ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

DETERMINATION OF THE PROCESS PERFORMANCE OF HIGH RATE MEMBRANE BIOREACTORS TREATING DOMESTIC WASTEWATER

M.Sc. THESIS

Cansın RAZBONYALI

Department of Environmental Engineering

Environmental Biotechnology Programme

JUNE 2013

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

DETERMINATION OF THE PROCESS PERFORMANCE OF HIGH RATE MEMBRANE BIOREACTORS TREATING DOMESTIC WASTEWATER

M.Sc. THESIS

Cansın RAZBONYALI

(501111802)

Department of Environmental Engineering

Environmental Biotechnology Programme

Thesis Advisor: Prof. Dr. Seval SÖZEN

JUNE 2013

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

EVSEL ATIKSU GİDERİMİ YAPAN YÜKSEK HIZLI MEMBRAN BİYOREAKTÖRLERİN PROSES PERFORMANSININ ARAŞTIRILMASI

YÜKSEK LİSANS TEZİ

Cansın RAZBONYALI

(501111802)

Çevre Mühendisliği Anabilim Dalı

Çevre Biyoteknolojisi Programı

Tez Danışmanı: Prof. Dr. Seval SÖZEN

HAZİRAN 2013

Name-surname, a **M.Sc.** student of ITU **Graduate School of Science Engineering and Technology** student ID 501111802, successfully defended the **thesis** entitled "**DETERMINATION OF THE PROCESS PERFORMANCE OF HIGH RATE MEMBRANE BIOREACTORS TREATING DOMESTIC WASTEWATER**", which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Prof. Dr. Seval SÖZEN** ....
Istanbul Technical University

Jury Members : **Prof. Dr. Barış ÇALLI** ....
Marmara University

Assoc. Prof. Mahmut ALTINBAŞ ....
Istanbul Technical University

Date of Submission : 03 May 2013

Date of Defense : 07 June 2013

To my family,

FOREWORD

There are so many people who I would like to thank for supporting me through this first step of my academic life. First of all, I would like to thank to my advisor Prof. Dr. Seval Sözen, who is also my role model for teaching, supporting and providing me the opportunity to work on this project. I am deeply grateful to Prof. Dr. Derin Orhon, who is a second advisor to me, for sharing his profound knowledge. It has been great privilege for me to work with these two valuable scientists.

Many of the experimental results would not have been possible without Prof. Dr. Emine Ubay Çokgör, Assist. Prof. Dr. Nevin Yağcı and Assist. Prof. Dr. Serdar Doğruel. I am grateful to Prof. Dr. Emine Ubay Çokgör for spending her valuable time for my modelling studies, Assist. Prof. Dr. Nevin Yağcı for instrumental analysis and Assist. Prof. Dr. Serdat Doğruel for his contribution to my particle size distrubution tests.

I would like to thank Senem Teksoy Başaran who has been like a sister to me, for sharing her bright knowledge and experiences and Merve Aysel who was the best research colleague and friend, for supporting me every possible way.

My special thanks go out to my research collegues Nazlı Lermioğlu, Cem Cantekin, Hazal Yıldız and Yester Biros. Laboratuary would be unbearable without their joy.

I would like to thank my dearest friend Aslı Dilara Uğurlu, who has been with me since I open my eyes, for supporting me every single day.

I would like to thank Berkay Yılmaz for his love and teaching me the patience is the key to happiness.

On top of it all, I would like to thank my mom, dad and brother for their support and experience. I am very lucky and also proud of being surrounded with their love.

