of BioTechnoogy*, *108*, 161-169.

Liu, Y. & Tay, J-H. (2004). State of the Art of Bio Granulation Technology for Wastewater Treatment. *Biotechnology Advances*, *22*, 533-563.

Liu, Y. & Fang, H.H.P. (2003). Influences of Extracellular Polymeric Substances (EPS) on Flocculation, Settling and Dewatering of Activated Sludge. *Environmental Science and Technology*, *33*, 237-273.

Liu, Y., Yang, S.F. & Tay, J-H. (2003). A Thermodynamic Interpretation of Cell Hydrophobicity in Aerobic Granulation. *Applied Microbial Cell Physiology*, *64*, 410-415.

Liu, Y-Q. & Tay, J-H. (2006). Variable aeration in sequencing batch reactor with aerobic granular sludge. *Journal of Biotechnology*, *124*, 338-346.

Liu, Y. & Tay, J-H. (2002). The Essential Role of Hydrodynamic Shear Force in the Formation of Biofilm and Granular Sludge. *Water Research, 36*, 1653-1665.

Lowry, O.H., Resebrough, N.J., Farr, A.L. & Randall, R.J. (1951). Protein measurement with the folin phenol reagent. *Journal of Biological Chemistry, 193*(2), 265–275.

McSwain, B.S., Irvine, R.L. & Wilderer, P.A. (2004). The Effect of Intermittent Feeding on Aerobic Granule Structure. *Water Science and Technology, 49*, 19-25.

Metcalf and Eddy (2004). *Wastewater Engineering: Treatment and Reuse. (4$^{th}$ ed.)*. New York: McGRAW-HILL:ISBN 007-124140-X.

Moy, B.Y.-P., Tay, J.-H., Toh, S.-K., Liu, Y. & Tay, S.T.-L. (2002). High Organic Loading Influences the Physical Characteristics of Aerobic Sludge Granules. *The Society for Applied Microbiology*, *34*, 407–412.

Morgenroth, E., Sherden, T., Van Loosdrecht, C. M., Heijnen, J.J. & Wllderer, A. (1997). Rapid Communication: Aerobic Granular Sludge in a Sequencing Batch Reactor. *Water Research, 31*(12), 3191-3196.

Munasinghe, P. C. (2008). *Comparison of Nitrogen Removal between Conventional Membrane bioreactor and Attached Growth Membrane Bioreactor*. Master thesis study will be published later, Asian Institute of Technology, Bangkok.

Pratt, S., Tan, M., Gapes, D. & Shilton, A. (2007). Development and examination of a granular nitrogen-fixing wastewater treatment system. *Process Biochemistry*, *42*, 863-872.

Qin, L. & Liu, Y. (2005). Aerobic Granulation for Organic Carbon and Nitrogen Removal In Alternating Aerobic-Anaerobic Sequencing Batch Reactor. *Chemosphere*, In Press.

Rosenberger, S., Laabs, C., Lesjean, B., Gnirss, R., Amy, G., Jekel, M. & Schrotter, J.C. (2006). Impact of colloidal and soluble organic material on membrane performance in membrane bioreactors for municipal wastewater treatment. *Water Research, 40*, 710-720.

Schwarzenbeck, N., Erley, R. & Wilderer, P.A. (2004). Aerobic Granule Sludge in an SBR-system Treating Wastewater Rich in Particulate Matter. *Water Science and Technology, 49*, 41-46.

Stephenson, T., Judd, S., Jefferson, B. & Brindle, K. (2000). Membrane bioreactors For Wastewater Treatment. Industrial Membrane Separation Technology. IWA Publishing, Alliance House, London: ISBN 1-900222-078.

Tam, L.S., Tang, T.W., Leung, W., Chen, G.H. & Sharma, K.R. (2006). Pilot study on performance of a membrane bio-reactor in treating fresh water sewage and saline sewage in Hong Kong. *Science Technology, 41*, 1253-1264.

Tay, J.H., Yang, P., Zhuang, W.Q., Tay, S.T.L. & Pan, Z. H. (2007). Rector Performance and Membrane Filtration in Aerobic Granular Sludge Membrane Bioreactor. *Journal Membrane Science, 304*, 24-32.

Tay, J.-H, Liu, J. & Sun, D.D. (2003), Quantification of membrane fouling using thermogravimetric method. *Journal of Membrane Science, 217*, 17–28.

Tay, J.-H., Liu, Q.S. & Liu, Y. (2001). Microscopic observation of aerobic granulation in sequential aerobic sludge reactor. *Journal of Applied Microbiology*, 91, 168-175.

Tay, J.H., Liu, Q.S. & Liu, Y. (2002). Aerobic Granulation in Sequential Sludge Blanket Reactor. *Water Science and Technology, 46*, No 4-5, 41-48.

Tay, J.-H., Liu, Q.S. & Liu, Y. (2004). The Effect of Upflow Air Velocity on The Structure of Aerobic Granules Cultivated in a Sequencing Batch Reactor. *Water Science and Technology, 49*, 35-40.

Tijhuis, L., Van Loosdrecht, M.C.M. & Heijnen, J.J. (1994). Formation and Growth of Heterotrophic Aerobic biofilms on Small Suspended Particles in Airlift Reactors, Biotechnology and Bioengineering, *44*, 595-608.

Thanh, B. X. (2005). *Aerobic Granulation Coupled Membrane Bioreactor*. Master thesis study No. EV-05-5, Asian Institute of Technology, 2005. Bangkok: Asian Institute of Technology.

Trigo, C., Campos, J. L., Garrido, J. M. & Mendez, R. (2006). Start-up of the Anammox Process in a Membrane Bioreactor. *Journal of Biotechnology, 126*, 475-487.

Tsuneda, S., Nagano, T., Hoshino, T., Ejiri, Y., Noda, N. & Hirata, A. (2003). Characterization of Nitrifying Granules Produced in an Aerobic Up flow Fluidized Bed Reactor. *Water Research, 37*, 4965-4973.

Visvanathan, C., Ben Aim, R. & Parameshwaran (2000). Membrane Separation Bioreactors for Wastewater Treatment. *Environmental Science and Technology*, *30*, 1-48.

Wang, S-G., Liu, X-W., Gong, W-X., Gao, B-Y., Zhang D-H. & Yu, H-Q. (2007). Aerobic Granulation with Brewery Wastewater in Sequencing Batch Reactor. *Bioresource Technology*, *98*, 2142-2147.

Wang, Z.-W., Liu, Y. & Tay, J.-H. (2006a). The Role of SBR Mixed Liqour Volume Exchange Ratio In Aerobic Granulation. *Chemosphere*, *62*, 767-771.

Wang, Z.-W., Liu, L., Yao, J. & Cai, W. (2006b). Effects of extracellular polymeric substances on aerobic granulation in sequencing batch reactors. *Chemosphere*, *63*, 1728-1735.

Wang, Q., Du, G. & Chen, J. (2004). Aerobic Granular Sludge Cultivated Under the Selective Pressure as a Driving Force. *Process Biochemistry*, *39*, 557-563.

Wang, Q., Du, G. & Chen, J. (2003). Aerobic Granular Sludge Cultivated Under the Selective Pressure as a Driving Force. *Process Biochemistry*, *39*, 557-563.

Wingender, J., Neu, T.R. & Flemming, H.-C. (1999). Microbial Extracellular Polymeric Substances: Characterization, Structure and Function. Springer: ISBN 3-540-65720-7.

Wisniewski, C. (2007). Membrane bioreactor for water reuse. *Desalination*, *203*, 15-19.

Wisniewski, C. & Grasmick, A. (1998). Floc size distribution in a membrane bioreactor and consequences for membrane fouling. *Colloids and Surfaces*, *138*, 403-411.

Yang, S-F., Tay, J-H. & Liu, Y. (2004) Inhibition of Free Ammonia to the Formation of Aerobic Granules. *Biochemical Engineering Journal*, *17*, 41-48.

Yang, S.F., Tay, J.-H. & Liu, Y. (2003). Inhibition of Free Ammonia to the Formation of Aerobic Granules. *Biochemical Engineering Journal*, *17*, 41–48.

Zhang, L., Feng, X., Zhu, N. & Chen, J.. (2007). Role of extracellular protein in the formation and stability of aerobic granules. *Enzyme and Microbial Technology*, *41*, 551-557.

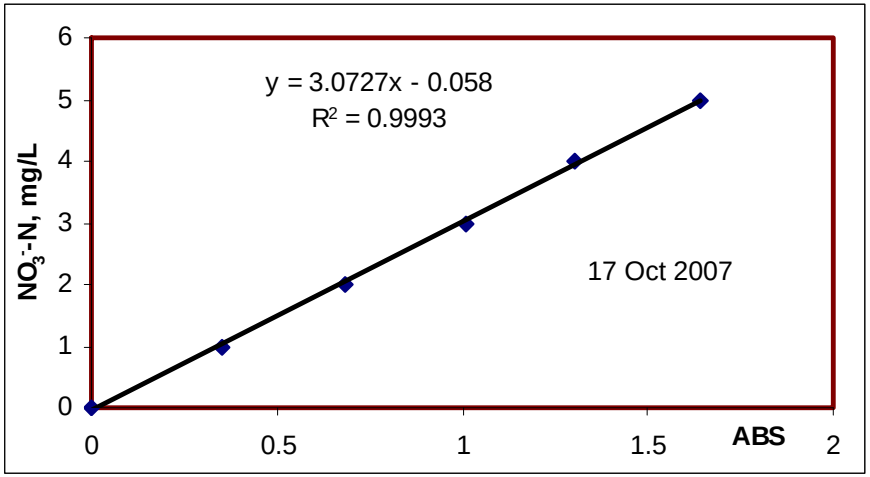
Zheng, Y.-M., Yu, H.-Q., Liu, S.-J. & Liu, X.-Z. (2005). Formation and Instability of Aerobic Granules under High Organic Loading Conditions. *Chemosphere*, In Press.

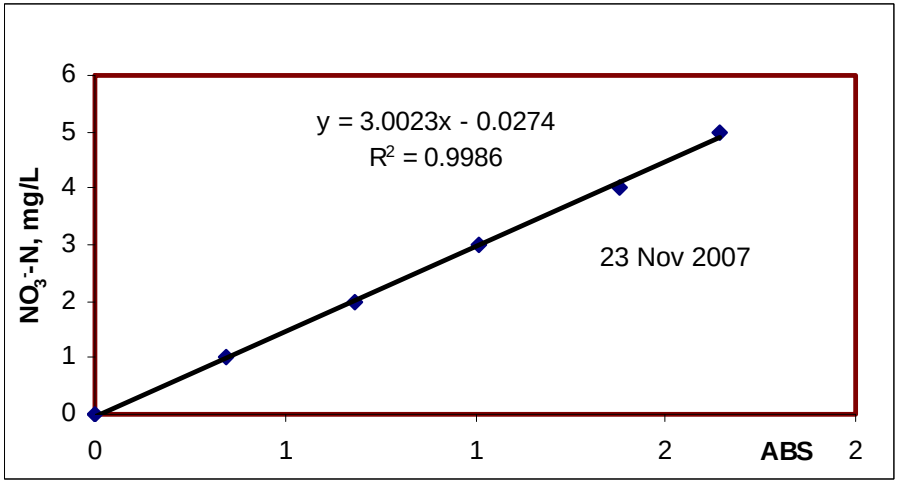
Zheng, Y.-M., Yu, H.-Q. & Sheng, G.-P. (2004). Physical and Chemical Characteristics of Granular Activated Sludge from a Sequencing Batch Airlift Reactor. *Process Biochemistry*, In-press.

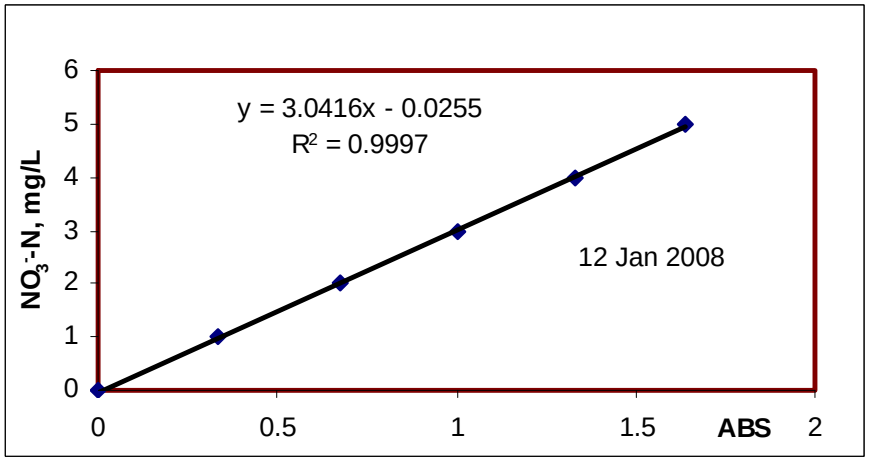
Zitomer, D. H., Duran, M., Albert, R. & Guven, E. (2007). Thermophilic Aerobic Granular Biomass for Enhanced Settleability. *Water Research*, *41*, 819-825.

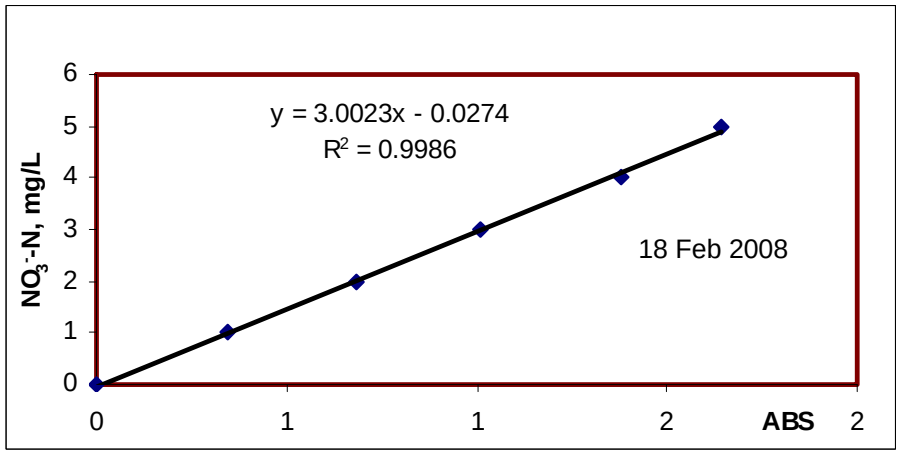
# Appendix A: Standard Curves

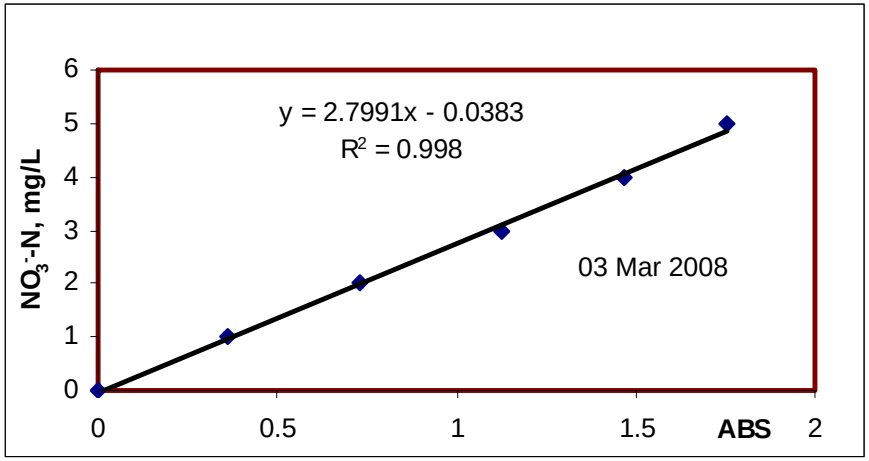
Table A.1 Nitrate Standard Curves





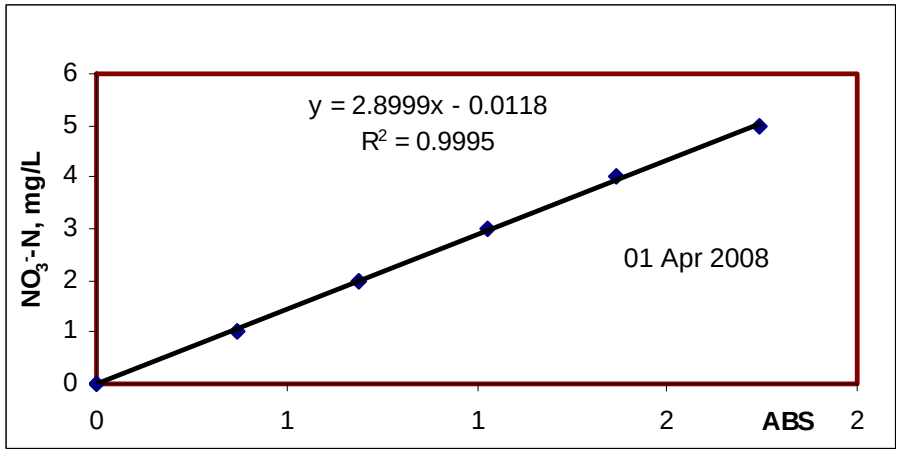
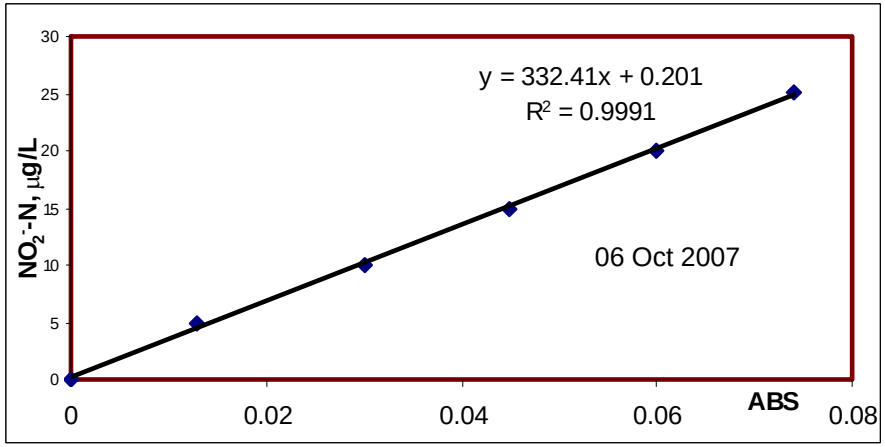




Table A.2 Nitrite Standard Curves



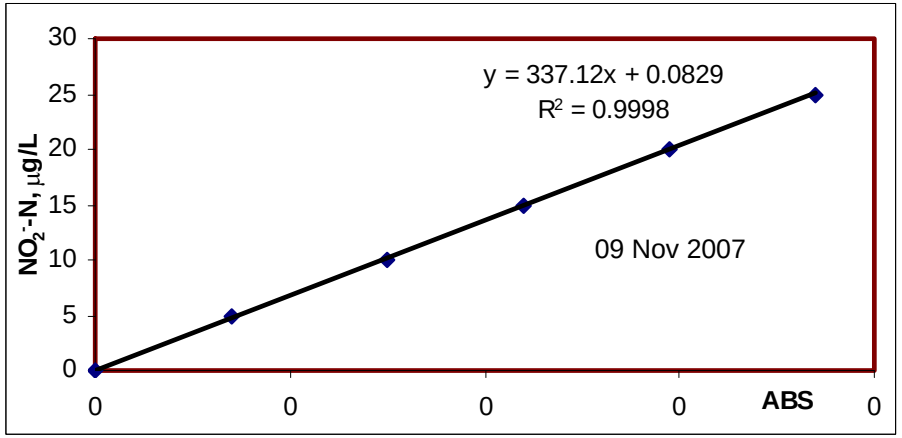
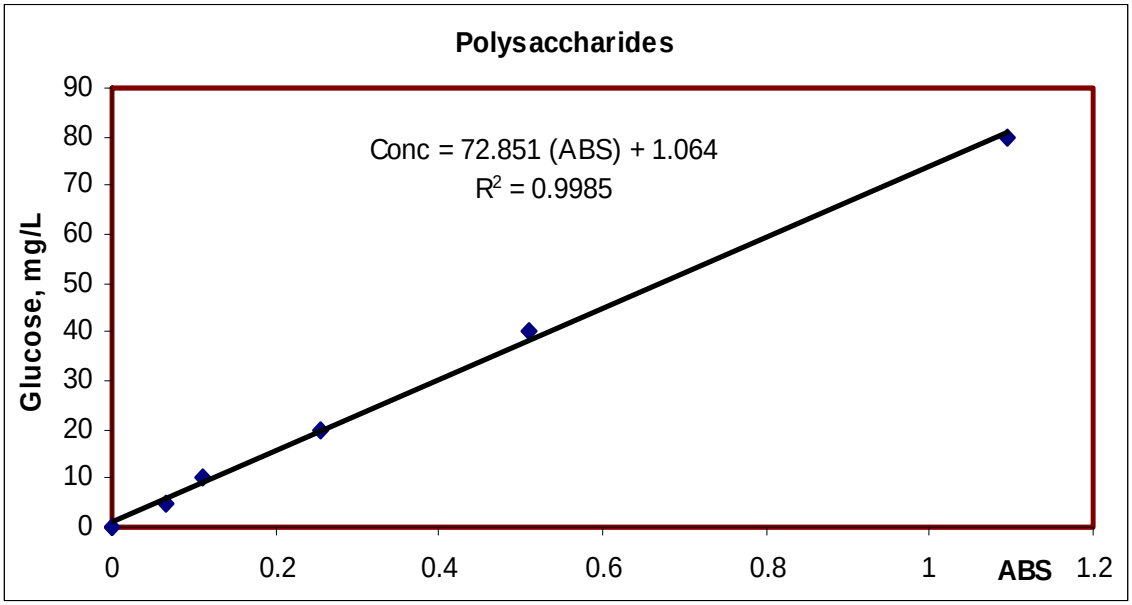
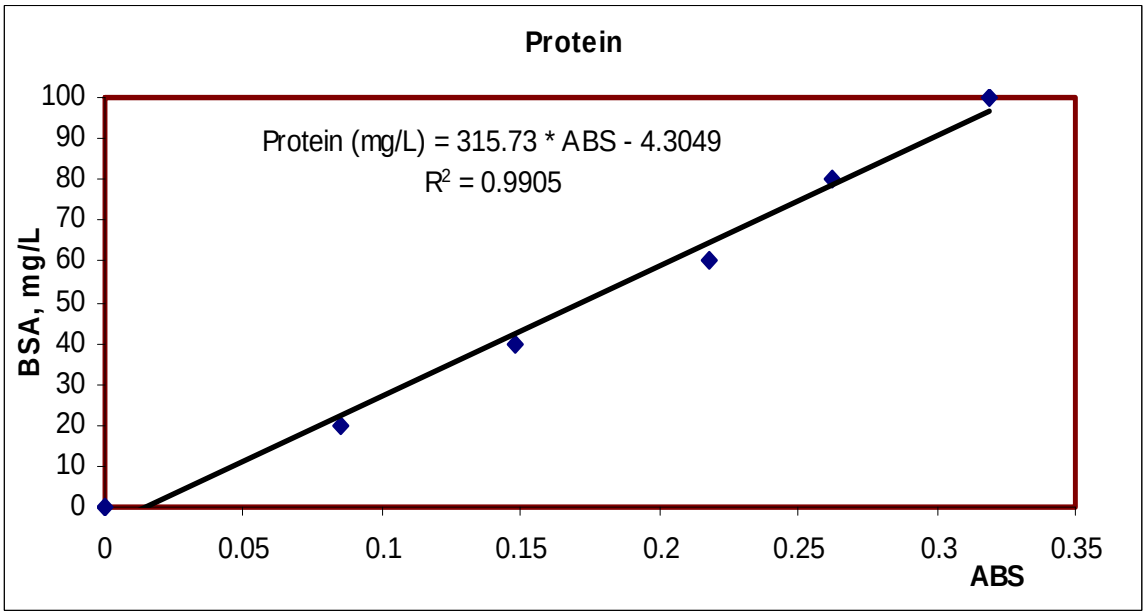



Table A.3 EPS (PS and PN) Standard Curves



## Appendix B: Raw Data for Run 1

Table B.1 Organic and Nitrogen concentration for various sampling points at OLR 2 & 4 kgCOD/$m^3$.d

**Run 1: OLR 2, NLR 0.6, air velocity 0.5 L/min**

| | | Inf | Eff-R | MABR | permeate | Inf | Eff-R | MABR | permeate | Inf | Eff-R | MABR | permeate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Inf | Eff-R | MABR | permeate | NO2-N (mg/L) = 357.58 * (ABS) + 0.4019 | | | | NO3-N (mg/L) = 3.4173 * (ABS) - 0.1239 | | | |
| **Date** | **Day** | **NH4-N** | | | | **NO2-N** | | | | **NO3-N** | | | |
| 17-Sep-07 | 4 | 159.6 | 1.1 | 0.6 | 0.3 | 0.03 | 61.01 | 10.93 | 2.13 | 1.12 | 49.53 | 89.04 | 97.92 |
| 20-Sep-07 | 7 | 156.8 | 1.4 | 0.6 | 0.3 | 0.02 | 25.25 | 0.21 | 0.05 | 0.00 | 86.99 | 105.65 | 106.94 |
| 24-Sep-07 | 11 | 173.6 | 1.1 | 0.3 | 0.1 | 0.08 | 30.62 | 0.31 | 0.10 | 0.32 | 88.90 | 115.88 | 118.20 |
| 01-Oct-07 | 18 | 168.0 | 0.8 | 0.6 | 0.1 | 0.03 | 1.83 | 0.64 | 0.05 | 0.63 | 110.91 | 102.62 | 109.18 |
| 11-Oct-07 | 28 | 154.0 | 1.1 | 0.6 | 0.3 | 0.01 | 7.37 | 0.50 | 0.15 | 0.00 | 102.30 | 145.54 | 154.43 |
| | | | | | | NO2-N (mg/L) = 332.41 * (ABS) + 0.201 | | | | NO3-N (mg/L) = 3.0727 * (ABS) - 0.058 | | | |
| 16-Oct-07 | 33 | 159.6 | 0.3 | 0.3 | 0.3 | 0.01 | 20.95 | 1.21 | 0.41 | 0.26 | 84.26 | 129.93 | 133.62 |