June 2013

Cansın RAZBONYALI
Environmental Engineer

TABLE OF CONTENTS

Page

ABREVATIONS

BOD	**:** Biological Oxygen Demand
COD	**:** Chemical Oxygen Demand
ÇMÜ	**:** Çözünmüş Mikrobiyal Ürün
ÇY	**:** Çamur Yaşı
DOC	**:** Dissolved Organic Carbon
EPS	**:** Extra Polymeric Substances
F/M	**:** Food to Microorganism ratio
HRT	**:** Hydraulic Retention Time
MBR	**:** Membrane Bioreactor
MF	**:** Microfiltration
MLSS	**:** Mixed Liquor Suspended Solids
MLVSS	**:** Mixed Liquor Volatile Suspended Solids
OLR	**:** Organic Loading Rate
PHA	**:** Poly hydroxyl alkanoate
PHB	**:** Poly-b-hydroxybutyrate
PHV	**:** Poly hydroxyvalerate
PLC	**:** Programmable Logic Controller
SMBR	**:** Submerged Membrane Bioreactor
SMP	**:** Soluble Microbial Products
SRT	**:** Sludge Retention Time
SS	**:** Suspended Solids
TMP	**:** Trans Membrane Pressure
TOC	**:** Total Organic Carbon
UF	**:** Ultrafiltration
VSS	**:** Volatile Suspended Solids

LIST OF TABLES

LIST OF FIGURES

DETERMINATION OF THE PROCESS PERFORMANCE OF HIGH-RATE MEMBRANE BIOREACTORS TREATING DOMESTIC WASTEWATER

SUMMARY

Membrane bioreactors (MBR) are the integration of membrane filtration modules with the biological reactor discarding the secondary settlement in the conventional activated sludge (CAS) systems. MBRs can be accepted as a good alternative for conventional activated sludge processes. In order to eliminate the biomass separation problems, MBRs use the separation ability of membrane technology which has higher separation ability than gravity settling especially for the separation of small flocs and colloidal particles. In MBR technology the solid/liquid separation is provided through a membrane filtration rather than a conventional gravity settling, the suspended solids are not lost in the settling step and that gives a total control of sludge retention time (SRT) and hydraulic retention time (HRT).

The general approach in MBR applications is to operate these systems at longer SRTs in order to have higher biomass concentrations in the bioreactor, to allow slowly-growing microorganism to grow in the system and to reduce the finger print of the system. Although the reduced amount of biomass production obtained at higher SRT may seem advantageous in terms of system operation and sludge handling, the new approaches in energy, especially the policies targeting self-sufficient treatment plants, are stating that the biomass is actually a valuable alternative fuel in terms of energy production.

The purpose of this study is to investigate and assess the carbon removal performance and biodegradation kinetics of submerged MBR system operated at extremely low SRT treating peptone and domestic wastewater. This study attempts to fill some gaps in complex substrate removal.

Experimental works covered; (i) the limits of high rate MBR operation, by assessing its performance at steady-state conditions for removal of complex substrates, (ii) evaluation of the biodegradation kinetics and substrate storage occurring in the operation by respirometric analysis. In this framework, a laboratory scale submerged MBR was operated at steady-state with extremely low operating conditions with three different SRTs of; 2.0 d, 1.0 d and 0.5 d. For each selected sludge age, HRT of the system was adjusted to 8 hours. Substrate feeding was adjusted to 200 mgCOD/L and involved peptone mixture representing the readily biodegradable and slowly biodegradable COD fraction in domestic wastewater. Other feed was domestic wastewater with an average COD of 250 mg/L obtained from ISKI Baltalimanı Wastewater Pre-Treatment Plant.

Results of the study revealed that high rate MBR yielded excellent effluent quality. System fed with peptone mixture resulted with an effluent COD of 40 mg/L (86% overall COD removal) or lower and system fed with domestic sewage resulted with an effluent COD of 70 mg/L (75% overall COD removal) or lower under tested

operational conditions which is significantly lower than the current limit of 125 mgCOD/L for wastewater discharges from urban wastewater treatment plants. The results were consistent with the literature findings.

Parallel batch respirometric analysis yielded OUR profiles for each set implemented with peptone mixture and domestic sewage. Model assessment of biodegradation kinetics was made by simulations conducted using AQUASIM program adopting the basic template of modified ASM 3 model.

Furthermore, particle size distribution (PSD) test conducted to investigate the effective filtration size created by the biomass suspension in the MBR system. PSD tests indicated that, current MBR system with a pore size of 40nm, entrapped organics above the size range of around 8 nm. This may be attributed to cake filtration effect due to biofilm formation on the surface of the membrane.