**Run 2a: OLR 2, NLR 0.6, air velocity 0.5 L/min**

| | | Inf | Eff-R | MABR | permeate | Inf | Eff-R | MABR | permeate | Inf | Eff-R | MABR | permeate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Inf | Eff-R | MABR | permeate | NO2-N (mg/L) = 357.58 * (ABS) + 0.4019 | | | | NO3-N (mg/L) = 3.4173 * (ABS) - 0.1239 | | | |
| 26-Oct-07 | 43 | 173.6 | 36.4 | 0.3 | 0.1 | 0.00 | 70.81 | 19.21 | 20.21 | 0.48 | 18.08 | 87.03 | 90.35 |
| 29-Oct-07 | 46 | 168.0 | 42.0 | 0.1 | 0.1 | 0.00 | 72.47 | 29.85 | 30.68 | 0.68 | 12.80 | 77.20 | 77.45 |
| 01-Nov-07 | 49 | 173.6 | 39.2 | 0.3 | 0.1 | 0.02 | 65.82 | 37.10 | 36.77 | 1.98 | 7.51 | 74.87 | 78.80 |
| 05-Nov-07 | 53 | 170.8 | 28.0 | 0.3 | 0.1 | 0.02 | 67.49 | 21.81 | 19.81 | 1.48 | 9.23 | 81.26 | 90.48 |
| 12-Nov-07 | 60 | 182.0 | 19.6 | 0.3 | 0.1 | 0.16 | 85.77 | 10.51 | 10.51 | 1.05 | 9.48 | 111.37 | 112.48 |

**Run 2b: OLR 4, NLR 0.4, air velocity 0.5 L/min**

| | | Inf | Eff-R | MABR | permeate | Inf | Eff-R | MABR | permeate | Inf | Eff-R | MABR | permeate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Inf | Eff-R | MABR | permeate | NO2-N (mg/L) = 332.41 * (ABS) + 0.201 | | | | NO3-N (mg/L) = 3.0727 * (ABS) - 0.058 | | | |
| **Date** | **Day** | **NH4-N** | | | | **NO2-N** | | | | **NO3-N** | | | |
| 16-Nov-07 | 64 | 182.0 | 19.6 | 0.3 | 0.1 | 0.01 | 64.16 | 0.15 | 0.04 | 1.63 | 7.64 | 94.04 | 89.98 |
| 19-Nov-07 | 67 | 173.6 | 84.0 | 1.1 | 1.1 | 0.01 | 10.98 | 18.05 | 13.23 | 0.26 | 3.33 | 66.39 | 77.45 |
| 22-Nov-07 | 70 | 112.0 | 39.2 | 0.3 | 0.1 | 0.01 | 6.18 | 0.12 | 0.03 | 0.26 | 3.21 | 57.17 | 57.78 |
| | | | | | | | | | | NO3-N (mg/L) = 3.0416 * (ABS) - 0.0255 | | | |
| 26-Nov-07 | 74 | 114.8 | 53.2 | 0.6 | 0.3 | 0.01 | 1.93 | 7.41 | 7.58 | 1.45 | 0.00 | 50.71 | 54.42 |

**Run 1: OLR 2, NLR 0.6, air velocity 0.5 L/min**

| | | Inf | Eff-R | MABR | permeate | Inf | Eff-R | MABR | permeate | Eff-R | MABR | permeate | Eff-R | MABR | permeate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Date** | **Day** | **TN** | | | | **TOC** | | | | **UVA** | | | **SUVA** | | |
| 17-Sep-07 | 4 | 160.76 | 111.66 | 100.53 | 100.33 | 282.47 | 0.00 | 0.83 | 0.00 | 0.155 | 0.159 | 0.088 | 0.00 | 0.19 | 0.00 |
| 20-Sep-07 | 7 | 156.81 | 113.64 | 106.42 | 107.28 | 277.52 | 0.00 | 7.42 | 0.00 | 0.162 | 0.167 | 0.093 | 0.00 | 0.02 | 0.00 |
| 24-Sep-07 | 11 | 174.00 | 120.64 | 116.47 | 118.45 | 279.42 | 0.00 | 17.38 | 0.80 | 0.137 | 0.182 | 0.106 | 0.00 | 0.01 | 0.13 |
| 01-Oct-07 | 18 | 168.66 | 113.58 | 103.82 | 109.38 | 236.13 | 0.00 | 12.38 | 0.00 | 0.122 | 0.208 | 0.108 | 0.00 | 0.02 | 0.00 |
| 11-Oct-07 | 28 | 154.00 | 110.79 | 146.60 | 154.86 | 233.49 | 9.15 | 54.32 | 7.29 | 0.128 | 0.215 | 0.110 | 0.01 | 0.00 | 0.02 |
| | | | | | | | | | | | | | | | |
| 16-Oct-07 | 33 | 159.88 | 105.49 | 131.42 | 134.31 | 258.42 | 6.35 | 33.34 | 3.50 | | | | | | |

**Run 2a: OLR 2, NLR 0.6, air velocity 0.5 L/min**

| | | Inf | Eff-R | MABR | permeate | Inf | Eff-R | MABR | permeate | Eff-R | MABR | permeate | Eff-R | MABR | permeate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 26-Oct-07 | 43 | 174.08 | 125.29 | 106.53 | 110.70 | 371.82 | 5.65 | 57.47 | 3.60 | 0.175 | 0.253 | 0.126 | 0.03 | 0.004 | 0.04 |
| 29-Oct-07 | 46 | 168.68 | 127.27 | 107.19 | 108.27 | 420.43 | 6.30 | 65.92 | 4.45 | 0.177 | 0.300 | 0.142 | 0.03 | 0.005 | 0.03 |
| 01-Nov-07 | 49 | 175.60 | 112.54 | 112.24 | 115.71 | 401.76 | 8.10 | 42.27 | 2.85 | 0.157 | 0.240 | 0.143 | 0.02 | 0.006 | 0.05 |
| 05-Nov-07 | 53 | 172.29 | 104.72 | 103.35 | 110.43 | 413.57 | 3.89 | 30.97 | 4.95 | 0.134 | 0.226 | 0.143 | 0.03 | 0.007 | 0.03 |
| 12-Nov-07 | 60 | 183.20 | 114.85 | 122.16 | 123.12 | 378.59 | 9.58 | 22.73 | 3.45 | 0.202 | 0.185 | 0.132 | 0.02 | 0.008 | 0.04 |

**Run 2b: OLR 4, NLR 0.4, air velocity 0.5 L/min**

| | | Inf | Eff-R | MABR | permeate | Inf | Eff-R | MABR | permeate | Eff-R | MABR | permeate | Eff-R | MABR | permeate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Date** | **Day** | **TN** | | | | **TOC** | | | | **UVA** | | | **SUVA** | | |
| 16-Nov-07 | 64 | 183.64 | 91.40 | 94.47 | 90.17 | 541.90 | 15.00 | 17.88 | 2.25 | 0.191 | 0.161 | 0.120 | 0.01 | 0.009 | 0.05 |
| 19-Nov-07 | 67 | 173.87 | 98.31 | 85.56 | 91.80 | 527.49 | 26.20 | 17.65 | 8.10 | 0.166 | 0.163 | 0.131 | 0.01 | 0.009 | 0.02 |
| 22-Nov-07 | 70 | 112.27 | 48.60 | 57.57 | 57.95 | 427.75 | 15.30 | 12.40 | 6.20 | 0.147 | 0.151 | 0.120 | 0.01 | 0.012 | 0.02 |
| | | | | | | | | | | | | | | | |
| 26-Nov-07 | 74 | 116.26 | 55.13 | 58.68 | 62.28 | 482.68 | 20.20 | 29.77 | 22.73 | | | | | | |

**Run 2b: OLR 4, NLR 0.4, air velocity 0.5 L/min (MABR & SBAR is separated)**

| | | Inf - SBAR | Eff-R | Inf SBAR | Eff-R | Inf SBAR | Eff-R | Inf SBAR | Eff-R | Inf SBAR | Eff-R | Inf SBAR | Eff-R |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | NO2-N (mg/L) = 337.12 * (ABS) + 0.0829 | | | | | | | | | |
| | | | | NO3-N (mg/L) = 3.0416 * (ABS) - 0.0255 | | | | | | | | | |
| **Date** | **Day** | **NH4-N** | | **NO2-N** | | **NO3-N** | | **TN** | | **COD, mg/L** | | **TOC** | |
| 07-Dec-07 | 85 | 112.0 | 67.2 | 0.13 | 4.09 | 1.99 | 0.32 | 114.11 | 71.61 | 1209.11 | 81.99 | 449.97 | 28.31 |
| 12-Dec-07 | 90 | 114.8 | 47.6 | 0.13 | 10.32 | 1.94 | 0.63 | 116.87 | 58.55 | 1307.76 | 84.17 | 486.88 | 29.13 |
| 19-Dec-07 | 97 | 114.8 | 14.0 | 0.12 | 32.11 | 2.91 | 2.29 | 117.83 | 48.40 | 1312.41 | 67.45 | 488.62 | 22.87 |
| 26-Dec-07 | 104 | 114.8 | 11.2 | 0.14 | 31.10 | 2.56 | 2.00 | 117.50 | 44.29 | 1304.79 | 48.83 | 485.77 | 15.91 |
| | | | | | | NO3-N (mg/L) = 3.0727 * (ABS) - 0.058 | | | | | | | |
| 02-Jan-08 | 111 | 114.8 | 11.2 | 0.13 | 32.11 | 2.64 | 1.93 | 117.57 | 45.24 | 1307.76 | 43.20 | 486.88 | 13.80 |
| 09-Jan-08 | 118 | 113.4 | 0.7 | 0.06 | 41.55 | 2.52 | 2.27 | 115.97 | 44.52 | 1309.10 | 34.21 | 487.38 | 10.43 |
| | | | | | | NO3-N (mg/L) = 3.0023 * (ABS) - 0.0274 | | | | | | | |
| 16-Jan-08 | 125 | 117.6 | 0.1 | 0.04 | 44.24 | 2.66 | 6.21 | 120.29 | 50.59 | 1324.59 | 36.58 | 493.17 | 11.32 |
| 23-Jan-08 | 132 | 117.6 | 0.1 | 0.13 | 34.13 | 2.51 | 8.67 | 120.23 | 42.94 | 1306.17 | 30.86 | 486.28 | 9.18 |
| 30-Jan-08 | 139 | 117.6 | 2.2 | 0.16 | 54.35 | 2.69 | 7.56 | 120.45 | 64.16 | 1276.78 | 36.11 | 475.29 | 11.15 |
| 06-Feb-08 | 146 | 117.6 | 4.5 | 0.14 | 39.18 | 2.28 | 6.09 | 120.02 | 49.75 | 1273.37 | 30.48 | 474.01 | 9.04 |
| 13-Feb-08 | 153 | 117.6 | 0.6 | 0.15 | 40.87 | 2.69 | 9.15 | 120.44 | 50.58 | 1249.21 | 31.45 | 464.97 | 9.40 |
| 20-Feb-08 | 160 | 114.8 | 0.1 | 0.14 | 39.18 | 2.55 | 9.21 | 117.49 | 48.54 | 1278.44 | 28.58 | 475.91 | 8.33 |

Table B.2 Intensive Monitoring for MABR at OLR 2 kgCOD/$m^3$.d

**Intensive Monitoring for MABR on 05 Nov 2007 (OLR 2 kgCOD/m3.day, NLR = 0.6 kg/m3.day)**

| Time, min | | 0 | 10 | 20 | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | In | 7.82 | 7.79 | 7.65 | 7.5 | 7.43 | 7.7 | 7.73 | 7.76 | 7.71 | 7.65 | 7.59 |
| | Out | | | | | | 7.67 | 7.69 | 7.71 | 7.65 | 7.59 | 7.57 |
| DO, mg/L | In | 6.76 | 6.75 | 6.72 | 6.7 | 6.59 | 6.15 | 5.18 | 5.17 | 5.55 | 5.56 | 5.56 |
| | Out | | | | | | 1.45 | 1.42 | 1.43 | 1.4 | 1.37 | 1.38 |
| COD, mg/L | | 16.71 | 73.57 | 69.61 | 69.77 | 73.27 | 77.76 | 89.10 | 93.51 | 97.01 | 105.19 | 114.25 |
| TOC, mg/L | | 3.89 | 25.16 | 23.68 | 23.74 | 25.05 | 26.73 | 30.97 | 32.62 | 33.93 | 36.99 | 40.38 |
| NH4, mg/L | | 28 | 25.2 | 21.3 | 15.6 | 8.4 | 2.2 | 0.28 | 0.28 | 0.28 | 0.18 | 0.14 |
| NO2, mg/L | | 67.49 | 35.91 | 39.23 | 42.56 | 37.57 | 35.10 | 21.81 | 16.82 | 8.84 | 4.19 | 2.20 |
| NO3, mg/L | | 7.89 | 52.32 | 65.99 | 67.49 | 71.32 | 79.93 | 87.99 | 97.56 | 99.70 | 106.53 | 116.78 |
| TN, mg/L | | 103.38 | 113.43 | 126.52 | 125.65 | 117.29 | 117.23 | 110.08 | 114.66 | 108.82 | 110.90 | 119.12 |

Table B.3 EPS measurement for MABR and SBAR at OLR 2 kgCOD/$m^3$.d

**Run 1a: OLR 2, NLR 0.6, Air velocity 0.5 L/min**

| | | **SBAR** | **Eff-R** | **MABR** | **Eff-R** | | **MABR** | | **Permeate** | | VSS_floc | $VSS_g/VSS_T$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | day | VSS | VSS | VSS | sPS | sPN | sPS | sPN | sPS | sPN | mgVSS/L | % |
| | | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | | |
| 18-Sep-07 | 5 | 10049 | 365 | 3846 | 9.8 | 3.1 | 19.0 | 4.9 | 11.0 | 0.0 | 276 | 97.3 |
| 25-Sep-07 | 12 | 11084 | 422 | 2727 | 11.4 | 2.2 | 29.0 | 10.6 | 13.1 | 1.6 | 229 | 97.9 |
| 02-Oct-07 | 19 | 10569 | 390 | 3631 | 11.8 | 3.1 | 28.2 | 10.0 | 15.2 | 0.0 | 230 | 97.8 |
| 19-Oct-07 | 36 | 10569 | 392 | 3631 | 11.8 | 3.1 | 28.2 | 10.0 | 15.2 | 0.0 | 230 | 97.8 |

| | | **Bound EPS of SBAR** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | day | DF-PS | PS | PS | DF-PN | PN | PN | sam.V | Ext. V | mgPS/gVSS | mgPN/gVSS |
| | | | ABS | mg/L | | ABS | mg/L | mL | mL | mg/g | mg/g |
| 18-Sep-07 | 5 | 4 | 0.119 | 38.93 | 1 | 0.19 | 54.3 | 27.5 | 92.5 | 13.03 | 18.17 |
| 25-Sep-07 | 12 | 4 | 0.102 | 33.98 | 1 | 0.195 | 55.8 | 25 | 92.5 | 11.34 | 18.62 |
| 02-Oct-07 | 19 | 4 | 0.111 | 36.60 | 1 | 0.192 | 54.9 | 30 | 95 | 10.97 | 16.44 |
| 19-Oct-07 | 36 | 4 | 0.111 | 36.60 | 1 | 0.192 | 54.9 | 30 | 95 | 10.97 | 16.44 |

| | | **Bound EPS of MABR** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | day | DF-PS | PS | PS | DF-PN | PN | PN | sam. V | Ext. V | mgPS/gVSS | mgPN/gVSS |
| | | | ABS | mg/L | | ABS | mg/L | mL | mL | mg/g | mg/g |
| 18-Sep-07 | 5 | 4 | 0.053 | 19.7 | 1 | 0.222 | 63.9 | 52.5 | 97.5 | 9.51 | 30.87 |
| 25-Sep-07 | 12 | 4 | 0.105 | 34.9 | 2 | 0.213 | 122.4 | 50.0 | 90.0 | 23.01 | 80.80 |
| 02-Oct-07 | 19 | 4 | 0.096 | 32.2 | 1 | 0.219 | 63.0 | 50.0 | 92.5 | 16.42 | 32.11 |
| 19-Oct-07 | 36 | 4 | 0.096 | 32.2 | 1 | 0.219 | 63.0 | 50.0 | 92.5 | 16.42 | 32.11 |

**Run 1b: OLR 2, NLR 0.6, Air velocity 0.5 L/min**

| | | SBAR | Eff-R | VSS_ | |
|---|---|---|---|---|---|
| Date | day | VSS | VSS | floc | VSSg/VSSt |
| | | mg/L | mg/L | mgVSS/L | % |
| 30-Oct-07 | 47 | 7803 | 390 | 790 | 89.9 |
| 02-Nov-07 | 50 | 7758 | 404 | 908 | 88.3 |

Due to less biomass concentration in SBAR the EPS measurement was not measured from 3rd Nov 2007 to 10th Jan 2008

Table B.4 SVI, MLSS and CST values of Granular and MABR sludge at OLR 2 & 4 kgCOD/$m^3$.d

| | | SBAR | MABR | SBAR | MABR | SBAR | Eff-R | MABR | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| **Date** | **Day** | **SVI, mL/g** | | **MLSS, mg/L** | | **CST, sec** | | | |
| | | | | | | | | | |
| 19-Sep-07 | 6 | 34.3 | 156.4 | 10200 | 4860 | 10.8 | 12.7 | 63.3 | |
| 26-Sep-07 | 13 | 28.9 | 87.5 | 12371 | 4080 | 11.2 | 11.9 | 24.2 | |
| 03-Oct-07 | 20 | 32.3 | 79.5 | 11048 | 4360 | 10.8 | 12.3 | 30.1 | **Run 1a OLR 2 & NLR 0.6** |
| 10-Oct-07 | 27 | 33.9 | 70.8 | 9923 | 3560 | 9.8 | 11.7 | 48.8 | |
| 17-Oct-07 | 34 | 25.4 | 84.9 | 9923 | 3340 | 9.8 | 11.2 | 56.7 | |
| 24-Oct-07 | 41 | 23.4 | 68.3 | 9382 | 3220 | 11.3 | 11.4 | 59.7 | **Run 1b OLR 2 & NLR 0.6** |
| 31-Oct-07 | 48 | 27.8 | 67.3 | 7564 | 3420 | 11.1 | 11.2 | 100.5 | |
| 14-Nov-07 | 62 | 27.8 | 80.2 | 7564 | 3740 | 11.2 | 11.5 | 15.4 | |
| 21-Nov-07 | 69 | 27.8 | 95.5 | 7564 | 4180 | 10.9 | 11.1 | 20.7 | |
| 30-Nov-07 | 78 | 54.1 | 84.7 | 4855 | 2360 | 11.4 | 11.4 | 31.6 | |
| 05-Dec-07 | 83 | 39.5 | MABR & SBAR are separated | 5067 | MABR & SBAR are separated | 10.8 | 11.4 | MABR & SBAR are separated | **Run 2a OLR 4 & NLR 0.4** |
| 12-Dec-07 | 90 | 28.9 | | 6920 | | 11.3 | 11.6 | | |
| 19-Dec-07 | 97 | 24.4 | | 6981 | | 11.2 | 11.7 | | |
| 26-Dec-07 | 104 | 24.1 | | 8308 | | 11 | 11.3 | | |
| 02-Jan-08 | 111 | 29.0 | | 8962 | | 11.3 | 11.5 | | |
| 09-Jan-08 | 118 | 33.5 | | 8948 | | 11.2 | 11.4 | | |
| 16-Jan-08 | 125 | 26.3 | | 7600 | | 11.4 | 11.2 | | |
| 23-Jan-08 | 132 | 28.3 | | 7783 | | 11.1 | 11.1 | | |
| 30-Jan-08 | 139 | 28.2 | | 7100 | | 10.9 | 11.2 | | |
| 06-Feb-08 | 146 | 28.8 | | 7640 | | 11.3 | 11.4 | | |
| 13-Feb-08 | 153 | 31.3 | | 7662 | | 11.2 | 11.2 | | |
| 20-Feb-08 | 160 | 30.2 | | 7945 | | 10.8 | 11.1 | | |

Table B.5 Granular Sludge Size and Settling Velocity at OLR 2 kgCOD/$m^3$.d

Height = 41.5 cm

| Date | **19-Sep-07** | | | **26-Sep-07** | | | **10-Oct-07** | | |
|---|---|---|---|---|---|---|---|---|---|
| No. | Size (mm) | Time | Velocity (m/h) | Size (mm) | Time | Velocity (m/h) | Size (mm) | Time | Velocity (m/h) |
| 1 | 6 | 9.41 | 158.77 | 5 | 8.81 | 169.58 | 6 | 12.25 | 121.96 |
| 2 | 7 | 8.32 | 179.57 | 6 | 9.75 | 153.23 | 4.5 | 10.69 | 139.76 |
| 3 | 5 | 10.91 | 136.94 | 4.5 | 8.5 | 175.76 | 4 | 9.8 | 152.45 |
| 4 | 6 | 9.32 | 160.30 | 5.5 | 10.6 | 140.94 | 5 | 16.75 | 89.19 |
| 5 | 6.5 | 10.07 | 148.36 | 6 | 9.22 | 162.04 | 6 | 10.97 | 136.19 |
| 6 | 6 | 9.25 | 161.51 | 6 | 11.79 | 126.72 | 6.5 | 9.56 | 156.28 |
| 7 | 4.5 | 11.13 | 134.23 | 4 | 13.12 | 113.87 | 6 | 8.88 | 168.24 |
| 8 | 5 | 8.37 | 178.49 | 5.5 | 9.95 | 150.15 | 8 | 9.97 | 149.85 |
| 9 | 6.5 | 10.37 | 144.07 | 6 | 12.7 | 117.64 | 6 | 11.31 | 132.10 |
| 10 | 6 | 10.25 | 145.76 | 7 | 9.33 | 160.13 | 5 | 10.29 | 145.19 |
| 11 | 7 | 9.45 | 158.10 | 6 | 11.86 | 125.97 | 8 | 10.66 | 140.15 |
| 12 | 5 | 9.25 | 161.51 | 4.5 | 10.7 | 139.63 | 7 | 8.78 | 170.16 |
| 13 | 8.5 | 10.87 | 137.44 | 7.5 | 9.46 | 157.93 | 6.5 | 10.56 | 141.48 |
| 14 | 7.5 | 10.06 | 148.51 | 7.5 | 11.04 | 135.33 | 6 | 12.97 | 115.19 |
| 15 | 6 | 9.72 | 153.70 | 5.5 | 10.26 | 145.61 | 7 | 14.88 | 100.40 |
| 16 | 6 | 11.44 | 130.59 | 5.5 | 9.58 | 155.95 | 8.5 | 12.09 | 123.57 |
| 17 | 6.5 | 11.56 | 129.24 | 6 | 13.28 | 112.50 | 7 | 12.88 | 115.99 |

| Date | 19-Sep-07 | | | 26-Sep-07 | | | 10-Oct-07 | | |
|---|---|---|---|---|---|---|---|---|---|
| No. | Size (mm) | Time | Velocity (m/h) | Size (mm) | Time | Velocity (m/h) | Size (mm) | Time | Velocity (m/h) |
| 18 | 5.5 | 10.06 | 148.51 | 5.5 | 9.65 | 154.82 | 7.5 | 9.41 | 158.77 |
| 19 | 7 | 10.37 | 144.07 | 8 | 12.63 | 118.29 | 6.5 | 8.62 | 173.32 |
| 20 | 7.5 | 10.91 | 136.94 | 7 | 10.3 | 145.05 | 7 | 15.91 | 93.90 |
| 21 | 6.5 | 11.12 | 134.35 | 6 | 12.88 | 115.99 | 7 | 9.97 | 149.85 |
| 22 | 5 | 10.41 | 143.52 | 4.5 | 11.02 | 135.57 | 8 | 10.18 | 146.76 |
| 23 | 8 | 11.46 | 130.37 | 5 | 11.47 | 130.25 | 7 | 12.72 | 117.45 |
| 24 | 7.5 | 10.45 | 142.97 | 6.5 | 11.45 | 130.48 | 5 | 10.72 | 139.37 |
| 25 | 4.5 | 12 | 124.50 | 8.5 | 12 | 124.50 | 6 | 10.1 | 147.92 |
| 26 | 4.5 | 11.59 | 128.90 | 4 | 15.15 | 98.61 | 5 | 12.25 | 121.96 |
| 27 | 5 | 10.97 | 136.19 | 4.5 | 11.64 | 128.35 | 3 | 12.13 | 123.17 |
| 28 | 5 | 10.63 | 140.55 | 3.5 | 12.07 | 123.78 | 4 | 15.19 | 98.35 |
| 29 | 5 | 11.35 | 131.63 | 5 | 13.06 | 114.40 | 4.5 | 11.97 | 124.81 |
| 30 | 9 | 11.38 | 131.28 | 5.5 | 13.93 | 107.25 | 6 | 14.47 | 103.25 |
| 31 | 6 | 10.4 | 143.65 | 6.5 | 11.35 | 131.63 | 5 | 12.13 | 123.17 |
| 32 | 6.5 | 10.35 | 144.35 | 6.5 | 11.02 | 135.57 | 5 | 12.78 | 116.90 |
| 33 | 7.5 | 11.34 | 131.75 | 7 | 12.41 | 120.39 | 3 | 12.69 | 117.73 |
| 34 | 6 | 11.12 | 134.35 | 5.5 | 11.31 | 132.10 | 3 | 13.41 | 111.41 |
| 35 | 7 | 11.02 | 135.57 | 4.5 | 12.27 | 121.76 | 4 | 15.72 | 95.04 |
| 36 | 6 | 12.78 | 116.90 | 7 | 13.97 | 106.94 | 3.5 | 12.34 | 121.07 |
| 37 | 8 | 10.78 | 138.59 | 8 | 10.99 | 135.94 | 4.5 | 16.18 | 92.34 |
| 38 | 5 | 10.3 | 145.05 | 6 | 12.73 | 117.36 | 3.5 | 10.63 | 140.55 |
| 39 | 5 | 10.35 | 144.35 | 6 | 12.27 | 121.76 | 3.5 | 10.63 | 140.55 |
| 40 | 4 | 10.5 | 142.29 | 5.5 | 12.24 | 122.06 | 3 | 13.29 | 112.42 |
| 41 | 6 | 11.44 | 130.59 | 5 | 11.72 | 127.47 | 2.5 | 15.5 | 96.39 |
| 42 | 6 | 11.4 | 131.05 | 5.5 | 12.09 | 123.57 | 4 | 13.94 | 107.17 |
| 43 | 5 | 11.97 | 124.81 | 5 | 11.25 | 132.80 | 4.5 | 15 | 99.60 |
| 44 | 5 | 10.98 | 136.07 | 5.5 | 11.44 | 130.59 | 5 | 14.47 | 103.25 |
| 45 | 5.5 | 11.95 | 125.02 | 5.5 | 14.89 | 100.34 | 5 | 12.37 | 120.78 |
| 46 | 5 | 11.98 | 124.71 | 4.5 | 11.3 | 132.21 | 5.5 | 13.69 | 109.13 |
| 47 | 4.5 | 10.5 | 142.29 | 4.5 | 12.12 | 123.27 | 4.5 | 13.59 | 109.93 |
| 48 | 4 | 12.03 | 124.19 | 5 | 12.81 | 116.63 | 4.5 | 11.9 | 125.55 |
| 49 | 3 | 12 | 124.50 | 5 | 14.45 | 103.39 | 4.5 | 12.6 | 118.57 |
| 50 | 3.5 | 10.44 | 143.10 | 4.5 | 14.46 | 103.32 | 4 | 17.09 | 87.42 |

| Date | 17-Oct-07 | | | 24-Oct-07 | | | 31-Oct-07 | | |
|---|---|---|---|---|---|---|---|---|---|
| No. | Size (mm) | Time | Velocity (m/h) | Size (mm) | Time | Velocity (m/h) | Size (mm) | Time | Velocity (m/h) |
| 1 | 6 | 10.06 | 148.51 | 7 | 8.69 | 171.92 | 6 | 8.34 | 179.14 |
| 2 | 5 | 12.13 | 123.17 | 5 | 8.81 | 169.58 | 4 | 7.94 | 188.16 |
| 3 | 7 | 9.06 | 164.90 | 4.5 | 8.57 | 174.33 | 5.5 | 10.25 | 145.76 |
| 4 | 4 | 9.71 | 153.86 | 5 | 8.57 | 174.33 | 5 | 9.94 | 150.30 |
| 5 | 4.5 | 8.5 | 175.76 | 4.25 | 8.41 | 177.65 | 4 | 9.59 | 155.79 |
| 6 | 5.5 | 8.38 | 178.28 | 7 | 7.44 | 200.81 | 5 | 11 | 135.82 |
| 7 | 5.5 | 9.88 | 151.21 | 6.5 | 9.59 | 155.79 | 6 | 9.65 | 154.82 |
| 8 | 7 | 9.28 | 160.99 | 5.25 | 9.03 | 165.45 | 4.75 | 8.97 | 166.56 |
| 9 | 6.5 | 9.91 | 150.76 | 7 | 10 | 149.40 | 7 | 12.28 | 121.66 |
| 10 | 6 | 12.01 | 124.40 | 5 | 10.47 | 142.69 | 5 | 10.22 | 146.18 |
| 11 | 6.5 | 12.54 | 119.14 | 7 | 11.5 | 129.91 | 5 | 11.31 | 132.10 |
| 12 | 6 | 11.59 | 128.90 | 7 | 10 | 149.40 | 6 | 10.09 | 148.07 |

| Date | 17-Oct-07 | | | 24-Oct-07 | | | 31-Oct-07 | | |
|---|---|---|---|---|---|---|---|---|---|
| No. | Size (mm) | Time | Velocity (m/h) | Size (mm) | Time | Velocity (m/h) | Size (mm) | Time | Velocity (m/h) |
| 13 | 5.5 | 11.22 | 133.16 | 6.5 | 11.13 | 134.23 | 6 | 11.22 | 133.16 |
| 14 | 5 | 13.43 | 111.24 | 5.25 | 11.84 | 126.18 | 5.25 | 9.37 | 159.45 |
| 15 | 4 | 11.97 | 124.81 | 5.5 | 8.81 | 169.58 | 4.5 | 12.52 | 119.33 |
| 16 | 6 | 12.87 | 116.08 | 6.75 | 10.16 | 147.05 | 6 | 12.34 | 121.07 |
| 17 | 5.5 | 9.6 | 155.63 | 6.75 | 8.88 | 168.24 | 6.75 | 10.72 | 139.37 |
| 18 | 5.5 | 14.81 | 100.88 | 4.5 | 9.44 | 158.26 | 4 | 10.81 | 138.21 |
| 19 | 7 | 12.62 | 118.38 | 5.5 | 9.41 | 158.77 | 6 | 12.22 | 122.26 |
| 20 | 5.5 | 11.03 | 135.45 | 6.5 | 9.5 | 157.26 | 6 | 11.1 | 134.59 |
| 21 | 5.5 | 11.31 | 132.10 | 8 | 9.93 | 150.45 | 7 | 11.4 | 131.05 |
| 22 | 5.5 | 12.16 | 122.86 | 6.5 | 9.03 | 165.45 | 5.5 | 11.91 | 125.44 |
| 23 | 6 | 10.75 | 138.98 | 6.5 | 9.44 | 158.26 | 5.5 | 11.92 | 125.34 |
| 24 | 5 | 12.47 | 119.81 | 4.5 | 10.97 | 136.19 | 4.5 | 12.22 | 122.26 |
| 25 | 5 | 12.69 | 117.73 | 7.25 | 10.28 | 145.33 | 6 | 11.14 | 134.11 |
| 26 | 5 | 13.31 | 112.25 | 4.5 | 13.28 | 112.50 | 4.5 | 10.16 | 147.05 |
| 27 | 5.5 | 15 | 99.60 | 5 | 11.8 | 126.61 | 5.5 | 12.28 | 121.66 |
| 28 | 4.5 | 15.13 | 98.74 | 4.75 | 11.34 | 131.75 | 5 | 11.91 | 125.44 |
| 29 | 4.5 | 12.59 | 118.67 | 6 | 11.37 | 131.40 | 6 | 12.63 | 118.29 |
| 30 | 4 | 16.81 | 88.88 | 5 | 8.38 | 178.28 | 5.5 | 15.53 | 96.20 |
| 31 | 4 | 14.87 | 100.47 | 6.5 | 13.34 | 111.99 | 5.5 | 12.54 | 119.14 |
| 32 | 5 | 14.81 | 100.88 | 6.75 | 11.29 | 132.33 | 5.75 | 8.84 | 169.00 |
| 33 | 3.5 | 14.25 | 104.84 | 5 | 10.44 | 143.10 | 5 | 11.41 | 130.94 |
| 34 | 4 | 10.53 | 141.88 | 5 | 13.87 | 107.71 | 5 | 13.87 | 107.71 |
| 35 | 4 | 12.43 | 120.19 | 6.5 | 12.25 | 121.96 | 7 | 14.1 | 105.96 |
| 36 | 5 | 12.68 | 117.82 | 4.5 | 13.1 | 114.05 | 5 | 14.1 | 105.96 |
| 37 | 5.5 | 11.44 | 130.59 | 4.75 | 13.31 | 112.25 | 5 | 13.97 | 106.94 |
| 38 | 6 | 14.18 | 105.36 | 4.75 | 10.34 | 144.49 | 4.75 | 12.62 | 118.38 |
| 39 | 5 | 13.24 | 112.84 | 6 | 13 | 114.92 | 6.5 | 14.1 | 105.96 |
| 40 | 4 | 10.5 | 142.29 | 6.25 | 17.78 | 84.03 | 6.25 | 14.84 | 100.67 |
| 41 | 3.5 | 9.45 | 158.10 | 5 | 12.59 | 118.67 | 5.5 | 10.5 | 142.29 |
| 42 | 3 | 15 | 99.60 | 3.5 | 11.06 | 135.08 | 3.5 | 12.37 | 120.78 |
| 43 | 5 | 14.16 | 105.51 | 3.75 | 15.09 | 99.01 | 3.25 | 14.19 | 105.29 |
| 44 | 5 | 13.78 | 108.42 | 3 | 12.78 | 116.90 | 3 | 15.22 | 98.16 |
| 45 | 4.5 | 15.85 | 94.26 | 4.5 | 13.14 | 113.70 | 3 | 13.16 | 113.53 |
| 46 | 5 | 13.09 | 114.13 | 2.5 | 15.21 | 98.22 | 2.5 | 12.16 | 122.86 |
| 47 | 6 | 12.34 | 121.07 | 2.75 | 12.44 | 120.10 | 2.25 | 13.69 | 109.13 |
| 48 | 6.5 | 13.34 | 111.99 | 3 | 12.65 | 118.10 | 2.75 | 14.03 | 106.49 |
| 49 | 5 | 12.69 | 117.73 | 3.5 | 10.75 | 138.98 | 3 | 14.5 | 103.03 |
| 50 | 5 | 11.38 | 131.28 | 3 | 15.16 | 98.55 | 3 | 11.47 | 130.25 |

## Appendix C: Raw Data for Run 2

Table C.1 Organic & Nitrogen concentration for various sampling points for Case 1, 2 & 3

**Run 2: OLR 4, NLR 0.4 (MABR & SBAR is separated)**
**Case 1 : Equal Nitrogen**

| | | Inf MABR | MABR | permeate | Inf MABR | MABR | permeate |
|---|---|---|---|---|---|---|---|
| | | NO2-N (mg/L) = 337.12 * (ABS) + 0.0829 | | | NO3-N (mg/L) = 3.0416 * (ABS) - 0.0255 | | |
| Date | Day | NO2-N | | | NO3-N | | |
| 05-Dec-07 | 83 | 5.25 | 0.13 | 0.01 | 2.66 | 3.51 | 4.05 |
| 07-Dec-07 | 85 | 4.57 | 0.04 | 0.00 | 1.58 | 3.80 | 4.09 |
| 10-Dec-07 | 88 | 4.40 | 0.04 | 0.00 | 1.27 | 2.67 | 2.78 |
| 12-Dec-07 | 90 | 4.82 | 0.10 | 0.01 | 1.58 | 3.05 | 3.39 |
| 17-Dec-07 | 95 | 4.49 | 0.02 | 0.01 | 1.62 | 2.81 | 2.91 |
| 19-Dec-07 | 97 | 4.82 | 0.05 | 0.01 | 1.85 | 2.87 | 3.01 |
| 21-Dec-07 | 99 | 4.82 | 0.39 | 0.11 | 1.64 | 2.32 | 2.63 |
| 24-Dec-07 | 102 | 4.57 | 0.26 | 0.09 | 1.55 | 2.72 | 2.91 |
| 26-Dec-07 | 104 | 4.40 | 0.28 | 0.07 | 1.53 | 2.41 | 2.61 |
| 28-Dec-07 | 106 | 4.57 | 0.27 | 0.06 | 1.58 | 2.69 | 2.87 |

| | | Inf MABR | MABR | permeate | Inf MABR | MABR | permeate | Inf MABR | MABR | permeate |
|---|---|---|---|---|---|---|---|---|---|---|
| Date | Day | TN | | | COD, mg/L | | | TOC | | |
| 05-Dec-07 | 83 | 7.90 | 3.64 | 4.07 | 109.09 | 24.56 | 24.46 | 38.45 | 6.83 | 6.79 |
| 07-Dec-07 | 85 | 6.15 | 3.84 | 4.09 | 111.05 | 24.38 | 26.14 | 39.18 | 6.76 | 7.42 |
| 10-Dec-07 | 88 | 5.67 | 2.71 | 2.78 | 111.02 | 23.89 | 16.25 | 39.17 | 6.57 | 3.72 |
| 12-Dec-07 | 90 | 6.40 | 3.15 | 3.39 | 110.75 | 27.49 | 12.35 | 39.07 | 7.92 | 2.26 |
| 17-Dec-07 | 95 | 6.11 | 2.83 | 2.92 | 108.07 | 26.24 | 12.97 | 38.07 | 7.45 | 2.49 |
| 19-Dec-07 | 97 | 6.67 | 2.92 | 3.02 | 108.00 | 23.84 | 14.18 | 38.04 | 6.56 | 2.94 |
| 21-Dec-07 | 99 | 6.46 | 2.71 | 2.74 | 112.33 | 22.80 | 14.23 | 39.66 | 6.17 | 2.96 |
| 24-Dec-07 | 102 | 6.12 | 2.98 | 3.01 | 113.83 | 22.54 | 15.04 | 40.22 | 6.07 | 3.26 |
| 26-Dec-07 | 104 | 5.93 | 2.69 | 2.68 | 112.64 | 22.82 | 14.57 | 39.78 | 6.17 | 3.09 |
| 28-Dec-07 | 106 | 6.15 | 2.96 | 2.93 | 111.50 | 23.26 | 14.25 | 39.35 | 6.34 | 2.97 |

**Case 2 : Low Nitrogen**

| | | Inf MABR | MABR | permeate | Inf MABR | MABR | permeate |
|---|---|---|---|---|---|---|---|
| | | NO2-N (mg/L) = 337.12 * (ABS) + 0.0829 | | | NO3-N (mg/L) = 3.0727 * (ABS) - 0.058 | | |
| Date | Day | NO2-N | | | NO3-N | | |
| 31-Dec-07 | 109 | 1.59 | 0.00 | 0.00 | 0.96 | 1.14 | 1.15 |
| 02-Jan-08 | 111 | 1.66 | 0.01 | 0.00 | 0.91 | 1.13 | 1.18 |
| 04-Jan-08 | 113 | 1.63 | 0.01 | 0.00 | 0.95 | 1.20 | 1.34 |
| 07-Jan-08 | 116 | 1.86 | 0.01 | 0.00 | 0.99 | 1.19 | 1.32 |
| 09-Jan-08 | 118 | 1.76 | 0.01 | 0.00 | 1.01 | 1.19 | 1.33 |
| 11-Jan-08 | 120 | 1.86 | 0.01 | 0.00 | 0.93 | 1.21 | 1.34 |
| 14-Jan-08 | 123 | 1.69 | 0.01 | 0.01 | 1.17 | 1.51 | 1.64 |
| 16-Jan-08 | 125 | 1.93 | 0.02 | 0.01 | 1.15 | 1.57 | 1.69 |
| 18-Jan-08 | 127 | 2.00 | 0.01 | 0.00 | 0.90 | 1.19 | 1.26 |

| | | Inf MABR | MABR | permeate | Inf MABR | MABR | permeate | Inf MABR | MABR | permeate |
|---|---|---|---|---|---|---|---|---|---|---|
| Date | Day | TN | | | COD, mg/L | | | TOC | | |
| 31-Dec-07 | 109 | 2.55 | 1.15 | 1.16 | 101.22 | 25.19 | 15.28 | 35.50 | 7.06 | 3.35 |
| 02-Jan-08 | 111 | 2.57 | 1.14 | 1.19 | 106.37 | 24.19 | 16.57 | 37.43 | 6.69 | 3.84 |
| 04-Jan-08 | 113 | 2.57 | 1.21 | 1.34 | 114.17 | 24.94 | 16.39 | 40.35 | 6.97 | 3.77 |
| 07-Jan-08 | 116 | 2.85 | 1.20 | 1.32 | 108.10 | 23.91 | 16.65 | 38.08 | 6.58 | 3.87 |
| 09-Jan-08 | 118 | 2.77 | 1.20 | 1.33 | 108.16 | 25.08 | 16.27 | 38.10 | 7.02 | 3.73 |
| 11-Jan-08 | 120 | 2.80 | 1.22 | 1.35 | 110.82 | 24.05 | 16.30 | 39.10 | 6.63 | 3.74 |
| 14-Jan-08 | 123 | 2.86 | 1.53 | 1.64 | 102.52 | 24.55 | 15.95 | 35.99 | 6.82 | 3.61 |
| 16-Jan-08 | 125 | 3.08 | 1.59 | 1.70 | 111.91 | 24.02 | 16.18 | 39.51 | 6.62 | 3.69 |
| 18-Jan-08 | 127 | 2.90 | 1.21 | 1.26 | 102.35 | 24.40 | 16.01 | 35.93 | 6.77 | 3.63 |

**Case 3 :High Nitrogen**

| | | Inf MABR | MABR | permeate | Inf MABR | MABR | permeate |
|---|---|---|---|---|---|---|---|
| | | NO2-N (mg/L) = 337.12 * (ABS) + 0.0829 | | | NO3-N (mg/L) = 3.0023 * (ABS) - 0.0274 | | |
| Date | Day | NO2-N | | | NO3-N | | |
| 21-Jan-08 | 130 | 8.47 | 1.02 | 0.40 | 1.61 | 5.33 | 6.08 |
| 23-Jan-08 | 132 | 8.30 | 0.68 | 0.20 | 1.99 | 5.00 | 5.49 |
| 25-Jan-08 | 134 | 8.13 | 0.59 | 0.13 | 2.08 | 5.10 | 5.57 |
| 28-Jan-08 | 137 | 8.30 | 0.56 | 0.11 | 1.84 | 5.19 | 5.70 |
| 30-Jan-08 | 139 | 8.47 | 0.29 | 0.05 | 1.69 | 4.86 | 5.16 |
| 01-Feb-08 | 141 | 8.47 | 0.21 | 0.04 | 1.95 | 4.62 | 5.00 |
| 04-Feb-08 | 144 | 8.98 | 0.09 | 0.03 | 1.99 | 4.89 | 5.27 |
| 06-Feb-08 | 146 | 8.81 | 0.09 | 0.02 | 2.01 | 5.37 | 5.52 |
| 08-Feb-08 | 148 | 8.81 | 0.07 | 0.02 | 1.98 | 5.34 | 5.46 |
| 11-Feb-08 | 151 | 8.81 | 0.07 | 0.04 | 1.93 | 5.39 | 5.57 |
| 13-Feb-08 | 153 | 8.81 | 0.07 | 0.02 | 2.02 | 5.42 | 5.64 |

| | | Inf MABR | MABR | permeate | Inf MABR | MABR | permeate | Inf MABR | MABR | permeate |
|---|---|---|---|---|---|---|---|---|---|---|
| Date | Day | TN | | | COD, mg/L | | | TOC | | |
| 21-Jan-08 | 130 | 10.08 | 6.35 | 6.47 | 104.41 | 14.47 | 13.17 | 36.70 | 3.05 | 2.56 |
| 23-Jan-08 | 132 | 10.30 | 5.68 | 5.70 | 98.62 | 14.35 | 12.96 | 34.53 | 3.01 | 2.49 |
| 25-Jan-08 | 134 | 10.22 | 5.70 | 5.70 | 106.34 | 14.30 | 12.96 | 37.42 | 2.99 | 2.49 |
| 28-Jan-08 | 137 | 10.15 | 5.75 | 5.81 | 106.93 | 14.25 | 11.60 | 37.64 | 2.97 | 1.98 |
| 30-Jan-08 | 139 | 10.16 | 5.15 | 5.21 | 99.94 | 13.14 | 11.98 | 35.03 | 2.55 | 2.12 |
| 01-Feb-08 | 141 | 10.42 | 4.83 | 5.04 | 99.15 | 14.35 | 14.3 | 34.73 | 3.01 | 2.98 |
| 04-Feb-08 | 144 | 10.97 | 4.98 | 5.30 | 106.42 | 14.61 | 12.3 | 37.45 | 3.10 | 2.23 |
| 06-Feb-08 | 146 | 10.82 | 5.46 | 5.54 | 101.17 | 12.57 | 11.34 | 35.49 | 2.34 | 1.88 |
| 08-Feb-08 | 148 | 10.79 | 5.41 | 5.48 | 103.13 | 13.85 | 12.39 | 36.22 | 2.82 | 2.27 |
| 11-Feb-08 | 151 | 10.74 | 5.46 | 5.61 | 106.90 | 14.14 | 12.03 | 37.63 | 2.93 | 2.14 |
| 13-Feb-08 | 153 | 10.83 | 5.49 | 5.66 | 102.72 | 14.61 | 12.43 | 36.07 | 3.10 | 2.29 |

Table C.2 Organic and Nitrogen concentration for various sampling points during addition of external carbon source

**External Carbon Addition to achieve 60% Denitrification**

| | | Inf | MABR | | | permeate | Inf | MABR | | | permeate |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | MABR | 60 mins | 120 mins | 230mins | 120 mins | MABR | 60 mins | 120 mins | 230 mins | 120 mins |
| | | NO2-N (mg/L) = 337.12 * (ABS) + 0.0829 | | | | | NO3-N (mg/L) = 3.0023 * (ABS) - 0.0274 | | | | |
| Date | Day | NO2-N | | | | | NO3-N | | | | |
| 14-Feb-08 | 154 | 8.64 | 1.53 | 0.00 | 0.00 | 0.00 | 1.98 | 3.53 | 4.59 | 4.28 | 4.76 |
| 14-Feb-08 | 154 | 8.30 | 1.49 | 0.00 | 0.00 | 0.00 | 1.95 | 3.48 | 4.61 | 4.25 | 4.67 |
| 15-Feb-08 | 155 | 8.47 | 1.73 | 0.01 | 0.01 | 0.01 | 1.89 | 3.47 | 4.10 | 3.80 | 4.34 |
| 15-Feb-08 | 155 | 8.47 | 1.63 | 0.01 | 0.00 | 0.01 | 1.98 | 3.44 | 4.04 | 3.83 | 4.38 |
| 16-Feb-08 | 156 | 8.47 | 1.63 | 0.02 | 0.01 | 0.00 | 1.93 | 3.50 | 4.29 | 3.96 | 4.50 |
| 16-Feb-08 | 156 | 8.47 | 1.59 | 0.01 | 0.00 | 0.00 | 1.93 | 3.42 | 4.34 | 3.93 | 4.47 |
| 17-Feb-08 | 157 | 8.64 | 1.59 | 0.01 | 0.00 | 0.00 | 1.96 | 3.53 | 4.14 | 3.89 | 4.29 |
| | | | | | | | NO3-N (mg/L) = 3.0077 * (ABS) - 0.0204 | | | | |
| 18-Feb-08 | 158 | 8.30 | 1.53 | 0.01 | 0.00 | 0.00 | 2.06 | 3.51 | 4.05 | 3.84 | 4.36 |
| 18-Feb-08 | 158 | 8.64 | 1.49 | 0.00 | 0.00 | 0.00 | 2.06 | 3.54 | 4.08 | 3.87 | 4.35 |

| | | Inf | MABR | | | permeate | Inf | MABR | | | permeate | Inf | MABR | | | permeate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | MABR | 60 mins | 120 mins | 230 mins | 120 mins | MABR | 60 mins | 120 mins | 230 mins | 120 mins | MABR | 60 mins | 120 mins | 230 mins | 120 mins |
| Date | Day | TN | | | | | COD, mg/L | | | | | TOC | | | | |
| 14-Feb-08 | 154 | 10.62 | 5.05 | 4.60 | 4.28 | 4.76 | 104.11 | 26.08 | 24.44 | 16.25 | 23.51 | 36.59 | 7.39 | 6.78 | 3.72 | 6.43 |
| 14-Feb-08 | 154 | 10.25 | 4.97 | 4.61 | 4.25 | 4.67 | 104.19 | 25.83 | 23.49 | 16.17 | 22.35 | 36.62 | 7.30 | 6.43 | 3.69 | 6.00 |
| 15-Feb-08 | 155 | 10.36 | 5.19 | 4.11 | 3.80 | 4.34 | 103.49 | 24.91 | 24.40 | 16.05 | 23.17 | 36.35 | 6.96 | 6.77 | 3.64 | 6.31 |
| 15-Feb-08 | 155 | 10.45 | 5.06 | 4.04 | 3.83 | 4.39 | 99.39 | 25.65 | 23.79 | 16.16 | 22.79 | 34.82 | 7.23 | 6.54 | 3.68 | 6.16 |
| 16-Feb-08 | 156 | 10.40 | 5.12 | 4.31 | 3.97 | 4.50 | 105.40 | 25.84 | 24.29 | 16.15 | 23.40 | 37.07 | 7.31 | 6.73 | 3.68 | 6.39 |
| 16-Feb-08 | 156 | 10.40 | 5.01 | 4.35 | 3.93 | 4.47 | 110.78 | 24.84 | 24.40 | 16.26 | 24.19 | 39.08 | 6.93 | 6.77 | 3.72 | 6.69 |
| 17-Feb-08 | 157 | 10.60 | 5.12 | 4.15 | 3.89 | 4.29 | 97.99 | 24.94 | 24.06 | 15.89 | 23.16 | 34.30 | 6.97 | 6.64 | 3.58 | 6.30 |
| 18-Feb-08 | 158 | 10.36 | 5.03 | 4.06 | 3.84 | 4.37 | 104.11 | 26.08 | 24.44 | 16.25 | 23.51 | 36.59 | 7.39 | 6.78 | 3.72 | 6.43 |
| 18-Feb-08 | 158 | 10.70 | 5.03 | 4.08 | 3.87 | 4.35 | 104.11 | 26.08 | 24.44 | 16.25 | 23.51 | 36.59 | 7.39 | 6.78 | 3.72 | 6.43 |