EVSEL ATIKSU GİDERİMİ YAPAN YÜKSEK HIZLI MEMBRAN BİYOREAKTÖRLERİN PROSES PERFORMANSININ ARAŞTIRILMASI

ÖZET

Membran biyoreaktörler (MBR), konvansiyonel aktif çamur sistemlerinde (KAS) bulunan ikincil çökelmeyi yok sayarak membran filtrasyon modülleri ile biyolojik reaktörün birleşiminden oluşmaktadır. MBR teknolojisi aktif çamur sistemlerinin yerine geçebilecek iyi bir alternatif kabul edilebilir. Membran biyoreaktörler, genellikle küçük flok ve kolloidal maddelerin sudan ayrılmasını sağlayan yerçekimi ile çökelme prosesinden daha kaliteli olarak maddelerin birbirinden ayrılmasını sağlayan membran teknolojisi ile biyokütle ayrılması kaynaklı problemleri ortadan kaldırır. MBR teknolojisinde katı/sıvı ayrımı KAS'larki gibi yerçekimi ile çökelmeden farklı olarak membran filtrasyonu ile sağlanmakta olup, çökelme prosesi sırasında askıda katı maddeler sistemden kaybolmadığı için sistemin çamur yaşı ve hidrolik bekletme süresi (HBS) üzerinde tam bir kontrol sağlanır.

MBR uygulamalarındaki genel yaklaşım, oluşan biyokütlenin sistemden uzaklaştırma problemi olmadığından reaktörde yüksek biyokütle konsantrasyonu sağlayacak, çoğalma hızları düşük (yavaş çoğalan) mikroorganizmaların sistemde çoğalmasına izin verecek ve atılan çamur miktarını azaltacak şekilde uzun çamur yaşlarında (ÇY) işletilmesidir. Fakat bu yaklaşım ile konvansiyonel aktif çamur arıtma sistemlerinde yürütülmekte olan uygulamalar devam ettirilmiş, MBR sistemleri yenilikçi bir arıtma yaklaşımı geliştirilmesinde kullanılamamıştır. Bu çalışmada sunulan işletme yaklaşımı ile MBR teknolojisinin atıksu arıtımında yenilikçi bir uygulama olarak performansı incelenerek, konvansiyonel atıksu arıtma yaklaşımına farklı ve çevresel açıdan daha gelişmiş ve ekonomik bir alternatif sunulmuştur.

Konvansiyonel atıksu arıtma tesislerinde yüksek çamur yaşı uygulanarak elde edilen düşük biyokütle üretimi işletme ve çamur bertarafı açısından avantajlı gözükmektedir. Fakat, enerji açısından kendi kendine yetebilen yeni tesis yaklaşımları biyokütlenin aslında enerji üretimi açısından kıymetli bir alternatif yakıt olarak kullanılması gerektiğini ortaya koymaktadır.

Bu çalışma, MBR teknolojisinin sunduğu işletme özelliklerini kullanarak, mevcut atıksu arıtma sistemlerinin konfigürasyonu ve işletme stratejisini yeniden şekillendirmeyi hedeflemiştir. Bu yenilikçi yaklaşımda MBR sisteminin, biyolojik reaktörlerin, biyokütle ve/veya çıkış suyu gereksinimleri ile ilgili bir kısıtlama olmaksızın, düşük çamur yaşı ve hidrolik bekletme sürelerinde işletilmesi, bu sayede ihtiyaç duyulan reaktör hacminin minimize edilmesi ve sistemde üretilen çamurun enerji potansiyelinin de dikkate alınması amaçlanmıştır. Bu MBR uygulaması ile hedeflenen yaklaşım, atıksu içindeki sadece çözünmüş organik maddenin kısmi olarak giderilmesi, partiküler fraksiyonunun ise biyokütle üzerine adsorbe olması ve biyokütle ile birlikte membran tarafından tutulması neticesinde atıksudan fiziksel

olarak ayrılmasıdır. "Yüksek hızlı MBR" işletme yaklaşımı ile, üretilen biyokütlenin ve sistemde kalan ve mikrobiyal floklar üzerine adsorbe olan partiküler organik maddenin enerjisi korunarak, yüksek kalitede ve partiküler madde içermeyen çıkış suyu elde edilmesi hedeflenmiştir.