**External Carbon Addition to achieve 75% Denitrification**

| | | Inf | MABR | | | permeate | | MABR | | | permeate |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | MABR | 60 mins | 120 mins | 230mins | 120 mins | Inf MABR | 60 mins | 120 mins | 230 mins | 120 mins |
| | | NO2-N (mg/L) = 337.12 * (ABS) + 0.0829 | | | | | NO3-N (mg/L) = 3.0077 * (ABS) - 0.0204 | | | | |
| Date | Day | NO2-N | | | | | NO3-N | | | | |
| 19-Feb-08 | 159 | 8.64 | 1.49 | 0.00 | 0.00 | 0.00 | 2.05 | 3.52 | 4.11 | 3.45 | 4.21 |
| 19-Feb-08 | 159 | 8.64 | 1.49 | 0.00 | 0.00 | 0.00 | 2.05 | 3.57 | 3.63 | 2.98 | 3.73 |
| 20-Feb-08 | 160 | 8.30 | 1.49 | 0.01 | 0.00 | 0.00 | 2.05 | 3.55 | 3.58 | 3.09 | 3.78 |
| 20-Feb-08 | 160 | 8.30 | 1.53 | 0.00 | 0.00 | 0.00 | 2.05 | 3.58 | 3.62 | 3.13 | 3.81 |
| 21-Feb-08 | 161 | 8.30 | 1.46 | 0.01 | 0.00 | 0.00 | 2.00 | 3.43 | 3.51 | 3.06 | 3.66 |
| 21-Feb-08 | 161 | 8.30 | 1.53 | 0.00 | 0.00 | 0.00 | 2.00 | 3.48 | 3.48 | 3.09 | 3.63 |
| 22-Feb-08 | 162 | 8.30 | 1.49 | 0.00 | 0.00 | 0.00 | 1.97 | 3.58 | 3.43 | 2.98 | 3.58 |
| 22-Feb-08 | 162 | 8.30 | 1.46 | 0.00 | 0.00 | 0.00 | 2.00 | 3.55 | 3.46 | 3.06 | 3.63 |
| 23-Feb-08 | 163 | 8.47 | 1.42 | 0.00 | 0.00 | 0.00 | 2.00 | 3.55 | 3.45 | 3.01 | 3.61 |
| 24-Feb-08 | 164 | 8.30 | 1.49 | 0.01 | 0.00 | 0.00 | 1.99 | 3.58 | 3.43 | 3.08 | 3.63 |
| 24-Feb-08 | 164 | 8.30 | 1.53 | 0.00 | 0.00 | 0.00 | 2.00 | 3.55 | 3.42 | 3.03 | 3.58 |

| | | Inf | MABR | | | permeate | Inf | MABR | | | permeate | Inf | MABR | | | permeate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | MABR | 60 mins | 120 mins | 230 mins | 120 mins | MABR | 60 mins | 120 mins | 230 mins | 120 mins | MABR | 60 mins | 120 mins | 230 mins | 120 mins |
| Date | Day | TN | | | | | COD, mg/L | | | | | TOC | | | | |
| 19-Feb-08 | 159 | 10.69 | 5.01 | 4.11 | 3.45 | 4.21 | 107.51 | 27.10 | 29.11 | 14.85 | 26.73 | 37.86 | 7.78 | 8.53 | 3.19 | 7.64 |
| 19-Feb-08 | 159 | 10.69 | 5.06 | 3.63 | 2.98 | 3.73 | 107.51 | 26.09 | 18.88 | 13.95 | 18.13 | 37.86 | 7.40 | 4.70 | 2.86 | 4.42 |
| 20-Feb-08 | 160 | 10.35 | 5.04 | 3.59 | 3.09 | 3.78 | 101.79 | 26.32 | 18.58 | 14.43 | 17.10 | 35.72 | 7.48 | 4.59 | 3.04 | 4.03 |
| 20-Feb-08 | 160 | 10.35 | 5.11 | 3.63 | 3.13 | 3.81 | 101.79 | 26.59 | 19.37 | 14.26 | 18.13 | 35.72 | 7.59 | 4.89 | 2.97 | 4.42 |
| 21-Feb-08 | 161 | 10.30 | 4.89 | 3.51 | 3.06 | 3.66 | 100.97 | 26.01 | 19.80 | 14.17 | 19.09 | 35.41 | 7.37 | 5.05 | 2.94 | 4.78 |
| 21-Feb-08 | 161 | 10.30 | 5.00 | 3.48 | 3.09 | 3.63 | 100.97 | 24.45 | 18.63 | 13.93 | 18.78 | 35.41 | 6.79 | 4.61 | 2.85 | 4.66 |
| 22-Feb-08 | 162 | 10.27 | 5.07 | 3.44 | 2.98 | 3.58 | 101.26 | 24.59 | 18.89 | 14.10 | 17.96 | 35.52 | 6.84 | 4.71 | 2.91 | 4.36 |
| 22-Feb-08 | 162 | 10.30 | 5.01 | 3.46 | 3.06 | 3.63 | 101.26 | 24.55 | 18.63 | 14.64 | 19.36 | 35.52 | 6.82 | 4.61 | 3.11 | 4.88 |
| 23-Feb-08 | 163 | 10.47 | 4.98 | 3.45 | 3.01 | 3.61 | 101.57 | 25.90 | 19.54 | 14.74 | 17.95 | 35.63 | 7.33 | 4.95 | 3.15 | 4.35 |
| 24-Feb-08 | 164 | 10.29 | 5.07 | 3.44 | 3.08 | 3.63 | 101.79 | 26.32 | 19.37 | 14.43 | 17.89 | 35.72 | 7.48 | 4.89 | 3.04 | 4.33 |
| 24-Feb-08 | 164 | 10.30 | 5.08 | 3.42 | 3.03 | 3.58 | 101.79 | 24.72 | 18.58 | 14.97 | 17.10 | 35.72 | 6.89 | 4.59 | 3.24 | 4.03 |

Table C.3 EPS (PS & PN) concentration at various sampling points

**Run 2: OLR 4, NLR 0.4 (MABR & SBAR Separated)**

**Case 1 : Equal Nitrogen**

| | | **MABR** | **MABR** | | **Permeate** | | **bound EPS of MABR** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | Day | VSS | sPS | sPN | sPS | sPN | DF-PS | PS | PS | DF-PN | PN | PN | sam. V | Ext. V | mgPS/ gVSS | mgPN/ gVSS |
| | | mg/L | mg/L | mg/L | mg/L | mg/L | | ABS | mg/L | | ABS | mg/L | mL | mL | | |
| 06-Dec-07 | 84 | 1234 | 13.2 | 3.3 | 3.0 | 0.0 | 4 | 0.024 | 11.2 | 1 | 0.069 | 17.8 | 50.0 | 95.0 | 17.3 | 27.5 |
| 11-Dec-07 | 89 | 643 | 8.5 | 0.0 | 4.0 | 0.0 | 4 | 0.019 | 9.8 | 1 | 0.03 | 6.1 | 50.0 | 97.5 | 29.7 | 18.4 |
| 13-Dec-07 | 91 | 620 | 6.7 | 0.1 | 2.6 | 0.0 | 2 | 0.023 | 5.5 | 1 | 0.028 | 5.5 | 50.0 | 96.0 | 17.0 | 17.0 |
| 18-Dec-07 | 96 | 571 | 4.6 | 0.0 | 2.3 | 0.0 | 2 | 0.026 | 5.9 | 1 | 0.033 | 7.0 | 50.0 | 95.0 | 19.7 | 23.3 |
| 20-Dec-07 | 98 | 550 | 3.0 | 0.0 | 1.5 | 0.0 | 2 | 0.025 | 5.8 | 1 | 0.029 | 5.8 | 50.0 | 102.0 | 21.4 | 21.5 |
| 25-Dec-07 | 103 | 565 | 2.3 | 0.0 | 1.7 | 0.0 | 2 | 0.024 | 5.6 | 1 | 0.033 | 7.0 | 50.0 | 99.5 | 19.8 | 24.6 |
| 27-Dec-07 | 105 | 565 | 2.4 | 0.0 | 1.5 | 0.0 | 2 | 0.025 | 5.8 | 1 | 0.034 | 7.3 | 50.0 | 98.0 | 20.0 | 25.3 |

**Case 2 : Low Nitrogen**

| | | **MABR** | **MABR** | | **Permeate** | | **bound EPS of MABR** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | Day | VSS | sPS | sPN | sPS | sPN | DF-PS | PS | PS | DF-PN | PN | PN | sam. V | Ext. V | mgPS/ gVSS | mgPN/ gVSS |
| | | mg/L | mg/L | mg/L | mg/L | mg/L | | ABS | mg/L | | ABS | mg/L | mL | mL | mg/g | mg/g |
| 03-Jan-08 | 112 | 560 | 3.4 | 0.0 | 2.2 | 0.0 | 2 | 0.039 | 7.8 | 1 | 0.04 | 9.1 | 50.0 | 97.5 | 27.2 | 31.7 |
| 05-Jan-08 | 114 | 558 | 3.5 | 0.0 | 1.9 | 0.0 | 2 | 0.036 | 7.4 | 1 | 0.045 | 10.6 | 50.0 | 95.0 | 25.1 | 36.1 |
| 08-Jan-08 | 117 | 587 | 3.3 | 0.0 | 2.3 | 0.0 | 2 | 0.041 | 8.1 | 1 | 0.042 | 9.7 | 50.0 | 102.5 | 28.3 | 33.9 |
| 10-Jan-08 | 119 | 585 | 3.7 | 0.0 | 2.5 | 0.0 | 2 | 0.054 | 10.0 | 1 | 0.05 | 12.1 | 50.0 | 97.5 | 33.3 | 40.3 |
| 15-Jan-08 | 124 | 554 | 3.3 | 0.7 | 2.4 | 0.0 | 2 | 0.054 | 10.0 | 1 | 0.046 | 10.9 | 50.0 | 90.0 | 32.5 | 35.4 |
| 17-Jan-08 | 126 | 569 | 3.4 | 0.0 | 2.6 | 0.0 | 2 | 0.052 | 9.7 | 1 | 0.047 | 11.2 | 50.0 | 95.0 | 32.4 | 37.4 |

**Case 3 : High Nitrogen**

| | | MABR | MABR | | Permeate | | bound EPS of MABR | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | Day | VSS | sPS | sPN | sPS | sPN | DF-PS | PS | PS | DF-PN | PN | PN | sam. V | Ext. V | mgPS/ gVSS | mgPN/ gVSS |
| | | mg/L | mg/L | mg/L | mg/L | mg/L | | ABS | mg/L | | ABS | mg/L | mL | mL | mg/g | mg/g |
| 22-Jan-08 | 131 | 560 | 3.2 | 0.0 | 2.4 | 0.0 | 2 | 0.03 | 6.5 | 1 | 0.028 | 5.5 | 50.0 | 100.0 | 23.2 | 19.6 |
| 24-Jan-08 | 133 | 589 | 3.1 | 0.0 | 2.4 | 0.0 | 2 | 0.028 | 6.2 | 1 | 0.025 | 4.6 | 50.0 | 97.5 | 20.6 | 15.2 |
| 29-Jan-08 | 138 | 556 | 2.4 | 0.0 | 2.0 | 0.0 | 2 | 0.026 | 5.9 | 1 | 0.028 | 5.5 | 50.0 | 98.0 | 20.9 | 19.3 |
| 31-Jan-08 | 140 | 585 | 2.2 | 0.0 | 2.0 | 0.0 | 2 | 0.025 | 5.8 | 1 | 0.022 | 3.7 | 50.0 | 97.5 | 19.2 | 12.2 |
| 05-Feb-08 | 145 | 554 | 2.4 | 0.7 | 2.0 | 0.0 | 2 | 0.028 | 6.2 | 1 | 0.028 | 5.5 | 50.0 | 100.0 | 22.4 | 19.8 |
| 07-Feb-08 | 147 | 569 | 2.2 | 0.0 | 2.1 | 0.0 | 2 | 0.026 | 5.9 | 1 | 0.029 | 5.8 | 50.0 | 102.5 | 21.3 | 20.8 |
| 12-Feb-08 | 152 | 574 | 2.4 | 0.0 | 1.9 | 0.0 | 2 | 0.027 | 6.1 | 1 | 0.029 | 5.8 | 50.0 | 97.5 | 20.6 | 19.6 |

Table C.4 Intensive Monitoring for MABR at Case 1, 2 & 3

**Case 1 : Equal Nitrogen**
**Date 12 Dec 2007 (COD =100mg/L & N = 5mg/L MABR )**

| Time, min | Feed | 10 | 20 | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 | P 120 | P 240 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COD, mg/L | 110.75 | 42.55 | 38.31 | 34.69 | 29.83 | 32.65 | 40.96 | 41.98 | 46.67 | 50.41 | 41.28 | 12.35 | 16.30 |
| TOC, mg/L | 39.07 | 13.55 | 11.97 | 10.62 | 8.80 | 9.85 | 12.96 | 13.34 | 15.10 | 16.50 | 13.08 | 2.26 | 3.74 |
| NO2, mg/L | 4.82 | 1.86 | 1.69 | 1.53 | 0.80 | 0.12 | 0.10 | 0.13 | 0.13 | 0.14 | 0.15 | 0.01 | 0.00 |
| NO3, mg/L | 1.43 | 1.12 | 1.28 | 1.57 | 2.01 | 2.44 | 2.92 | 2.71 | 2.63 | 2.86 | 2.69 | 3.26 | 2.89 |
| TN, mg/L | 6.26 | 2.99 | 2.97 | 3.09 | 2.81 | 2.56 | 3.02 | 2.84 | 2.76 | 3.00 | 2.84 | 3.27 | 2.89 |

**Case 2 : Low Nitrogen**
**Date 14 Jan 2008 (COD =100mg/L & N = 3mg/L MABR )**

| Time, min | Feed | 10 | 20 | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| COD, mg/L | 106.90 | 28.44 | 26.32 | 22.14 | 22.61 | 21.08 | 19.19 | 22.54 | 24.62 | 28.73 | 19.43 |
| TOC, mg/L | 37.63 | 8.28 | 7.49 | 5.92 | 6.10 | 5.53 | 4.82 | 6.07 | 6.85 | 8.39 | 4.91 |
| NO2, mg/L | 2.03 | 0.85 | 0.73 | 0.66 | 0.44 | 0.16 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| NO3, mg/L | 1.18 | 1.23 | 1.27 | 1.33 | 1.39 | 1.48 | 1.51 | 1.57 | 1.60 | 1.62 | 1.66 |
| TN, mg/L | 3.21 | 2.08 | 2.00 | 1.99 | 1.83 | 1.64 | 1.53 | 1.58 | 1.61 | 1.63 | 1.67 |

**Case 3 : High Nitrogen**
**Date 11 Feb 2008 (COD =100mg/L & N = 10mg/L MABR )**

| Time, min | Feed | 10 | 20 | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| COD, mg/L | 106.90 | 31.09 | 21.78 | 20.06 | 17.93 | 17.83 | 14.14 | 17.81 | 19.71 | 21.69 | 23.20 |
| TOC, mg/L | 37.63 | 9.27 | 5.79 | 5.14 | 4.34 | 4.31 | 2.93 | 4.30 | 5.01 | 5.75 | 6.32 |
| NO2, mg/L | 8.81 | 2.91 | 2.57 | 2.27 | 1.20 | 0.11 | 0.07 | 0.05 | 0.03 | 0.02 | 0.02 |
| NO3, mg/L | 1.93 | 2.76 | 3.21 | 3.50 | 4.05 | 4.59 | 5.39 | 5.42 | 5.43 | 5.45 | 5.43 |
| TN, mg/L | 10.74 | 5.67 | 5.78 | 5.76 | 5.25 | 4.70 | 5.46 | 5.47 | 5.46 | 5.47 | 5.45 |

Table C.5 SVI, MLSS and CST values of MABR sludge at Case 1, 2 & 3

**Run 2: OLR 4, NLR 0.4, SBAR & MABR are separated**

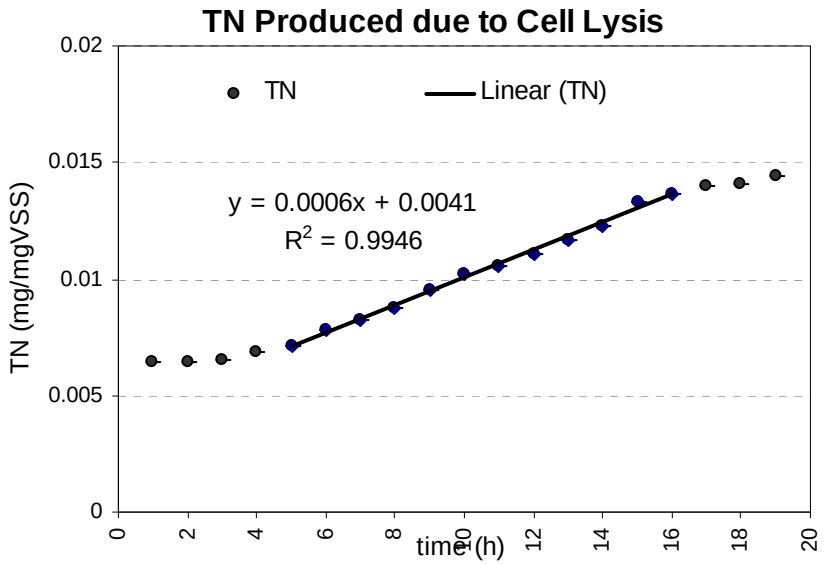
| | | MABR | MABR | MABR | |
|---|---|---|---|---|---|
| **Date** | **Day** | **SVI, mL/g** | **MLSS, mg/L** | **CST, sec** | **Remarks** |
| 05-Dec-07 | 83 | 59.5 | 1680 | 11.4 | Separated MABR & SBAR Case 1: Equal N |
| 12-Dec-07 | 90 | 56.8 | 880 | 10.2 | |
| 19-Dec-07 | 97 | 55.6 | 900 | 9.3 | |
| 26-Dec-07 | 104 | 54.3 | 920 | 8.5 | |
| **average** | | **56.6** | **900.0** | **9.9** | |
| **STDV** | | **2.2** | **20.0** | **1.2** | |
| 02-Jan-08 | 111 | 56.8 | 880 | 9.1 | Case 2 : Low N |
| 09-Jan-08 | 118 | 55.6 | 900 | 8.8 | |
| 16-Jan-08 | 125 | 56.8 | 880 | 8.7 | |
| **average** | | **56.4** | **886.7** | **8.9** | |
| **STDV** | | **0.7** | **11.5** | **0.2** | |
| 23-Jan-08 | 132 | 34.9 | 860 | 7.8 | Case 3 : High N |
| 30-Jan-08 | 139 | 38.9 | 810 | 7.4 | |
| 06-Feb-08 | 146 | 36.6 | 860 | 8.2 | |
| 13-Feb-08 | 153 | 60.3 | 870 | 7.7 | |
| **average** | | **42.7** | **850.0** | **7.8** | |
| **STDV** | | **11.9** | **27.1** | **0.3** | |
| 20-Feb-08 | 160 | 53.5 | 1870 | 8.6 | External Carbon |

Table C.6 Cell Lysis for MABR Sludge

**Date 29 Dec 07**

| | **8.00** | **9.00** | **10.00** | **11.00** | **12.00** | **13.00** | **14.00** | **15.00** | **16.00** | **17.00** | **18.00** | **19.00** | **20.00** | **21.00** | **22.00** | **23.00** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Time, min | 0 | 60 | 120 | 180 | 240 | 300 | 360 | 420 | 480 | 540 | 600 | 660 | 720 | 780 | 840 | 900 |
| time, h | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| | | | | | | | | | | | | | | | | |
| sPS, mg/L | 3.3 | 3.2 | 3.3 | 3.1 | 3.2 | 3.3 | 3.2 | 3.2 | 3.5 | 2.9 | 2.5 | 2.7 | 2.8 | 2.7 | 3.0 | 3.1 |
| sPN, mg/L | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 1.9 |
| TN, mg/L | 2.2 | 2.2 | 2.3 | 2.4 | 2.5 | 2.7 | 2.9 | 3.0 | 3.3 | 3.6 | 3.7 | 3.9 | 4.1 | 4.3 | 4.6 | 4.7 |
| $VSS_{TOC}$ | 346 | | 345 | | 345 | | 346 | | 350 | | 351 | | 352 | | 346 | |
| Ratio PS/EPS | 1.00 | 0.98 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.76 | 0.62 |
| TN (mg/mgVSS) | 0.006 | 0.006 | 0.007 | 0.007 | 0.007 | 0.008 | 0.008 | 0.009 | 0.010 | 0.010 | 0.011 | 0.011 | 0.012 | 0.012 | 0.013 | 0.014 |

| Time, min | **24.00** | | **1.00** | | **2.00** | |
|---|---|---|---|---|---|---|
| time, h | 960 | | 1020 | | 1080 | |
| | 17 | | 18 | | 19 | |
| sPS, mg/L | in | out | in | out | in | out |
| sPN, mg/L | 3.0 | 3.2 | 3.0 | 3.2 | 3.1 | 3.2 |
| TN, mg/L | 1.6 | 1.6 | 1.3 | 1.9 | 1.6 | 1.9 |
| $VSS_{TOC}$ | 4.9 | 4.9 | 5.0 | 5.1 | 5.1 | 5.2 |
| Ratio PS/EPS | 353 | 323 | | | 353 | 319 |
| TN (mg/mgVSS) | 0.65 | 0.67 | 0.71 | 0.64 | 0.66 | 0.63 |
| | 0.014 | 0.015 | 0.014 | 0.016 | 0.014 | 0.016 |




The equation of the graph will give the TN produced.
Say for example
At 2 hrs time
The TN Produced = 0.0006*(2)+0.0041 = 0.0053 mg/mgVSS
= 0.0053 * 345 = 1.83 mg/L