Yapılan çalışma da, pepton ve evsel atıksu giderimi yapan, düşük çamur yaşında işletilen batık membran konfigürasyonlu bir MBR sisteminin (bMBR) karbon giderim performası araştırılmıştır. Çalışmada kullanılan gerçek atıksu, İSKİ Baltalimanı Biyolojik Atıksu Arıtma Tesisi'nden temin edilmiştir (Tablo 3.4). Kumu, köpüğü, yağı arıtılan atıksu, parshall savağı çıkışından alınmış, çöktürmeye bırakılarak üst faz kullanılmıştır. Bu çalışma karmaşık substrat giderimi alanındaki bazı boşlukları doldurmak için yapılmıştır. Deneysel çalışmalar; (i) kararlı haldeki karmaşık substrat giderim performansının ölçülmesi ile yüksek hızlı MBR sistemin limitlerini değerlendirmek, (ii) repirometrik analizlerle biyolojik çözünme kinetikleri ve substrat depolama mekanizmasının saptanmasını kapsamaktadır.

Bu çerçevede; laboratuvar ölçekli bMBR sistemi, 2 gün, 1 gün ve 0.5 gün olmak üzere üç farklı çamur yaşında ve hidrolik bekletme suresi 8 saat olacak şekilde işletilmiştir. Deneysel çalışmalarda, 200 mg/L kimyasal oksijen ihtiyacı (KOİ) konsantrasyonuna ayarlanmış, atıksudaki hızlı ayrışabilen ve yavaş ayrışabilen çözünmüş organik maddeyi temsil eden pepton karışımı ile ortalama KOİ konsantrasyonu 250mg/L olan İSKİ Baltalimanı Ön Atıksu Arıtma Tesisi'nden temin edilen evsel atıksu ile çalışılmıştır. Çalışmanın sonucunda, yüksek hızlı MBR sistemi çok iyi kalitede çıkış suyu elde etmiştir. Pepton karışımı ile yürütülen deneylerde çıkış suyu KOİ konsantrasyonu 40 mg/L (%86 genel KOİ giderimi) veya daha düşük, evsel atıksu ile yürütülen deneylerde ise KOİ konsantrasyonu 70 mg/L (%75 genel KOİ giderimi) veya daha düşük çıkış suyu kalitesi elde edilmiştir. Bu değerler, kentsel atıksu arıtma tesislerinde uygulanan mevcut 125 mgKOİ/L sınır değerinin oldukça altındadır. Ayrıca, elde edilen sonuçlar literatür çalışmalarında elde edilen sonuçlar ile tutarlıdır.

Hızlı MBR'nin karbon giderim performansının belirlenmesine yönelik olarak yapılan değerlendirmelerinde, organik maddenin sistemdeki seyri dikkate alınarak iki ana gözlemin altı çizilmiştir: (i) Reaktör içindeki çözünmüş KOİ seviyeleri her zaman çıkış suyundaki değerlere kıyasla daha yüksek seviyede kalmıştır (ii) Aynı HBS'de yürütülen MBR deneylerinde, reaktör içi çözünmüş KOİ konsantrasyonu çamur yaşına bağlı olarak hemen hemen iki kat olacak şekilde önemli bir artış göstermiştir. Bunun neticesinde, reaktör içi ile permeat arasındaki KOİ farkı, membran filtrasyonuna bağlı olarak önemli seviyede bir tutulma etkisinin olduğuna işaret edecek şekilde, artan çamur yaşı ile gittikçe artmıştır. Bu gözlemlere dayanarak, reaktör içinde kalan çözünmüş organik maddenin çözünmüş mikrobiyal ürünler (ÇMÜ) olduğu düşünülmüştür.