## Appendix D: Raw Data for Run 3

Table D.1 Organic and Nitrogen concentration for various sampling points at OLR 4 kgCOD/$m^3$.d and NLR 0.4 kgN/$m^3$.d

| | | Inf | Eff-R | MABR | permeate | Inf | Eff-R | MABR | permeate | Inf | Eff-R | MABR | permeate | Inf | Eff-R | MABR | permeate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Date** | **Day** | **NH4-N** | | | | **NO2-N (mg/L) = 337.12 * (ABS) + 0.0829** | | | | **NO3-N (mg/L) = 3.0077 * (ABS) - 0.0204** | | | | **TN** | | | |
| 28-Feb-08 | 172 | 117.6 | 0.3 | 0.0 | 0.0 | 0.13 | 40.87 | 1.18 | 0.66 | 2.68 | 9.12 | 26.72 | 26.78 | 120.41 | 50.27 | 27.91 | 27.44 |
| | | | | | | **NO2-N (mg/L) = 318.33 * (ABS) - 0.0742** | | | | **NO3-N (mg/L) = 2.7991 * (ABS) - 0.0383** | | | | | | | |
| 03-Mar-08 | 176 | 114.8 | 0.1 | 0.0 | 0.0 | 0.11 | 3.11 | 0.46 | 0.30 | 2.50 | 50.23 | 56.67 | 58.57 | 117.41 | 53.48 | 57.13 | 58.87 |
| 06-Mar-08 | 179 | 120.4 | 0.3 | 0.0 | 0.0 | 0.03 | 4.06 | 0.43 | 0.33 | 2.20 | 57.01 | 56.90 | 59.81 | 122.63 | 61.35 | 57.32 | 60.14 |
| 10-Mar-08 | 183 | 117.6 | 0.1 | 0.0 | 0.0 | 0.06 | 3.75 | 0.31 | 0.27 | 1.82 | 45.14 | 53.82 | 55.16 | 119.49 | 49.03 | 54.13 | 55.43 |
| 13-Mar-08 | 186 | 126.0 | 0.3 | 0.0 | 0.0 | 0.05 | 3.78 | 0.35 | 0.24 | 2.20 | 57.01 | 56.90 | 59.81 | 128.25 | 61.07 | 57.24 | 60.04 |
| 16-Mar-08 | 189 | 117.6 | 0.1 | 0.0 | 0.0 | 0.05 | 2.99 | 0.39 | 0.33 | 1.81 | 45.64 | 54.43 | 54.77 | 119.46 | 48.77 | 54.83 | 55.10 |
| 18-Mar-08 | 191 | 117.6 | 0.1 | 0.0 | 0.0 | 0.02 | 4.10 | 0.35 | 0.28 | 2.29 | 45.14 | 52.81 | 54.60 | 119.91 | 49.38 | 53.16 | 54.88 |
| 20-Mar-08 | 193 | 117.6 | 0.1 | 0.0 | 0.0 | 0.05 | 2.99 | 0.39 | 0.33 | 1.81 | 45.64 | 54.43 | 54.77 | 119.46 | 48.77 | 54.83 | 55.10 |
| | | | | | | | | | | **NO3-N (mg/L) = 2.8999 * (ABS) - 0.0118** | | | | | | | |
| 01-Apr-08 | 205 | 114.8 | 0.1 | 0.0 | 0.0 | 0.04 | 3.46 | 0.33 | 0.16 | 2.10 | 46.97 | 53.37 | 54.43 | 116.94 | 50.58 | 53.70 | 54.59 |
| 03-Apr-08 | 207 | 117.6 | 0.1 | 0.0 | 0.0 | 0.04 | 3.78 | 0.30 | 0.17 | 2.07 | 47.32 | 52.92 | 54.10 | 119.71 | 51.25 | 53.22 | 54.27 |
| 07-Apr-08 | 211 | 114.8 | 0.1 | 0.0 | 0.0 | 0.04 | 3.94 | 0.35 | 0.24 | 2.00 | 47.61 | 53.14 | 54.04 | 116.84 | 51.69 | 53.49 | 54.28 |
| 10-Apr-08 | 214 | 117.6 | 0.1 | 0.0 | 0.0 | 0.05 | 3.78 | 0.31 | 0.12 | 1.94 | 47.90 | 52.98 | 54.26 | 119.59 | 51.83 | 53.29 | 54.39 |

| | | Inf | Eff-R | MABR | permeate | Inf | Eff-R | MABR | permeate | Eff-R | MABR | permeate | Eff-R | MABR | permeate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Date** | **Day** | **COD, mg/L** | | | | **TOC** | | | | **UVA** | | | **SUVA** | | |
| 28-Feb-08 | 172 | 1115.95 | 29.62 | 36.55 | 15.19 | 415.12 | 8.72 | 11.31 | 3.32 | 0.155 | 0.159 | 0.088 | 0.02 | 0.01 | 0.026 |
| 03-Mar-08 | 176 | 1110.77 | 28.53 | 32.01 | 13.33 | 413.18 | 8.31 | 9.62 | 2.63 | 0.117 | 0.150 | 0.099 | 0.01 | 0.02 | 0.038 |
| 06-Mar-08 | 179 | 1121.88 | 28.61 | 31.65 | 14.10 | 417.34 | 8.34 | 9.48 | 2.92 | 0.139 | 0.125 | 0.094 | 0.02 | 0.01 | 0.032 |
| 10-Mar-08 | 183 | 1110.28 | 27.46 | 30.59 | 13.46 | 413.00 | 7.91 | 9.08 | 2.67 | 0.106 | 0.131 | 0.105 | 0.01 | 0.01 | 0.039 |
| 13-Mar-08 | 186 | 1044.68 | 27.28 | 31.34 | 12.82 | 388.46 | 7.84 | 9.36 | 2.44 | 0.102 | 0.144 | 0.115 | 0.01 | 0.02 | 0.047 |
| 16-Mar-08 | 189 | 1121.88 | 29.61 | 31.44 | 14.10 | 417.34 | 8.71 | 9.40 | 2.92 | 0.139 | 0.129 | 0.102 | 0.02 | 0.01 | 0.035 |
| 18-Mar-08 | 191 | 1118.52 | 28.42 | 30.27 | 13.74 | 416.08 | 8.27 | 8.96 | 2.78 | 0.125 | 0.128 | 0.099 | 0.02 | 0.01 | 0.036 |
| 20-Mar-08 | 193 | 1120.04 | 28.06 | 31.47 | 12.70 | 416.65 | 8.13 | 9.41 | 2.39 | 0.112 | 0.143 | 0.118 | 0.01 | 0.02 | 0.049 |
| 01-Apr-08 | 205 | 1059.76 | 26.52 | 30.81 | 13.97 | 394.10 | 7.56 | 9.16 | 2.87 | 0.096 | 0.137 | 0.098 | 0.01 | 0.01 | 0.034 |
| 03-Apr-08 | 207 | 1087.45 | 27.46 | 31.89 | 13.24 | 404.46 | 7.91 | 9.57 | 2.59 | 0.100 | 0.140 | 0.101 | 0.01 | 0.01 | 0.039 |
| 07-Apr-08 | 211 | 1080.53 | 26.07 | 33.00 | 12.85 | 401.87 | 7.39 | 9.98 | 2.45 | 0.105 | 0.138 | 0.106 | 0.01 | 0.01 | 0.043 |
| 10-Apr-08 | 214 | 1080.99 | 26.17 | 30.83 | 13.37 | 402.04 | 7.43 | 9.17 | 2.64 | 0.100 | 0.133 | 0.110 | 0.01 | 0.01 | 0.042 |

Table D.2 Intensive Monitoring for SBAR & MABR at OLR 4 kgCOD/$m^3$.d and NLR 0.4 kgN/$m^3$.d

**SBAR - Date 18 Mar 2008 OLR 4 & NLR 0.4**

| Time, min | Feed | 10 | 20 | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | 7.65 | 7.9 | 8.13 | 8.14 | 8.25 | 8.25 | 8.22 | 8.11 | 8.13 | 7.81 | 7.82 |
| DO, mg/L | | 6.94 | 6.95 | 7.18 | 6.94 | 7.05 | 7.1 | 7.05 | 7.01 | 3.88 | |
| COD, mg/L | 1118.52 | 753.36 | 489.77 | 405.22 | 324.24 | 248.17 | 151.47 | 74.55 | 46.95 | 42.84 | 28.40 |
| TOC, mg/L | 416.08 | 279.47 | 180.86 | 149.23 | 118.94 | 90.48 | 54.30 | 25.53 | 15.20 | 13.66 | 8.26 |
| NH4, mg/L | 117.60 | 56.00 | 50.40 | 43.40 | 36.40 | 28.00 | 14.00 | 5.60 | 1.40 | 0.70 | 0.14 |
| NO2, mg/L | 0.02 | 1.38 | 2.20 | 3.38 | 4.97 | 8.47 | 10.06 | 12.77 | 11.34 | 6.72 | 4.18 |
| NO3, mg/L | 2.29 | 0.61 | 0.97 | 2.70 | 5.22 | 9.61 | 17.88 | 23.42 | 31.14 | 35.73 | 45.14 |
| TN, mg/L | 119.91 | 57.98 | 53.57 | 49.48 | 46.59 | 46.08 | 41.94 | 41.79 | 43.88 | 43.16 | 49.45 |

**MABR - Date 18 Mar 2008 OLR 4 & NLR 0.4**

| Time, min | | Feed | 10 | 20 | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | in | 7.86 | 7.99 | 7.98 | 7.99 | 7.95 | 7.96 | 7.85 | 7.82 | 7.8 | 7.82 | 7.84 |
| | out | | | | | | 7.9 | 7.96 | 7.95 | 7.95 | 7.9 | 7.9 |
| DO, mg/L | in | 4.22 | 4.5 | 4.52 | 4.55 | 4.51 | 4.53 | 4.55 | 4.57 | 4.6 | 4.55 | 4.43 |
| | out | | | | | | 0.9 | 0.7 | 0.72 | 0.71 | 0.8 | 0.75 |
| COD, mg/L | | 29.61 | 53.70 | 53.06 | 44.32 | 41.58 | 37.05 | 31.44 | 36.60 | 48.53 | 52.69 | 52.28 |
| TOC, mg/L | | 8.71 | 17.73 | 17.49 | 14.22 | 13.19 | 11.50 | 9.40 | 11.33 | 15.79 | 17.35 | 17.20 |
| NH4, mg/L | | 0.14 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| NO2, mg/L | | 3.06 | 1.38 | 1.12 | 0.77 | 0.77 | 0.77 | 0.40 | 0.42 | 0.40 | 0.39 | 0.12 |
| NO3, mg/L | | 45.64 | 49.06 | 49.84 | 52.42 | 53.82 | 54.10 | 54.43 | 55.44 | 55.38 | 56.11 | 56.11 |
| TN, mg/L | | 48.84 | 50.43 | 50.96 | 53.19 | 54.59 | 54.87 | 54.83 | 55.86 | 55.79 | 56.50 | 56.23 |

Table D.3 SVI, MLSS and CST values of Granular and MABR sludge at OLR 4 kgCOD/$m^3$.d and NLR 0.4 kgN/$m^3$.d

| | | SBAR | MABR | SBAR | MABR | SBAR | Eff-R | MABR |
|---|---|---|---|---|---|---|---|---|
| **Date** | **Day** | **SVI, mL/g** | | **MLSS, mg/L** | | **CST (s)** | | |
| 27-Feb-08 | 167 | 26.1 | 69.6 | 9180 | 1960 | 10.5 | 12.5 | 10.0 |
| 29-Feb-08 | 169 | | | | 4380 | | | |
| 05-Mar-08 | 174 | 24.6 | 42.6 | 10980 | 5420 | 11 | 13.0 | 13.5 |
| 12-Mar-08 | 181 | 20.0 | 48.6 | 10983 | 5400 | 10.5 | 12.8 | 13.2 |
| 19-Mar-08 | 188 | 27.2 | 57.1 | 7354 | 5520 | 11.2 | 10.0 | 13.5 |
| 26-Mar-08 | 195 | 18.3 | 61.4 | 9840 | 5640 | 10.8 | 8.2 | 13.2 |
| 02-Apr-08 | 202 | 19.5 | 43.4 | 10280 | 5560 | 11 | 8.4 | 13.4 |
| 09-Apr-08 | 209 | 18.7 | 47.9 | 10723 | 5480 | 11 | 8.5 | 13.0 |

Table D.4 EPS measurement for MABR and SBAR at OLR 4 kgCOD/$m^3$.d

| | | **SBAR** | **SBAR Flocs** | **MABR** | **Eff-R** | | **MABR** | | **Permeate** | |
|---|---|---|---|---|---|---|---|---|---|---|
| Date | day | VSS | VSS | VSS | sPS | sPN | sPS | sPN | sPS | sPN |
| | | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L |
| 04-Mar-08 | 173 | 7976 | 329 | 3846 | 5.8 | 0.0 | 7.5 | 10.6 | 4.9 | 5.8 |
| 07-Mar-08 | 176 | 7904 | 392 | 3765 | 6.1 | 0.0 | 7.7 | 9.4 | 5.1 | 5.5 |
| 11-Mar-08 | 180 | 7940 | 352 | 3992 | 6.2 | 0.1 | 7.6 | 9.4 | 6.0 | 6.1 |
| 15-Mar-08 | 184 | 6596 | 369 | 3860 | 6.1 | 0.0 | 7.5 | 9.7 | 5.8 | 5.8 |
| 17-Mar-08 | 186 | 6257 | 399 | 3859 | 7.5 | 0.0 | 8.7 | 8.5 | 6.2 | 4.3 |
| 02-Apr-08 | 202 | 8033 | 359 | 3882 | 7.3 | 0.0 | 8.3 | 11.8 | 6.2 | 4.0 |
| 05-Apr-08 | 205 | 8037 | 334 | 3898 | 7.2 | 0.0 | 8.4 | 9.4 | 6.1 | 3.4 |

| | | **Bound EPS of SBAR - Granular Sludge** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | day | DF-PS | PS | PS | DF-PN | PN | PN | sam.V | Ext. V | mgPS/gVSS | mgPN/gVSS |
| | | | ABS | mg/L | | ABS | mg/L | mL | mL | mg/g | mg/g |
| 04-Mar-08 | 173 | 4 | 0.039 | 15.6 | 1 | 0.03 | 4.9 | 25 | 95 | 7.44 | 2.32 |
| 07-Mar-08 | 176 | 4 | 0.036 | 14.7 | 1 | 0.03 | 4.9 | 22.5 | 90 | 7.46 | 2.47 |
| 11-Mar-08 | 180 | 4 | 0.036 | 14.7 | 1 | 0.03 | 5.5 | 27.5 | 85 | 5.74 | 2.13 |
| 15-Mar-08 | 184 | 4 | 0.034 | 14.2 | 1 | 0.03 | 6.1 | 30 | 82.5 | 5.91 | 2.54 |
| 17-Mar-08 | 186 | 4 | 0.035 | 14.5 | 1 | 0.03 | 5.8 | 35 | 95 | 6.27 | 2.51 |
| 02-Apr-08 | 202 | 4 | 0.047 | 18.0 | 1 | 0.03 | 5.8 | 35 | 95 | 6.07 | 1.95 |
| 05-Apr-08 | 205 | 4 | 0.052 | 19.4 | 1 | 0.03 | 6.7 | 40 | 100 | 6.04 | 2.08 |

| | | **Bound EPS of SBAR - Flocs** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | day | DF-PS | PS | PS | DF-PN | PN | PN | sam.V | Ext. V | mgPS/gVSS | mgPN/gVSS |
| | | | ABS | mg/L | | ABS | mg/L | mL | mL | mg/g | mg/g |
| 04-Mar-08 | 173 | 2 | 0.01 | 3.6 | 1 | 0.01 | 0.0 | 25 | 85 | 37.1 | 0 |
| 07-Mar-08 | 176 | 2 | 0.007 | 3.1 | 1 | 0.01 | 0.0 | 30 | 95 | 25.4 | 0 |
| 11-Mar-08 | 180 | 1 | 0.02 | 2.5 | 1 | 0.01 | 0.0 | 35 | 75.5 | 15.5 | 0 |
| 15-Mar-08 | 184 | 1 | 0.022 | 2.7 | 1 | 0.01 | 0.0 | 40 | 80 | 14.4 | 0 |
| 17-Mar-08 | 186 | 1 | 0.024 | 2.8 | 1 | 0.01 | 0.0 | 40 | 100 | 17.6 | 0 |
| 02-Apr-08 | 202 | 1 | 0.026 | 3.0 | 1 | 0.01 | 0.0 | 42.5 | 100 | 19.4 | 0 |
| 05-Apr-08 | 205 | 1 | 0.027 | 3.0 | 1 | 0.01 | 0.0 | 40 | 97.5 | 22.1 | 0 |

| | | **Bound EPS of MABR** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | day | DF-PS | PS | PS | DF-PN | PN | PN | sam. V | Ext. V | mgPS/gVSS | mgPN/gVSS |
| | | | ABS | mg/L | | ABS | mg/L | mL | mL | mg/g | mg/g |
| 04-Mar-08 | 173 | 4 | 0.035 | 14.5 | 1 | 0.07 | 16.6 | 35.0 | 100.0 | 10.7 | 12.4 |
| 07-Mar-08 | 176 | 4 | 0.037 | 15.0 | 1 | 0.07 | 17.2 | 32.5 | 92.5 | 11.4 | 13.0 |
| 11-Mar-08 | 180 | 4 | 0.038 | 15.3 | 1 | 0.07 | 17.5 | 32.5 | 92.0 | 10.9 | 12.4 |
| 15-Mar-08 | 184 | 4 | 0.04 | 15.9 | 1 | 0.06 | 16.0 | 35.0 | 95.0 | 11.2 | 11.3 |
| 17-Mar-08 | 186 | 4 | 0.063 | 22.6 | 1 | 0.05 | 12.7 | 30.0 | 92.5 | 18.1 | 10.2 |
| 02-Apr-08 | 202 | 4 | 0.061 | 22.0 | 1 | 0.05 | 12.1 | 30.0 | 95.0 | 18.0 | 9.9 |
| 05-Apr-08 | 205 | 4 | 0.059 | 21.4 | 1 | 0.05 | 11.5 | 35.0 | 100.0 | 15.7 | 8.4 |

Table D.5 Granule Size at OLR 4 kgCOD/$m^3$.d

| Date | 27-Feb-08 | 05-Mar-08 | 12-Mar-08 | 19-Mar-08 | 26-Mar-08 | 02-Apr-08 | 09-Apr-08 | 16-Apr-08 |
|---|---|---|---|---|---|---|---|---|
| No. | Size (mm) | | | | | | | |
| 1 | 3 | 1.5 | 2 | 2.5 | 2 | 3 | 2 | 2 |
| 2 | 2 | 2 | 2 | 2 | 1.5 | 2.5 | 2 | 3 |
| 3 | 1 | 1 | 1 | 1 | 2.5 | 2 | 2 | 1 |
| 4 | 2.5 | 2 | 3.5 | 3 | 3 | 1.5 | 2.5 | 2 |
| 5 | 2.5 | 2 | 2.5 | 2.5 | 2.5 | 2.5 | 1.5 | 1 |
| 6 | 1.5 | 2.5 | 2 | 2 | 2 | 2 | 2 | 2 |
| 7 | 1.5 | 2.5 | 1.5 | 2 | 1.5 | 1.5 | 1 | 1.5 |
| 8 | 0.5 | 3 | 2.5 | 2.5 | 2 | 1 | 1.5 | 1.5 |
| 9 | 1.5 | 3.5 | 1 | 1 | 1 | 1.5 | 1.5 | 1.5 |
| 10 | 2 | 0.5 | 1.5 | 0.5 | 1.5 | 2 | 2.5 | 1.5 |
| 11 | 1 | 1 | 1 | 1 | 1 | 1 | 0.5 | 1.5 |
| 12 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1 | 0.5 |
| 13 | 1.5 | 0.5 | 1 | 1 | 1 | 1.5 | 1.5 | 1.5 |
| 14 | 2 | 2 | 2 | 1.5 | 2 | 1.5 | 1 | 1 |
| 15 | 1 | 1.5 | 1 | 1 | 1 | 1 | 1.5 | 0.5 |
| 16 | 1 | 1 | 1.5 | 1.5 | 1.5 | 1.5 | 2 | 2 |
| 17 | 1 | 1.5 | 1 | 1.5 | 1 | 1 | 2 | 2.5 |
| 18 | 1.5 | 2 | 1.5 | 0.5 | 1.5 | 1.5 | 1.5 | 1.5 |
| 19 | 0.5 | 0.5 | 1.5 | 1.5 | 1 | 1 | 2 | 3 |
| 20 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 21 | 2.5 | 2 | 0.5 | 0.5 | 1 | 1.5 | 1.5 | 1.5 |
| 22 | 3 | 3 | 3 | 0.5 | 3 | 2.5 | 2.5 | 2 |
| 23 | 3.5 | 2.5 | 3.5 | 3 | 3.5 | 3.5 | 2.5 | 2.5 |
| 24 | 2.5 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| 25 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2.5 |
| 26 | 1 | 1.5 | 0.5 | 3 | 1 | 2 | 2.5 | 2.5 |
| 27 | 1.5 | 3.5 | 1.5 | 1.5 | 1.5 | 1 | 1 | 1 |
| 28 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1 | 3 | 2.5 |
| 29 | 1 | 1 | 1 | 3 | 1 | 1 | 1 | 1 |
| 30 | 1.5 | 1.5 | 0.5 | 0.5 | 1 | 1.5 | 1.5 | 1.5 |
| 31 | 1 | 1.5 | 1 | 1 | 1 | 1.5 | 2.5 | 2.5 |
| 32 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 33 | 1.5 | 1.5 | 2 | 2.5 | 2 | 2 | 2 | 1.5 |
| 34 | 2 | 1 | 2 | 2 | 2 | 1.5 | 3 | 3 |
| 35 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1 |
| 36 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2 | 2.5 | 2.5 |
| 37 | 2 | 1 | 2 | 2.5 | 2 | 2 | 2 | 2 |
| 38 | 1.5 | 1 | 1.5 | 1.5 | 1.5 | 1.5 | 2 | 2 |
| 39 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 40 | 1.5 | 1.5 | 2 | 2 | 2 | 2.5 | 2 | 1 |
| 41 | 1 | 1 | 1 | 1.5 | 1 | 1 | 1 | 2 |
| 42 | 1.5 | 1.5 | 1.5 | 0.5 | 1.5 | 1 | 2.5 | 2 |
| 43 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2.5 |
| 44 | 2 | 2 | 2.5 | 2.5 | 2.5 | 2 | 2 | 2 |
| 45 | 1.5 | 3 | 1.5 | 1.5 | 1.5 | 1.5 | 1 | 1 |
| 46 | 1 | 1 | 2 | 2 | 2 | 2.5 | 2.5 | 2.5 |
| 47 | 0.5 | 0.5 | 0.5 | 1.5 | 1 | 1 | 1 | 1 |
| 48 | 0.5 | 0.5 | 2.5 | 2.5 | 2.5 | 3 | 2.5 | 2.5 |
| 49 | 1.5 | 2 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1 |
| 50 | 1 | 1.5 | 2 | 2 | 2 | 2 | 2 | 3 |

Table D.6 Particle Size Distribution of MABR sludge and Effluent of SBAR at OLR 4 kgCOD/$m^3$.d by % Volume

| | MABR | Eff-R | Conventional MBR | | MABR | Eff-R | Conventional MBR |
|---|---|---|---|---|---|---|---|
| Size (um) | % | | | Size (um) | % | | |
| 0.05 | 0 | 0 | 0 | 6.63 | 0.19 | 0.56 | 0.43 |
| 0.06 | 0 | 0 | 0 | 7.72 | 0.21 | 0.65 | 0.42 |
| 0.07 | 0 | 0 | 0 | 9 | 0.23 | 0.77 | 0.4 |
| 0.08 | 0 | 0 | 0 | 10.48 | 0.26 | 0.93 | 0.39 |
| 0.09 | 0.01 | 0 | 0 | 12.21 | 0.3 | 1.16 | 0.37 |
| 0.11 | 0.01 | 0 | 0 | 14.22 | 0.37 | 1.48 | 0.37 |
| 0.13 | 0.01 | 0 | 0.01 | 16.57 | 0.46 | 1.89 | 0.37 |
| 0.15 | 0.02 | 0 | 0.01 | 19.31 | 0.59 | 2.41 | 0.4 |
| 0.17 | 0.02 | 0 | 0.02 | 22.49 | 0.77 | 3.01 | 0.47 |
| 0.2 | 0.03 | 0 | 0.03 | 26.2 | 1 | 3.64 | 0.58 |
| 0.23 | 0.04 | 0.01 | 0.05 | 30.53 | 1.29 | 4.26 | 0.77 |
| 0.27 | 0.05 | 0.03 | 0.06 | 35.56 | 1.63 | 4.78 | 1.06 |
| 0.31 | 0.06 | 0.06 | 0.06 | 41.43 | 2.02 | 5.13 | 1.45 |
| 0.36 | 0.06 | 0.08 | 0.06 | 48.27 | 2.44 | 5.27 | 1.96 |
| 0.42 | 0.06 | 0.11 | 0.06 | 56.23 | 2.88 | 5.21 | 2.59 |
| 0.49 | 0.06 | 0.14 | 0.05 | 65.51 | 3.31 | 5 | 3.3 |
| 0.58 | 0.06 | 0.16 | 0.05 | 76.32 | 3.73 | 4.7 | 4.06 |
| 0.67 | 0.05 | 0.17 | 0.04 | 88.91 | 4.13 | 4.37 | 4.84 |
| 0.78 | 0.05 | 0.14 | 0.05 | 103.58 | 4.49 | 4.06 | 5.58 |
| 0.91 | 0.04 | 0.12 | 0.05 | 120.67 | 4.83 | 3.8 | 6.13 |
| 1.06 | 0.03 | 0.09 | 0.06 | 140.58 | 5.15 | 3.6 | 6.49 |
| 1.24 | 0.03 | 0.06 | 0.07 | 163.77 | 5.45 | 3.45 | 6.66 |
| 1.44 | 0.03 | 0.04 | 0.09 | 190.8 | 5.75 | 3.34 | 6.66 |
| 1.68 | 0.03 | 0.04 | 0.12 | 222.28 | 6.05 | 3.39 | 6.56 |
| 1.95 | 0.03 | 0.05 | 0.15 | 258.95 | 6.34 | 3.34 | 6.41 |
| 2.28 | 0.04 | 0.07 | 0.21 | 301.68 | 6.63 | 3.41 | 6.04 |
| 2.65 | 0.05 | 0.11 | 0.27 | 351.46 | 6.65 | 3.31 | 5.58 |
| 3.09 | 0.07 | 0.17 | 0.33 | 409.45 | 6.33 | 3.03 | 4.97 |
| 3.6 | 0.1 | 0.25 | 0.38 | 477.01 | 5.61 | 2.59 | 4.19 |
| 4.19 | 0.12 | 0.33 | 0.42 | 555.71 | 4.54 | 2.04 | 3.3 |
| 4.88 | 0.14 | 0.41 | 0.44 | 647.41 | 3.21 | 1.44 | 2.35 |
| 5.69 | 0.16 | 0.48 | 0.44 | 754.23 | 1.69 | 0.78 | 1.28 |