Bu çalışma kapsamında ayrıca, uygulanan çamur yaşı ve test edilen substratlar özelinde mikrobiyal davranışın ve giderim kinetiklerinin gözlemlenmesi amacıyla respirometrik analizlerden oksijen tüketim hızı (OTH) profilleri elde edilmiştir. Respirometrik ölçümler, giriş besleme konsantrasyonları 200 mg KOİ/L ve 250 mg KOİ/L olacak şekilde, yavaş ayrışan çözünmüş organik maddeyi temsil eden pepton çözeltisi ile beslenen, 2 gün, 1 gün ve 0,5 gün çamur yaşı ile işletilen ve evsel atıksu ile beslenen ve 2 gün, 1 gün ve 0,5 gün çamur yaşı uygulanan setlerde yürütülmüştür. Yavaş ayrışan çözünmüş organik maddeyi temsil eden pepton çözeltisi beslenerek yürütülen setlerde, başlangıçta sisteme verilen organik maddenin tamamının tüketildiği ve respirometrik ölçümlerin içsel solunum fazı seviyesine düştüğü gözlenmiştir. Bu durum respirometrik ölçümlere paralel olarak yürütülen KOI giderimi ölçümleri ile de desteklenmiştir. Çamur yaşının azalması ile birlikte respirometrik ölçümlerde organik madde gideriminin daha kısa sürede gerçekleştiği gözlemlenmiştir. Bu da daha düşük çamur yaşlarında aktif biyokütlenin karışım içinde daha fazla olduğunu göstermektedir. Atıksu ile yapılan respirometrik analizler de ise OTH grafiklerinde dalgalanmalar oluşmuş bu da farklı KOİ fraksiyonlarının ayrışmasından kaynaklanmaktadır.

Genel yaklaşım itibarıyla, 450 nm filtreden geçebilen organik fraksiyon olarak kabul edilen çözünmüş KOİ'nin reaktör içinde tutulan miktarının yalnızca HBS ile kontrol edilebildiği konvansiyonel aktif çamur sistemlerinden farklı olarak, MBR sistemlerinde çözünmüş KOİ'nin sistemde tutulan miktarını yalnızca HBS değil, sistemin işletim koşullarına özel 'efektif filtrasyon boyutu' da belirlemektedir. MBR sistemlerinde çözünmüş KOİ'nin reaktör içinde tutulmasında kullanılan membranın gözenek çapı kadar, sistemdeki biyokütle süspansiyonu tarafından membran üzerinde ikinci bir filtrasyon ortamı yaratan 'kek' tabakasının da gözenek yapısı etkili olmaktadır. Boyutları efektif gözenek çapından daha küçük olan çözünmüş organik maddeler kek tabakası ve membranı by-pass ederek çıkış suyuna karışacak, daha büyük olanlar ise sistemde tutularak, biyokütle gibi sistemde birikeceklerdir. Sistemde tutulan çözünmüş fazdaki organik maddenin boyut dağılımı PBD testi ile araştırılmıştır. PBD testleri, 40 nm gözenek çapına sahip membranın, yaklaşık 8 nm boyutunun üzerindeki organik maddeyi tutabildiğini göstermiştir.

1. INTRODUCTION

1.1 Problem Statement

Membrane bioreactors (MBR) are the integration of membrane filtration modules with the biological reactor discarding the secondary settlement in the conventional activated sludge (CAS) systems (Noor et al., 2007). Today MBR systems have become a substantial alternative to other treatment techniques especially for conventional activated sludge process. Compared to other treatment techniques, an MBR system features several advantages. First, better water quality effluent which meets the strict discharge standards, due to high retention of total suspended solids and most soluble compounds within the reactor is achieved. Since, in MBR systems the solid/liquid separation is provided through a membrane filtration rather than a conventional gravity settling, the suspended solids are not lost in the settling step and that gives a total control of solids retention time (SRT) and hydraulic retention time (HRT). Eliminating the problems that settling create, the operation of MBR system at high solid retention time allows high biomass concentration. Thus, highly polluted wastewater can be treated and lower biomass yields are observed. These conditions occur in compact systems rather than conventional processes that reduces plants footprint. Ultimately, due to high effluent quality, reduced sludge production and smaller footprint over CAS, MBR systems are the most advantageous and promising technology for wastewater treatment (Li et al., 2006; Pollice et al., 2008).