## Appendix E: Photographs

Figure E.1View of SBAR and MABR

Figure E.2 View of Cleaned Membrane

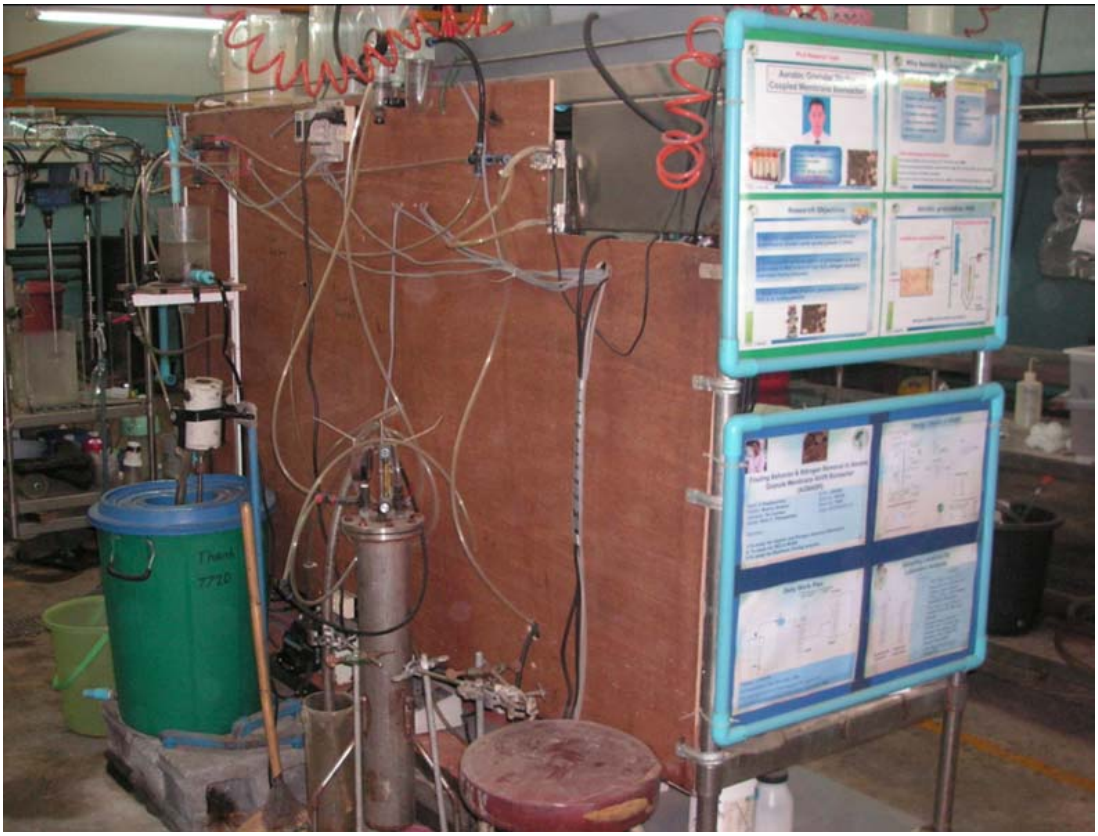


Figure E.3 Backside of the Experimental Setup

Figure E.4 The Overall Experimental Setup

# Investigation on Simultaneous Nitrification/Denitrification and Fouling of an Aerobic Granular Membrane Airlift Bioreactor

Ms. V. Prashanthini

Examination Committee:

Prof. C. Visvanathan (Chairperson)

Dr. Oleg Shipin

Dr. Preeda Parkpian

May 8, 2008

# Contents

# Background

Conventional Treatments

- Not good effluent quality
- High retention time
- Large area

Membrane Technology

-Good effluent quality
- Small area requirement
- Fouling
- Expensive

-Good effluent quality
- Small area requirement
- Low fouling
-Good settling of sludge

**Aerobic Granulation** + **Membrane Technology**

# Overall Experiment

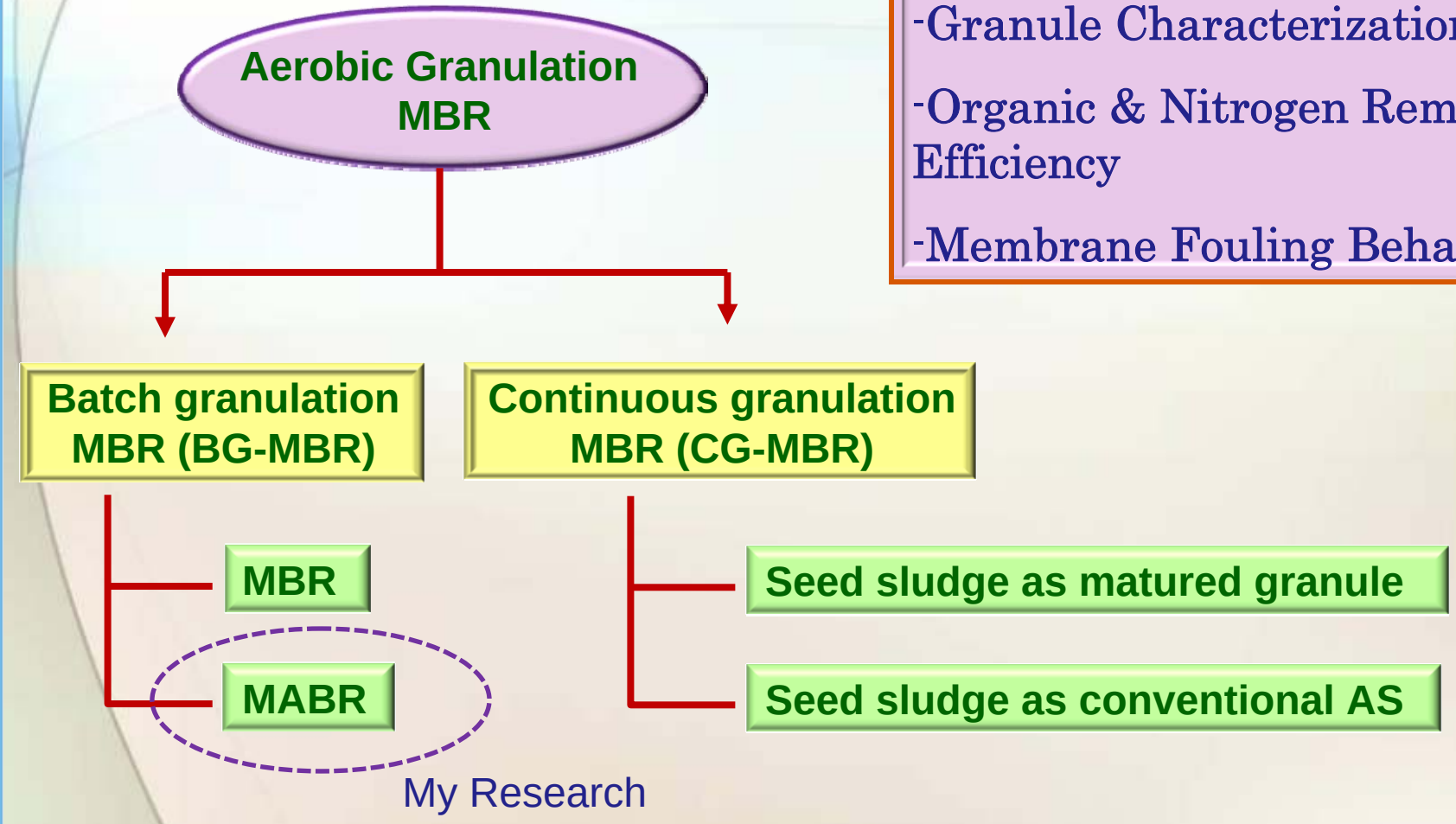
Mr. Bui Xuan Thanh's Research Work

**Objectives**

-Granule Characterization

-Organic & Nitrogen Removal Efficiency

-Membrane Fouling Behavior



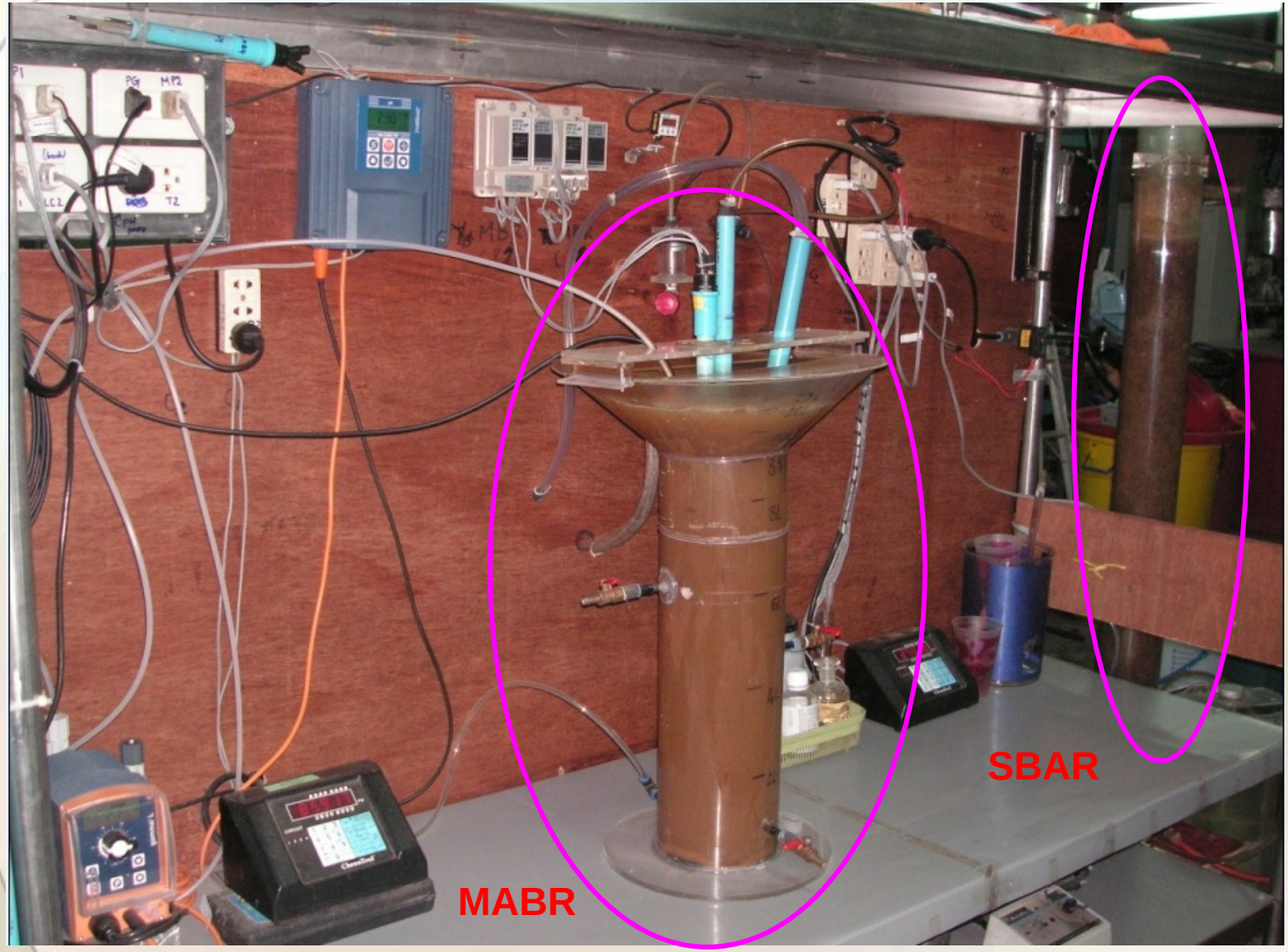
# Objectives of the Research

1. To study the simultaneous nitrification and denitrification in MABR

2. To study the organic removal and nitrogen removal patterns in the batch granulation MABR system

3. To study the membrane fouling behavior of MABR on granulation supernatant through MABR system

# Aerobic Granular Membrane Airlift Bioreactor



# Original Scope of the Research

| | Run 1 | Run 2 | Run 3 | Run 4 |
|---|---|---|---|---|
| OLR | 2 kgCOD/m$^3$.d | 4 kgCOD/m$^3$.d | 7 kgCOD/m$^3$.d | 10 kgCOD/m$^3$.d |
| NLR | 0.6 kgN/m$^3$.d | | | |

Granule Characterization

Treatability

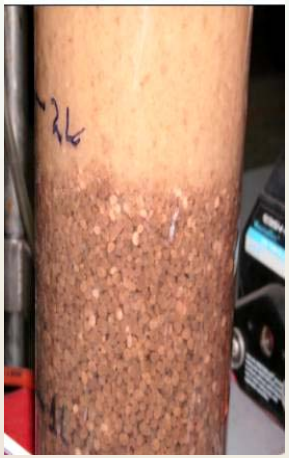
Fouling Behavior

Optimum OLR

# Results and Discussion

## Run 1: Granule Stability and its Effects

Granules started to disintegrate after 20 days of operation

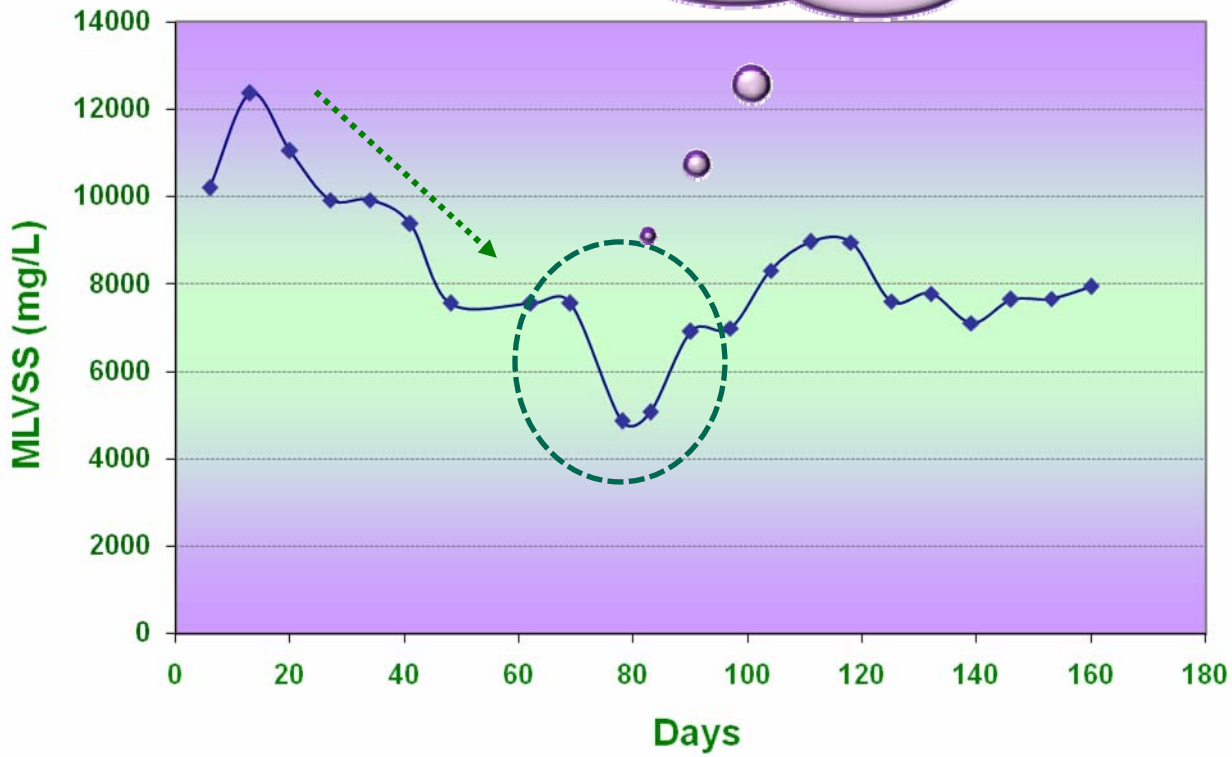
| | Day 12 | Day 36 | Day 50 |
|---|---|---|---|
| |  |  |  |
| MLVSS = | 11084 mg/L | 9737mg/L | 7758mg/L |

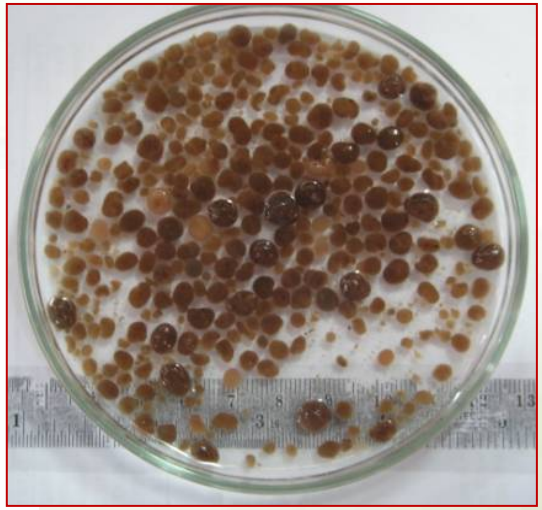
Page 45

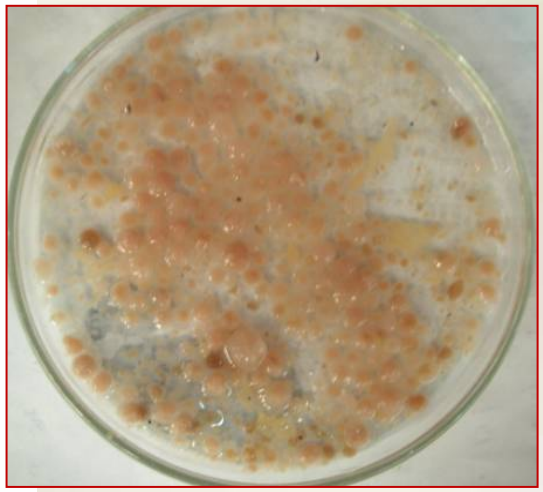
# Results and Discussion

## MLSS of Granular Sludge

White granules were separated





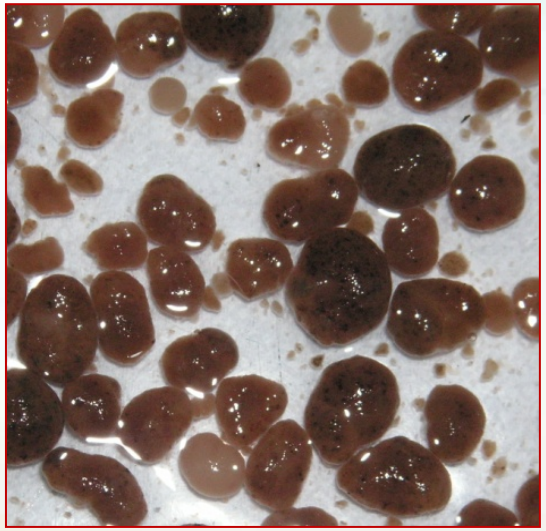
Page 45

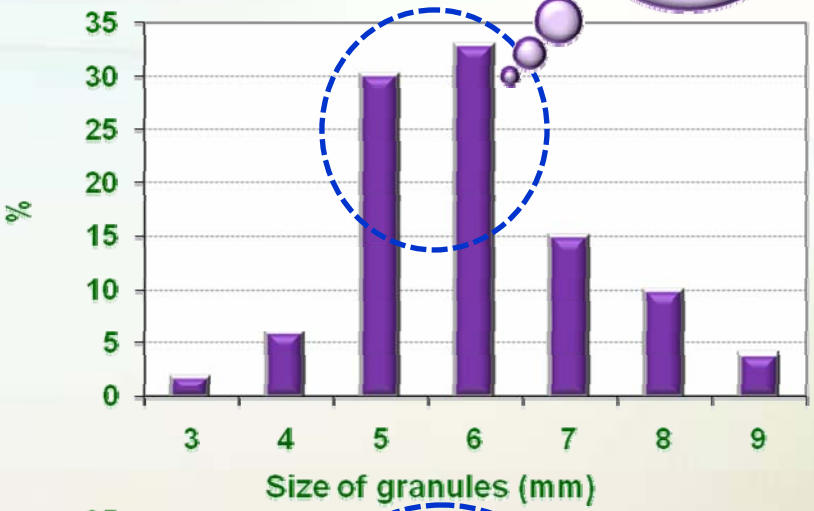
# Results and Discussion

## Morphological Change in Granules

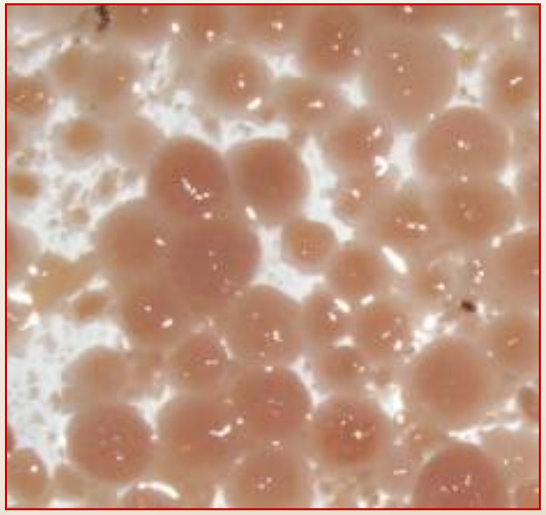
Evidence for Granule Breakage

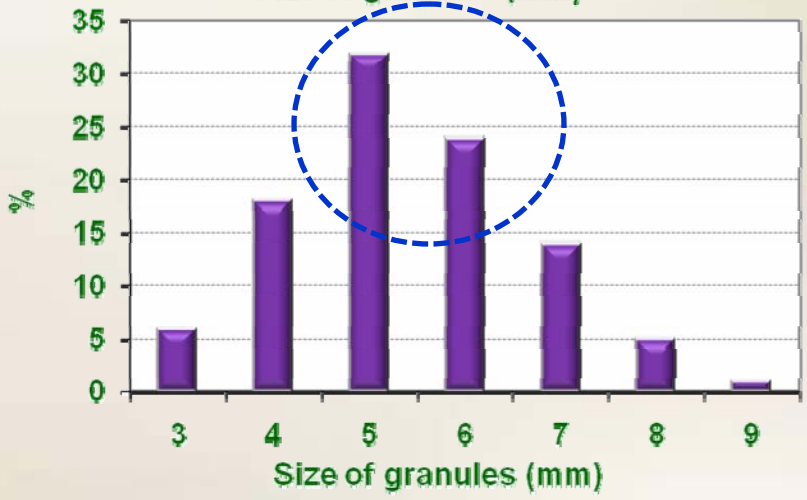
Day 6





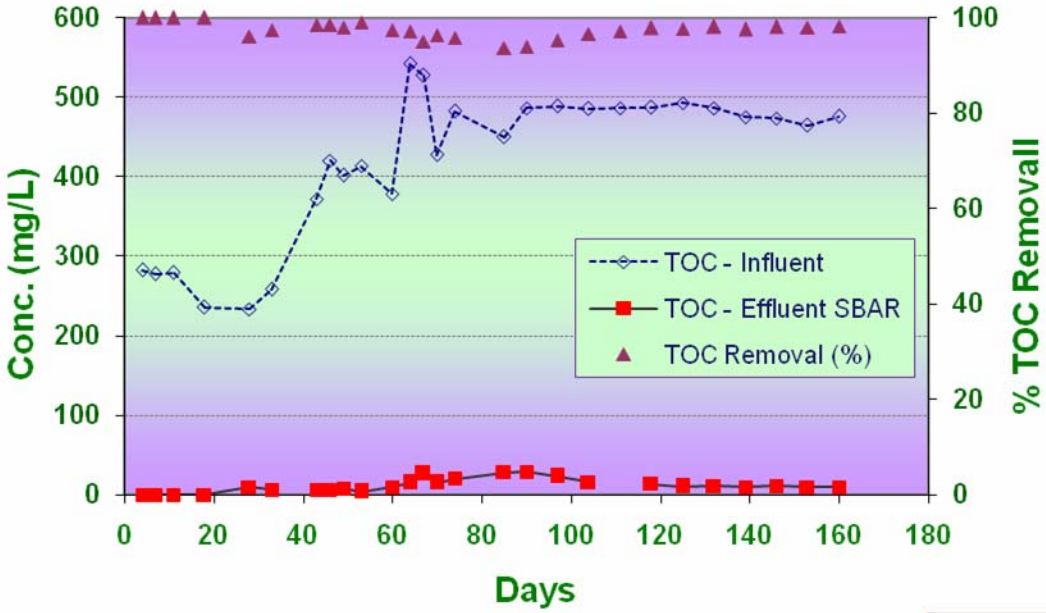

Day 34






Page 44

# Results and Discussion




## Organic Removal in SBAR

Organic Removal Efficiency varied between 94 – 99%

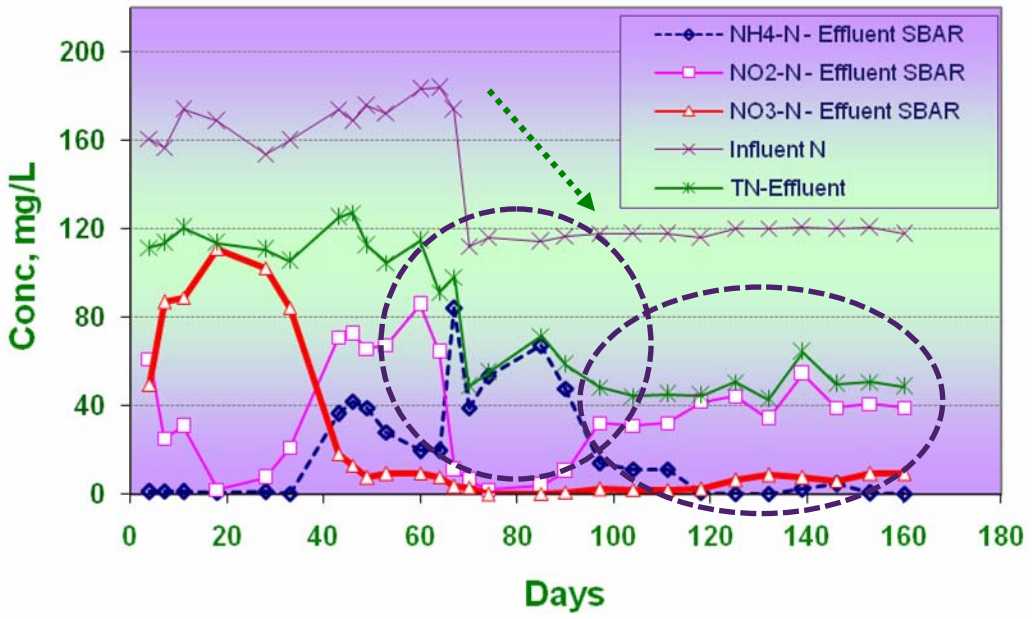
## Nitrogen Removal in SBAR

Complete Nitrification is not achieved

↓

Free Ammonia and

High pH (>8.5)




Page 47,48

# Results and Discussion

The Granular sludge disintegration might be due to

Long Sludge Retention Time of Granular Sludge

(More than 300 days)

Old granules accumulated while the new granules were washed out in every batch operation

Need to change the scope of the study !

# New Scope of the Research

**Run 1**

OLR = 2 kgCOD/m³.d
NLR = 0.6 kgN/m³.d

- Granule Stability
- Treatability
- Fouling Behavior

→ Granule Characterization

**Run 2**

COD = 100 mg/L

- Case 1: 0.012 kgN/m³.d (5 mg/L)
- Case 2: 0.007 kgN/m³.d (3 mg/L)
- Case 3: 0.024 kgN/m³.d (10 mg/L)
- Case 3a: 0.024 kgN/m³.d (10 mg/L), External Carbon 60 mg/L
- Case 3b: 0.024 kgN/m³.d (10 mg/L), External Carbon 150 mg/L

→ Performance of MABR based on Nitrogen Removal

**Run 3**

OLR = 4 kgCOD/m³.d
NLR = 0.4 kgN/m³.d

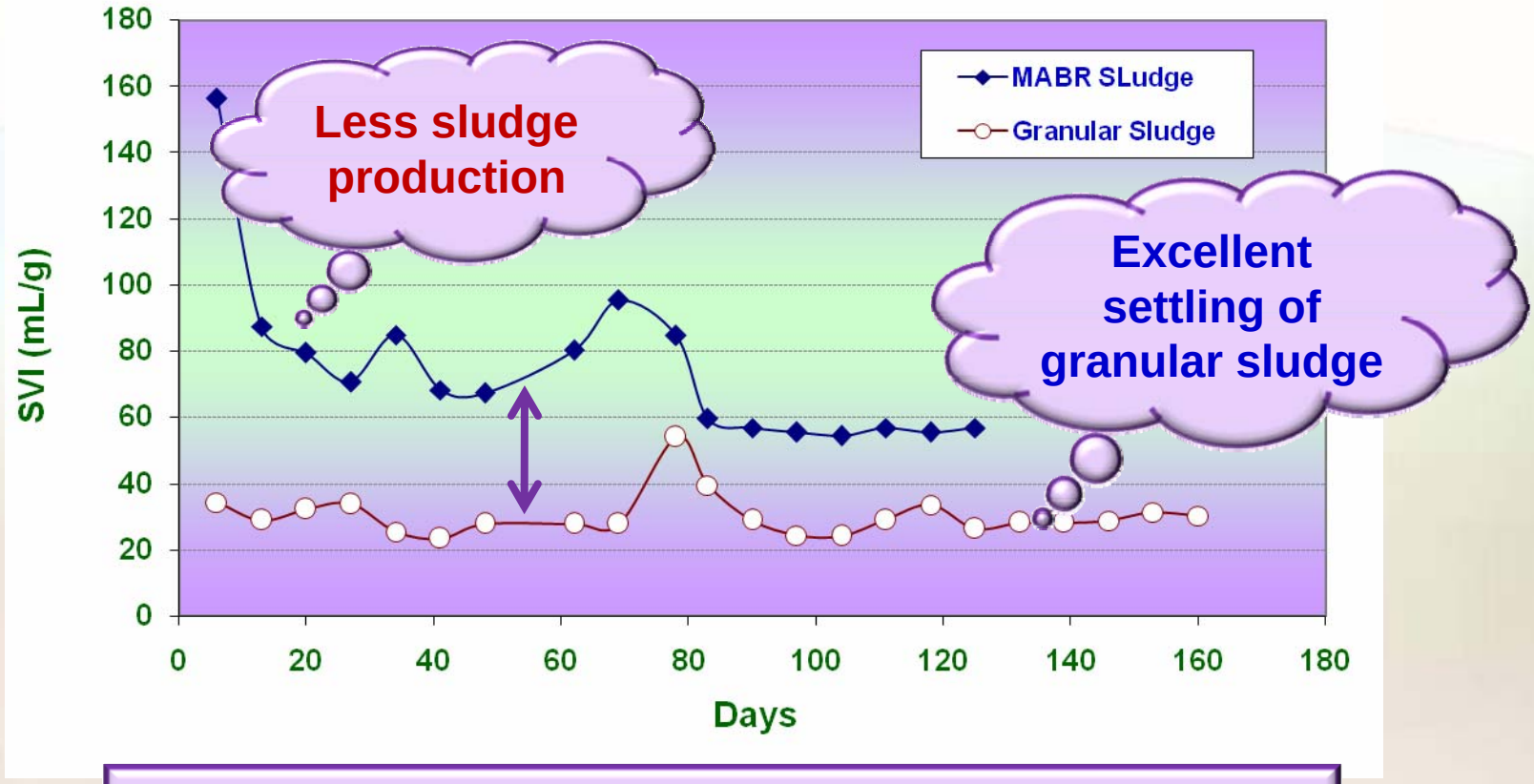
- Granule Characteristics
- Treatability
- Fouling Behavior

→ Comparison with Conventional MBR

Page 30

# Results and Discussion

## SVI of Granular Vs MABR Sludge



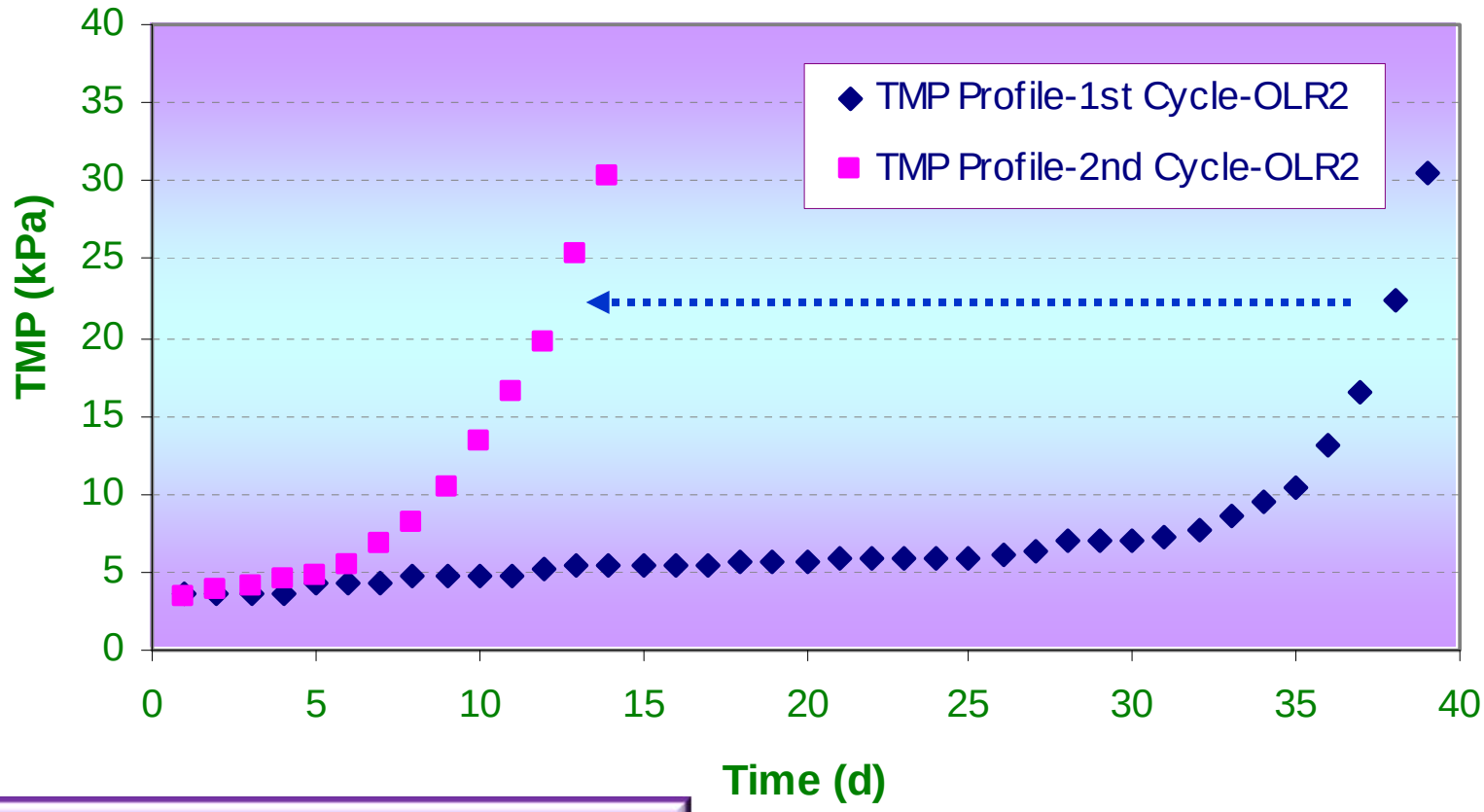

SVI of MABR Sludge = 2 fold of Granular Sludge

Sludge Production in SBAR = 6.7 fold in MABR

Page 51

# Results and Discussion

## Fouling in MABR



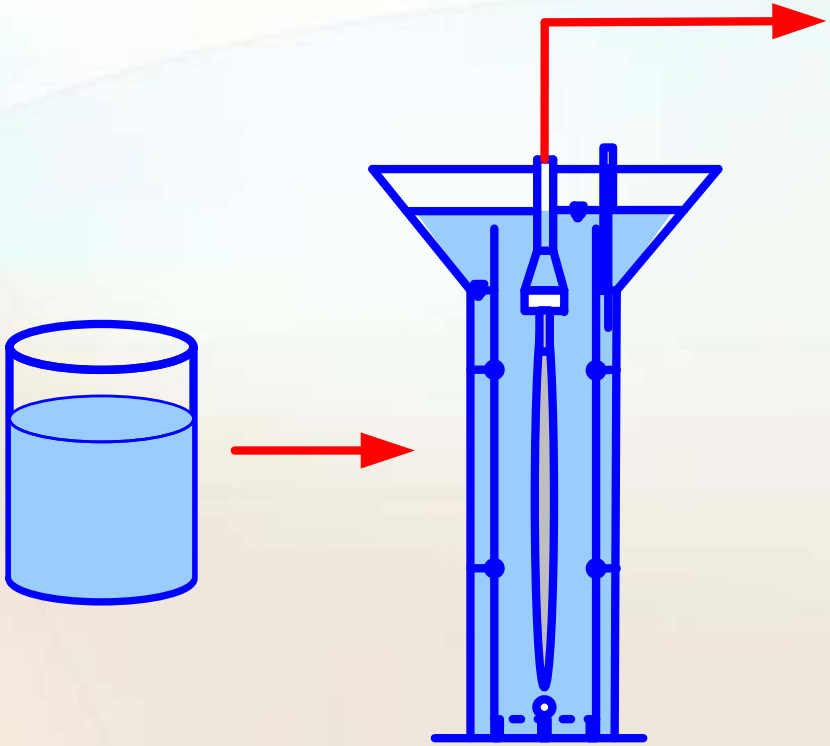

Due to unstable operation of SBAR, the performance of MABR was not evaluated

Granular Sludge could reduce the membrane fouling

Page 52

# The Experimental Setup

## Evaluation of MABR Performance



# Results and Discussion

## Evaluation of MABR Performance

| Parameter | Unit | Case 1 : Equal Nitrogen | Case 2 : Low Nitrogen | Case 3: High Nitrogen | Case 3a : 60mg/L Carbon Addition | Case 3b: 150mg/L Carbon Addition |
|---|---|---|---|---|---|---|
| Organic Removal (TOC) | % | 89 | 90 | 94 | 82 | 88 |
| Organic removal Rate | mgTOC/ gVSS.hr | 20.0 | 19.2 | 20.2 | 17.8 | 18.6 |
| Nitrogen Removal by Denitrification | % | 24 | 4 | 30 | 42 | 47 |
| Denitrification Rate | mgDN/ gVSS.hr | 1.1 | 0.1 | 2.1 | 3.1 | 3.4 |
| Total N removal | % | 62 | 71 | 54 | 64 | 70 |
| Total Nitrogen Removal Rate | mgTN/ gVSS.hr | 2.8 | 1.8 | 3.9 | 4.6 | 5.1 |
| Bound PS | mg/gVSS | 19.6 ± 1.6 | 29.8 ± 3.4 | 21.3 ± 0.4 | | |
| Bound PN | mg/gVSS | 22.3 ± 3.3 | 35.8 ± 3.0 | 17.8 ± 3.4 | | |
| Soluble PS | mg/L | 3.1 ± 1.1 | 3.4 ± 0.1 | 3.2 ± 0.5 | | |
| Soluble PN | mg/L | 0.0 | 0.0 | 0.0 | | |

Lack of electron donor

Page 55,59

# Results and Discussion

## Evaluation of MABR Performance

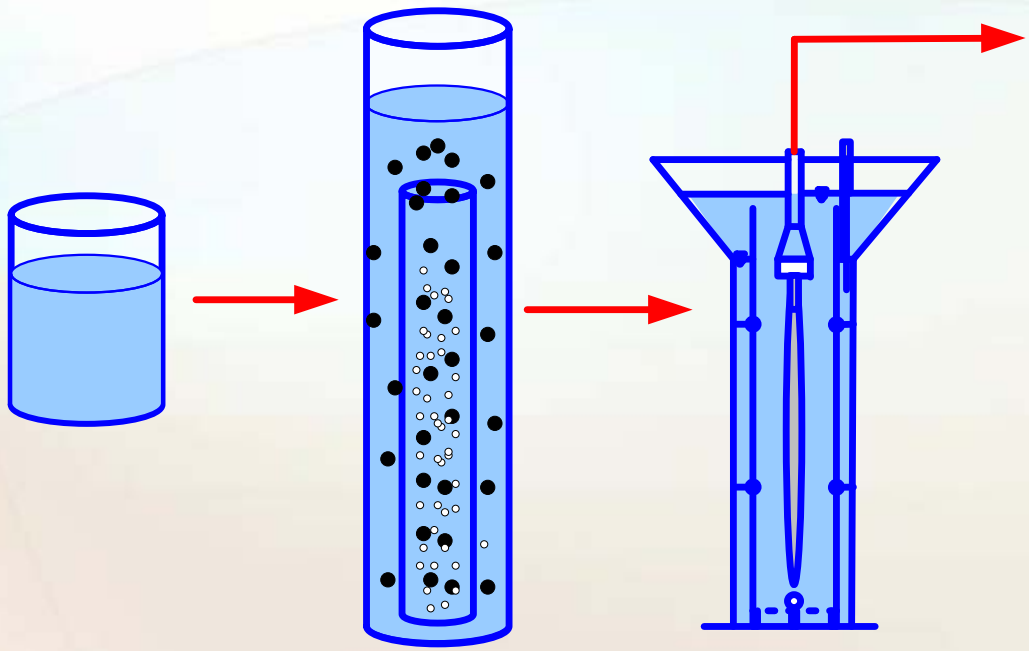
| Parameter | Unit | Case 1 : Equal Nitrogen | Case 2 : Low Nitrogen | Case 3: High Nitrogen | Case 3a : 60mg/L Carbon Addition | Case 3b: 150mg/L Carbon Addition |
|---|---|---|---|---|---|---|
| Organic Removal (TOC) | % | 89 | 90 | 94 | 82 | 88 |
| Organic removal Rate | mgTOC/ gVSS.hr | 20.0 | 19.2 | 20.2 | 17.8 | 18.6 |
| Nitrogen Removal by Denitrification | % | 24 | 4 | 30 | 42 | 47 |
| Denitrification Rate | mgDN/ gVSS.hr | 1.1 | 0.1 | 2.1 | 3.1 | 3.4 |
| Total N removal | % | 62 | 71 | 54 | 64 | 70 |
| Total Nitrogen Removal Rate | mgTN/ gVSS.hr | 2.8 | 1.8 | 3.9 | 4.6 | 5.1 |
| Bound PS | mg/gVSS | 19.6 ± 1.6 | 29.8 ± 3.4 | 21.3 ± 0.4 | | |
| Bound PN | mg/gVSS | 22.3 ± 3.3 | 35.8 ± 3.0 | 17.8 ± 3.4 | | |
| Soluble PS | mg/L | 3.1 ± 1.1 | 3.4 ± 0.1 | 3.2 ± 0.5 | | |
| Soluble PN | mg/L | 0.0 | 0.0 | 0.0 | | |

Nutrient deficiency

Page 55,59

# The Experimental Setup

## Performance of AGMABR



# Results and Discussion

## Performance of AGMABR

Excellent settling of Granular Sludge

## Sludge Characteristics

$SVI_M > SVI_G$

| Parameter | Unit | MABR Sludge | Granular Sludge | Conventional MBR Sludge * |
|---|---|---|---|---|
| MLSS | mg/L | 5500 | 9900 | 10000 |
| SVI | mL/g | 50.6 | 21.9 | - |
| CST | s | 13.4 | 10.8 | 13.4 |
| Settling Velocity | m/s | < 10 | 140 | <10 |
| Size | mm | 0.3 | 1.7 | 0.2 |

* Source : Munasinghe (2008)

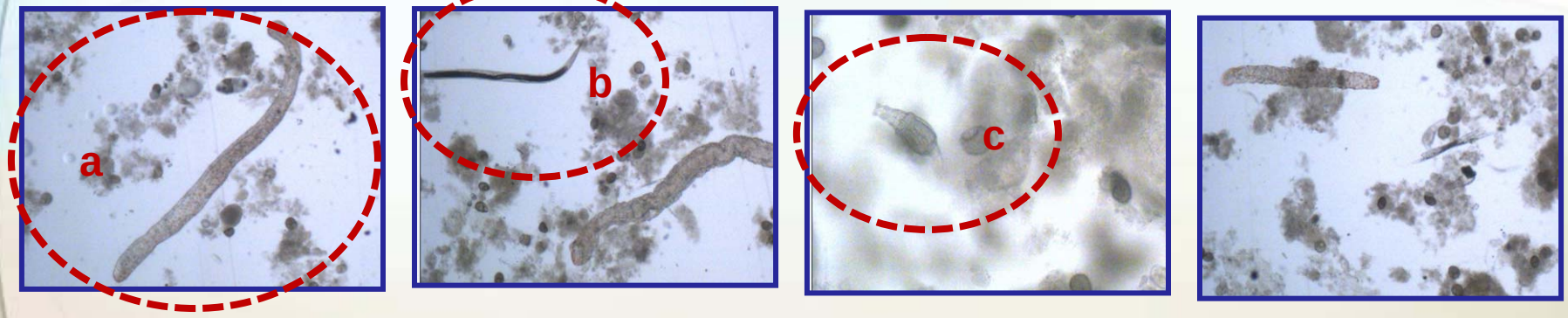
Page 61

# Results and Discussion

## Microbial Community

(a)Aeoloosma hemprochii
(b) Nematodes
(c) Rotifer
(d) Vorticella

### MABR Sludge




### Granular Sludge


Page 62

# Results and Discussion

## Organic and Nitrogen Removal

Limiting factors:
Granule size &
Electron donor

| Parameter | Unit | SBAR | MABR | AGMABR | Conventional MBR* |
|---|---|---|---|---|---|
| TOC | % | 98 | 67 | 99 | 98 |
| | mgTOC/gVSS.h | 26.3 | 0.7 | 27.0 | 16.3 |
| TN | % | 56 | 26 | 61 | 27 |
| | mgTN/gVSS.h | 4.3 | 2.5 | 6.8 | 3.0 |
| Denitrification | % | 27 | 25 | 35 | 10 |
| | mgDN/gVSS.h | 2.0 | 2.5 | 4.5 | 1.3 |
| MLVSS | mgVSS/L | 7600 | 3900 | - | 9050 |

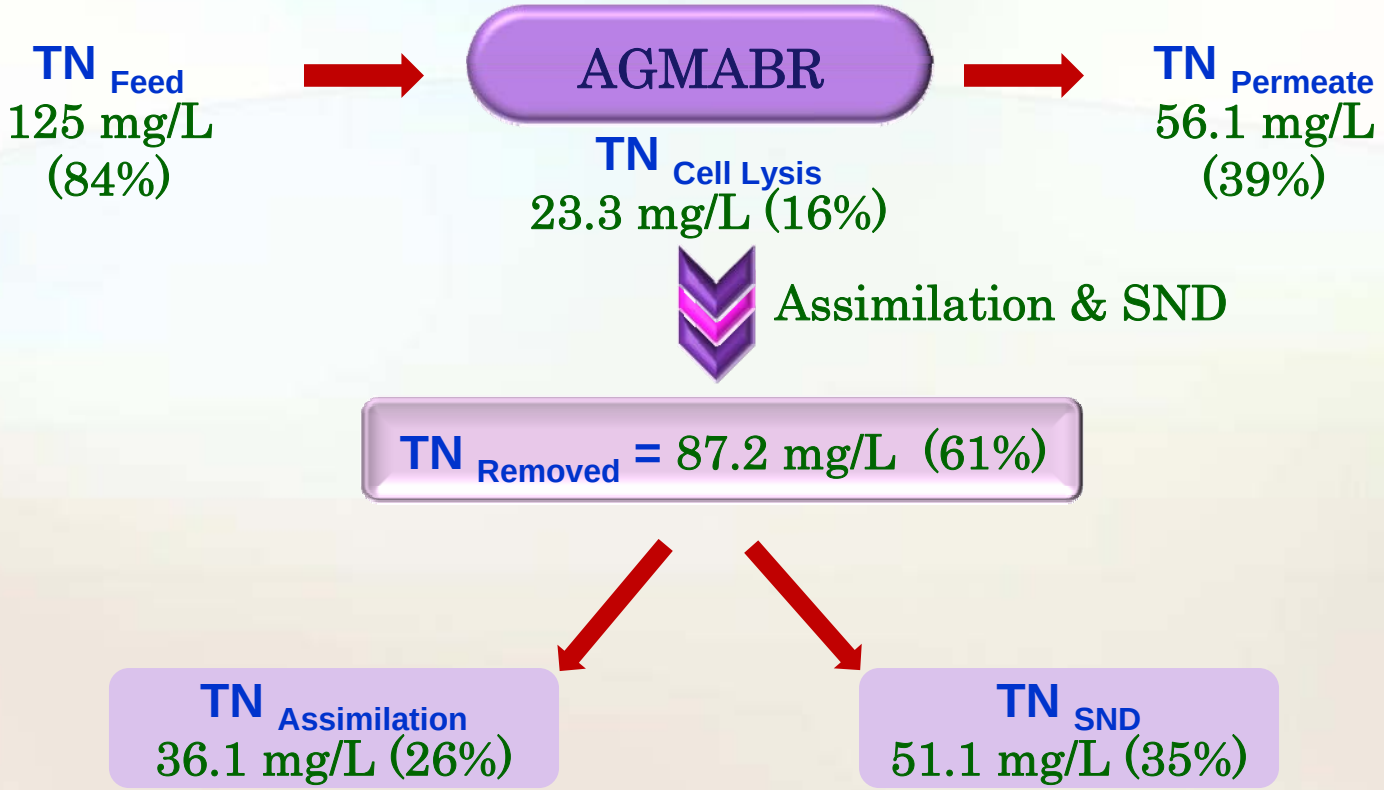
* Source : Munasinghe (2008)