Many researchers are working to find the optimum operating conditions to increase MBR treatment performance. Ng and Hermanowicz operated a lab scale submerged MBR at low SRT levels ranging from 0,25d to 5d and HRT ranging from 3h to 6h. Submerged MBR system fed with simple substrate that represents the soluble, readily biodegradable and hydrolysable COD. After this study, Harper et al. examined the biomass characteristics and microbial yield with a lab-scale submerged MBR at a SRT of 5-0,25d, fed with again simple substrates composed of acetic acid, casamino acids and nutrients. Then, Duan et al. operated a submerged MBR system at SRT of 3d, 5d and 10 d, and at HRT 6h. They also used synthetic wastewater with simple substrates. After this study, Başaran et al. operated a lab-scale side stream MBR at SRTs between 0, 5-2d and HRTs between 0, 5-2h to examine the removal of readily biodegradable substrate.

This thesis attempts to fill some gaps in complex substrate removal by operating high rate membrane systems.

1.2 Purpose of Thesis

Aim of this thesis is to investigate and provide experimental support on treatment of domestic wastewater in “high rate MBR”, which is operated at extremely low SRT of 0,5-2d with HRT of 8 h.

This thesis essentially targets on:

- The removal of complex substrate by comparing the removal performance of peptone and domestic wastewater.
- The formation and fate of soluble residual organics.

1.3 Scope of Thesis

The written thesis is consists of five chapters. The brief explanations of the chapters are given below.

Chapter 1. Introduction

In Chapter 1, the main problem that triggers this thesis to be written, also the purpose and scope of the thesis is stated.

Chapter 2. Literature Review

In this chapter, a brief background on evolution of MBR systems, application and operation of MBRs and carbon removal performance are given.

Chapter 3. Materials and Methods

In this section, the lab-scale MBR system is presented with detailed equipment operational parameters. The synthetic wastewater composition, the characteristics of the domestic wastewater and the procedures and analysis that is used in the experimental runs are described.

Chapter 4. Results and Discussion

This chapter consist of three sections.

Section 1: Carbon removal performance of high rate MBR

Section 2: Sludge Characteristics

Chapter 5. Conclusions

The summary of the study and the recommendations for further studies are given in this chapter.

2. LITERATURE REVIEW

2.1 Membrane Bioreactor (MBR) Technology

2.1.1 Definition of MBRs

Membrane is thin layer of material that detaches materials by a driving force which can be differing by concentration, pressure electrical charge or temperature. Membranes are divided into groups according to their materials, rejected particle size and operational modes. Characterization of membranes according to their materials are respectively, inorganic membranes (metal and ceramic) and organic membranes (polymers). Classifications by the rejected particle size are namely, micro filtration, ultra filtration, nano filtration and reverse osmosis. Differentiations of the classification of membranes by the rejected particle size are shown in table. 2.1. Lastly, dead end filtration and cross flow filtration are the two main groups of membranes according to their operational modes.

Table 2.1 Comparison between membrane processes (Munasinghe, PhD, 2012).

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

Membrane bioreactors are the integration of membrane filtration modules with the biological reactor (Stephenson et al., 2000), in other words it is a combination of membrane technology with a biological treatment process. In the last decade, serious improvements are made and this leads membrane technology a promising alternative against conventional biochemical treatment processes.