AGMABR Showed better removal than Conventional MBR

Page 63

# Results and Discussion

## Nitrogen Balance in AGMABR

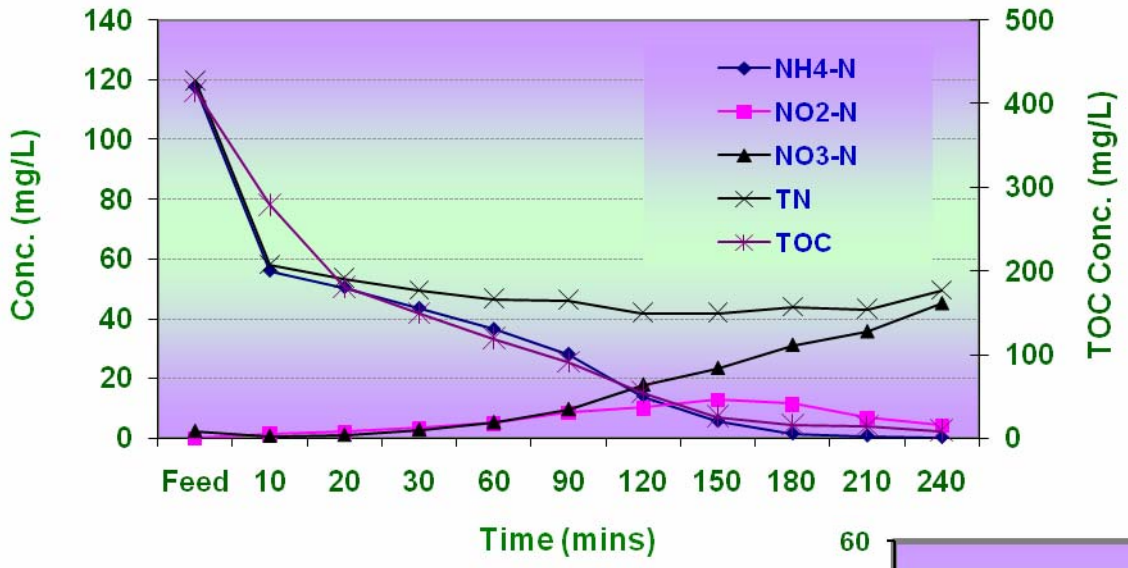



TN for assimilation = (CODin – COD out)/30

SND – Simultaneous Nitrification/Denitrification

# Results and Discussion

## Intensive Monitoring

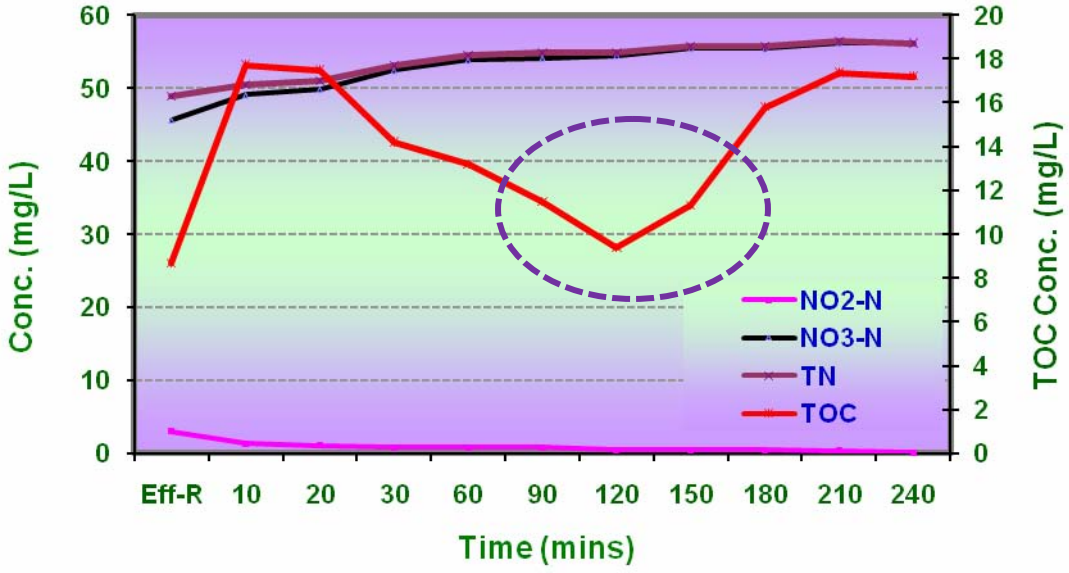



**SBAR**

- Complete Nitrification
- Organic Removal in 1 hr

**MABR**

- TOC and TN increment
- Cell Lysis after 2 hrs of operation



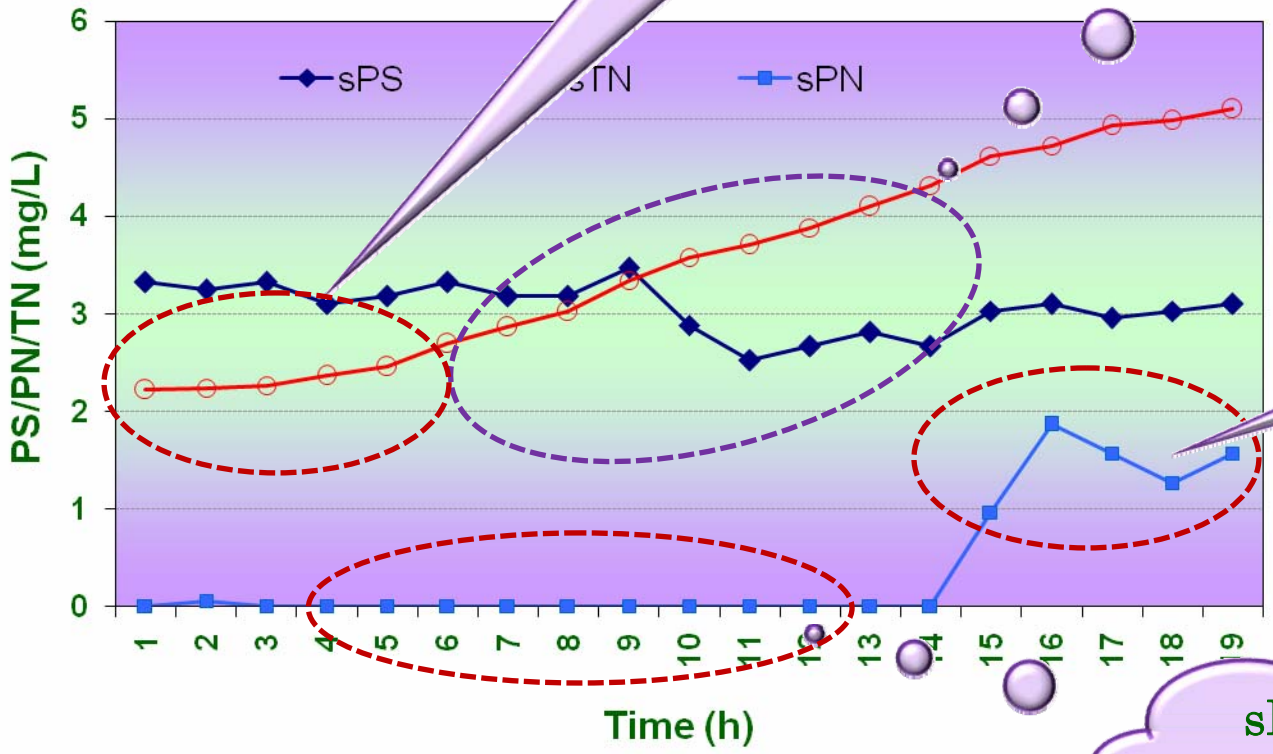

Page 64

# Results and Discussion

## Cell Lysis Test

2-5 hrs of HRT is the optimum range

TN increment due to Cell Lysis

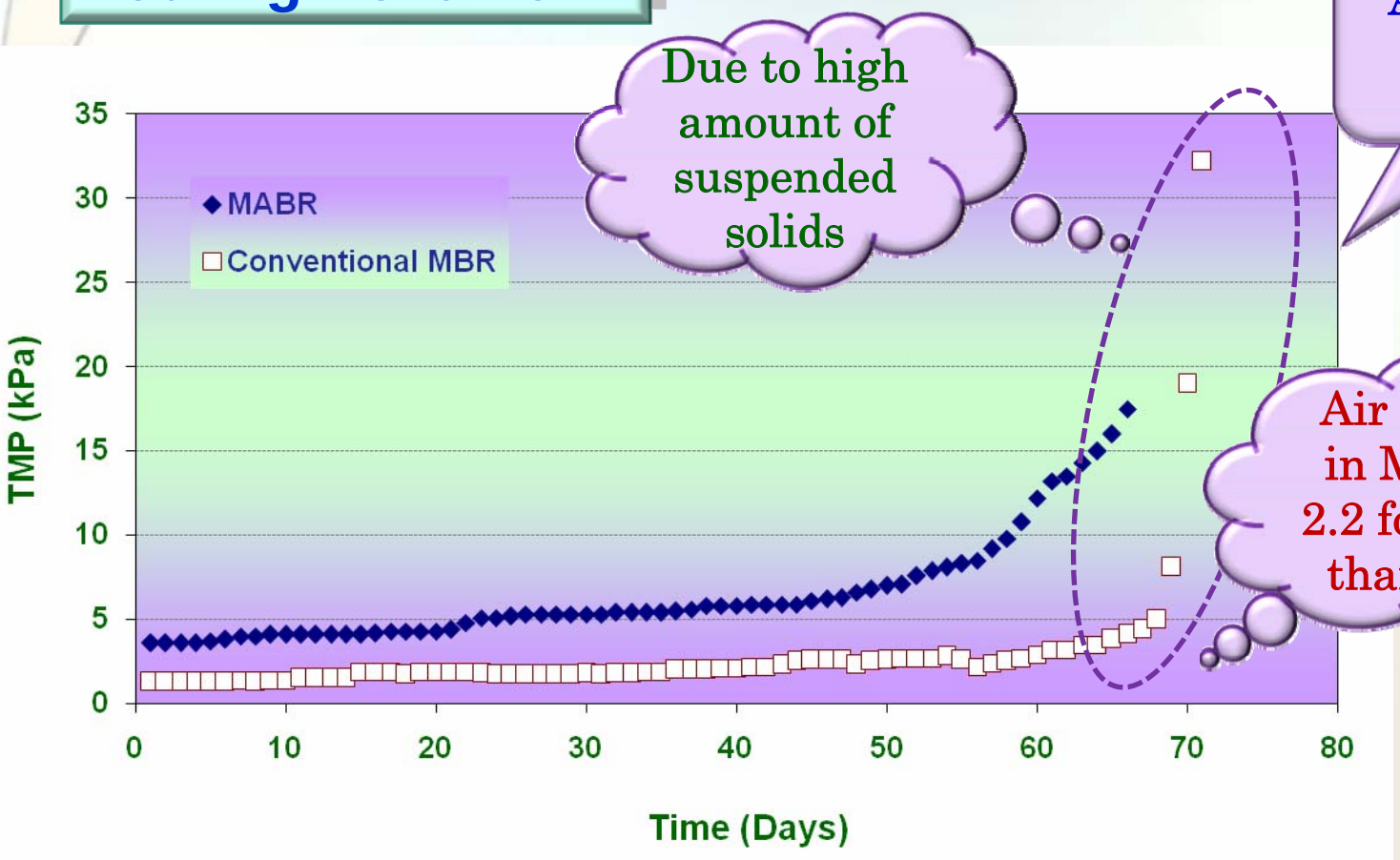



No Circulation Anoxic Zone High amount of Cell Lysis

sPN is easily degradable than sPS

# Results and Discussion

## Fouling Behavior




AGMABR can treat high OLR with low fouling

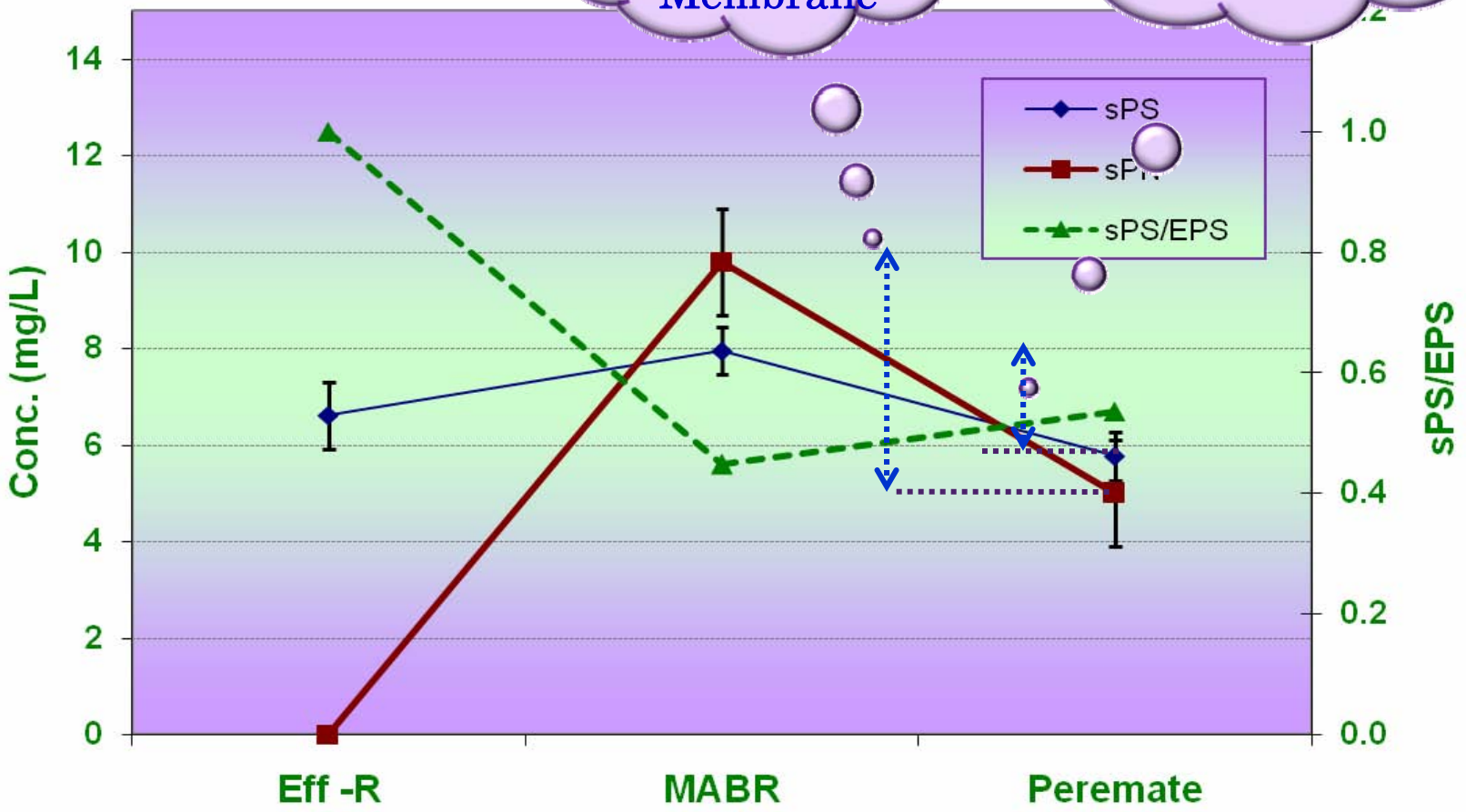
Page 45

# Results and Discussion

## Soluble EPS

50% of sPN is retained by the Membrane

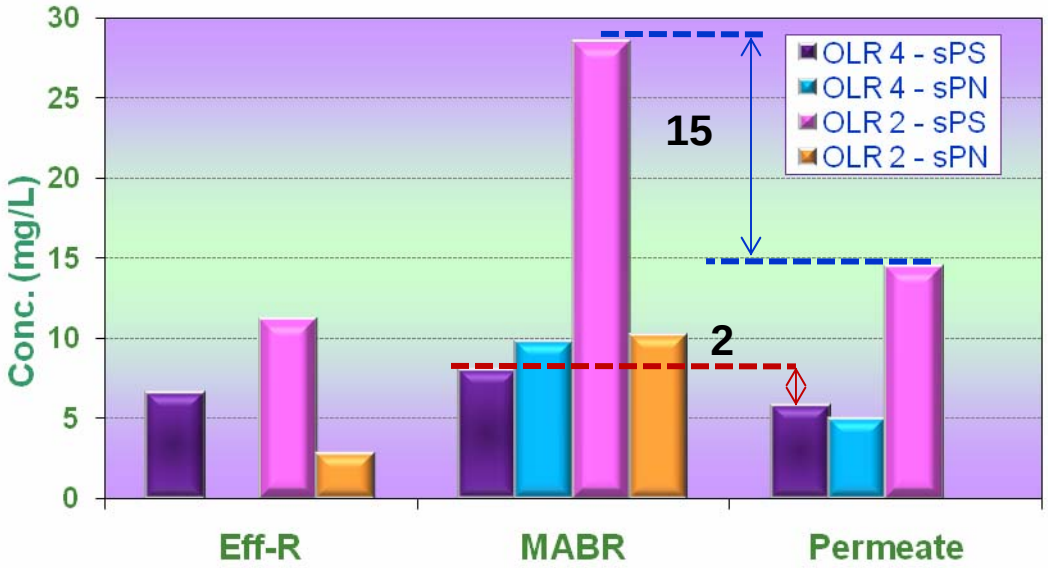
30% of sPS is retained by the Membrane




Page 66

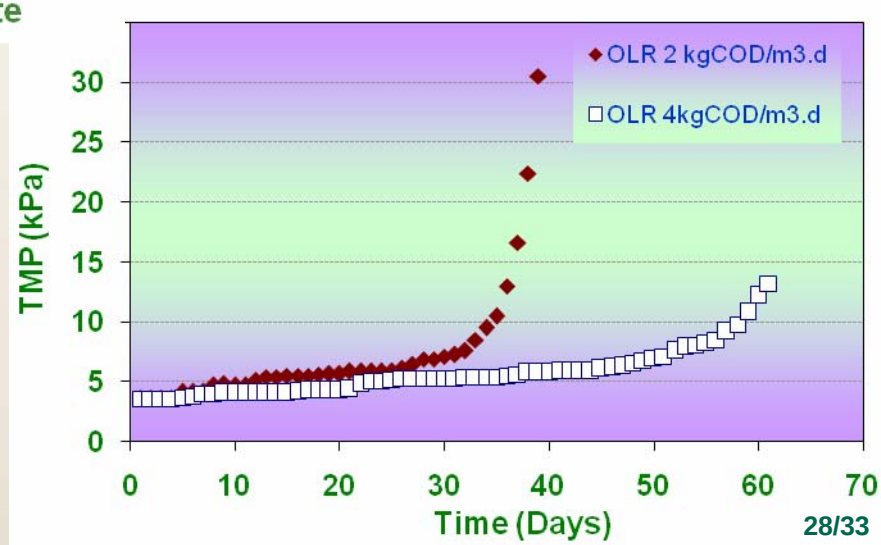
# Results and Discussion

## Soluble EPS Vs. Fouling




High amount of sPS might have contributed for rapid fouling

Better performance at high OLR




Page 52,53,66,67

# Results and Discussion

## Bound EPS

| Parameter | Unit | MABR Sludge | SBAR Sludge | | Conventional MBR Sludge |
|---|---|---|---|---|---|
| | | | Granule | Floc | * |
| Bound PS | mgPS/mgVSS | 13.7 | 6.4 | 19.1 | 5.2 |
| Bound PN | mgPN/mgVSS | 11.1 | 2.3 | 0.0 | 2.8 |
| MLVSS | mgVSS/L | 3900 | 7600 | 360 | 9050 |

* Source: Munasinghe (2008)

Bound EPS of flocs contributed for high EPS in MABR

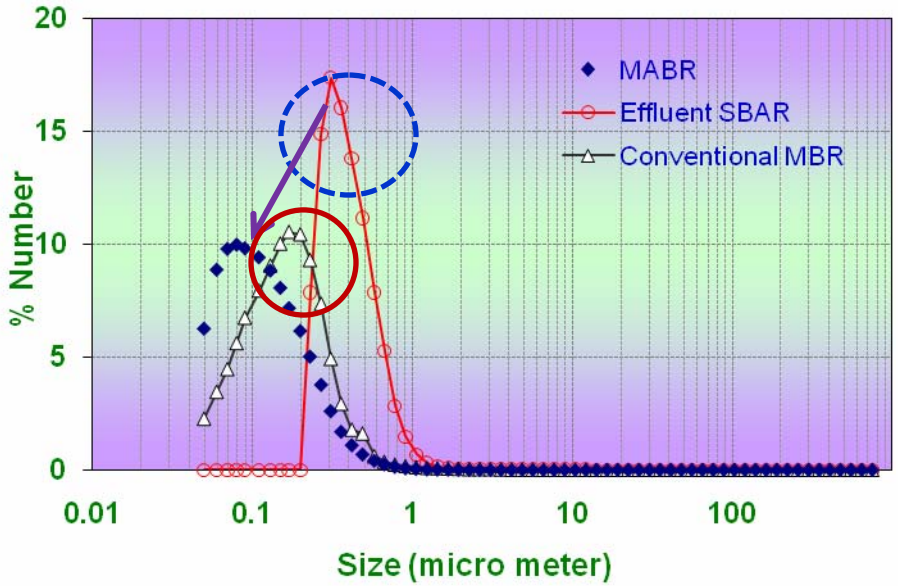
If granules become matured and big, flocs wash out would be reduced

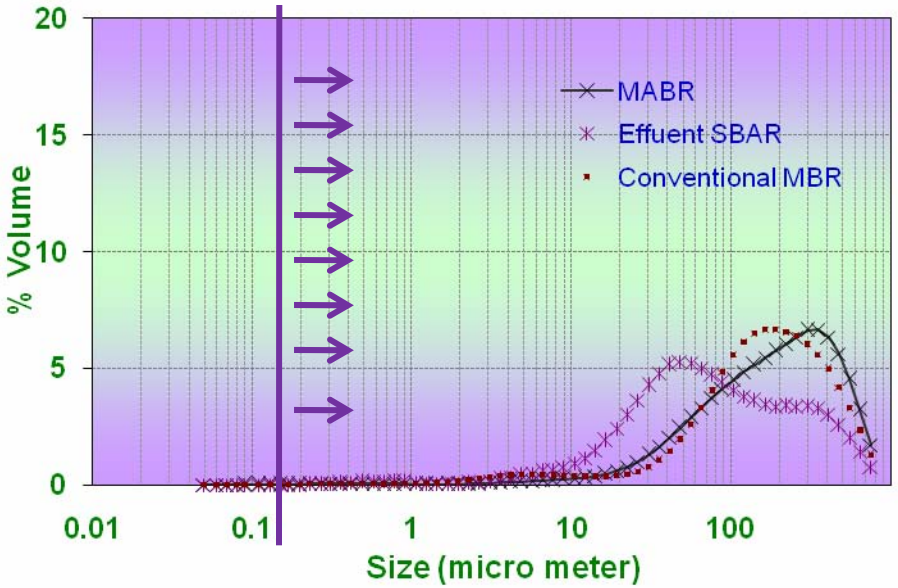
High removal efficiency in SBAR & Less fouling in MABR

Page 66

# Results and Discussion

## Particle Size Distribution




Due to granules and carriers (0.4 µm )

Granules broken down (0.12 µm)

Due to flocculation (0.29 µm)

All the particles are more than the pore size of the membrane

Page 67,68

# Conclusions

1. Long SRT and sudden change in OLR disturbed the stability of the granular sludge.
2. Granular sludge has excellent settling ability than MABR sludge.
3. The MABR could achieve maximum of 70% of nitrogen removal including 50% of denitrification and 80% organic removal with external carbon addition.
4. The HRT of 2-5 h could be the optimum condition for filtering the supernatant of granulation reactor.
5. The organic and nitrogen removal in AGMABR were 99% and 61% respectively and 35% of the nitrogen removal by denitrification.
6. The potential for rapid fouling at high OLR might be less.
7. Benefits of MABR are Low biomass concentration, no direct contact with substrate, high N-removal and low aeration requirement when compared to MBR.

# Recommendations

1. Operation of SBAR at various organic loadings to optimize the loading based on removal and membrane fouling.

2. Cultivation of aerobic granules could be done for domestic or industrial wastewater having high organic and nitrogen contents to study the stability of granules.

3. AGMABR performance based on EPS to be studied with different C/N ratio which could increase the fouling.

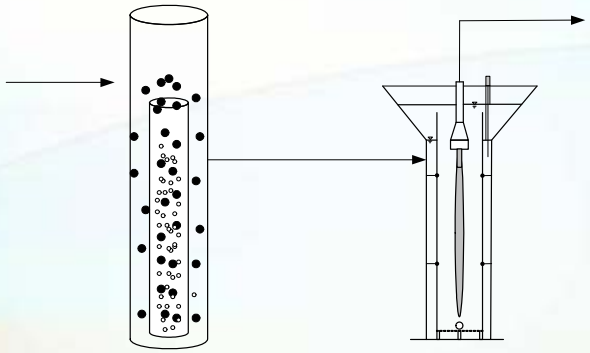
4. Further investigation could be done to evaluate the fouling potential with different HRTs of MABR or MBR.

5. Investigation to be done with intermittent feeding in MABR which would reduce the HRT of the reactor.

Page 70,71

# Recommendations

## Current System



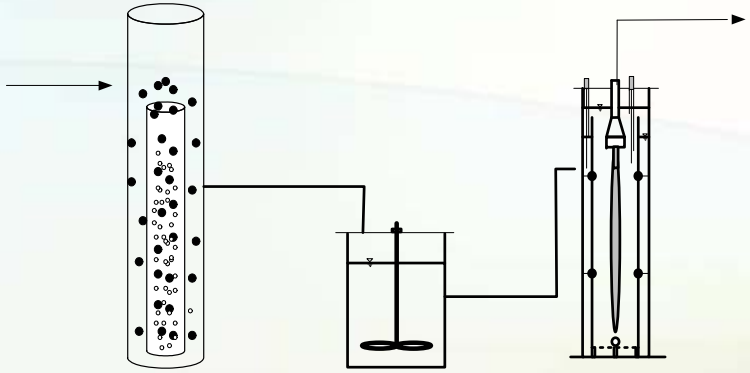
Batch Feeding

Volume of MABR = 13.0 L

HRT = 11 hrs

More denitrification

## Proposed New System



Intermittent Feeding

Volume of MABR = 8.6 L

HRT = 7 hrs

35% volume reduction

Less cell lysis

Page 33,72

# Thank you