2.1.2 Configurations of MBRs

There are two main configuration of MBRs, side-stream MBRs and submerged MBRs (Figure 2.1). In side-stream MBRs, membrane module is placed outside of the bioreactor. Sludge in the bioreactor is pumped into the membrane module. Consequently, a permeate stream is generated and the concentrated sludge is preserved by the membrane and returned to the bioreactor. In order to reduce the energy consumption from recirculation pumps in side-stream MBRs, Yamamoto et al. (1989) put forward the submerged MBRs which membrane module directly submerged in the bioreactor.

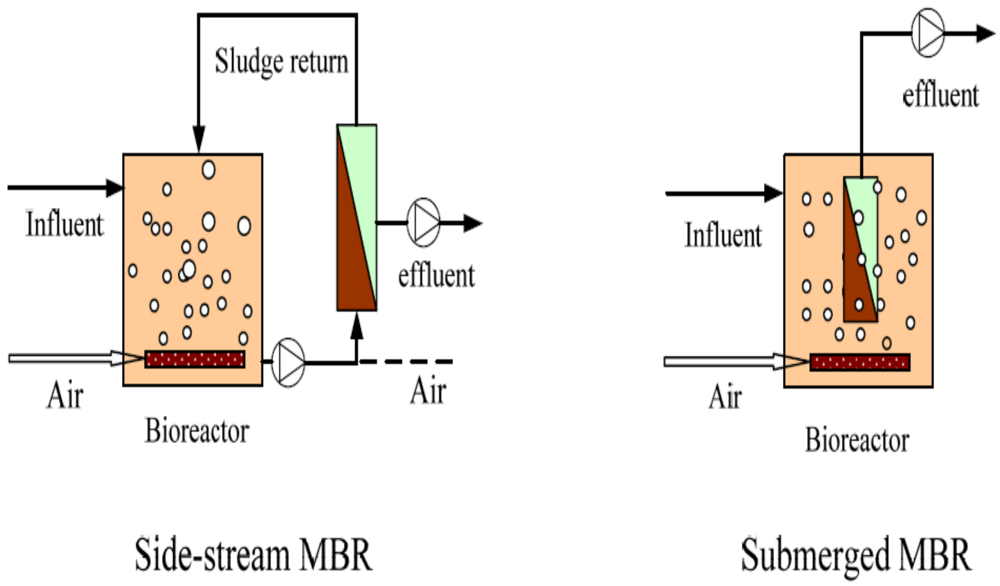


Figure 2.1 MBR configurations.

Submerged MBRs have an untroublesome configuration due to its less need of equipment. Furthermore, with the coarse bubble aeration, the fouling of the membrane is controlled the oxygen for biological process is obtained and ultimately saves more energy. Submerged MBRs have less fouling problems and can be cleaned easier than side-stream MBRs (Gander et al., 2000).

2.1.3 Advantage and disadvantage of MBRs

MBRs can be accepted as a good alternative for conventional activated sludge processes. In order to eliminate the biomass separation problems, MBRs use the separation ability of membrane technology which has higher separation ability than gravity settling especially for the separation of small flocs and colloidal particles. In conventional systems sludge bulking is the serious problem due to the floc formations. MBRs eliminate the bulking problem with the high separation ability. Furthermore, in MBRs the solid/liquid separation is provided through a membrane filtration rather than a conventional gravity settling, the suspended solids are not lost in the settling step and that gives a total control of SRT and HRT. The MBR system offer the following advantages compared to CAS (Cicek, 2003; Judd, 2007):

- Excellent reusable effluent quality
- Independence between HRT and SRT
- High loading rate
- Small foot print
- No sludge bulking risk
- Low sludge production
- Possibility to grow specific microorganisms
- Treat wastewater under extreme conditions
- Flexible modular design

On the contrary, there are several disadvantages of MBR systems that summarized below:

- Inevitable membrane fouling
- High capital cost, no economy scale
- Complicated control system
- Low oxygen transfer efficiency

2.1.4 Carbon removal performance of MBRs

2.1.4.1 Effect of SRT on MBR performance

Sludge age, which is a significant operational parameter associated with the membrane fouling is the main investigated property in the development of MBR performances. According to the researches, it was established that soluble organic matter, particulate size distribution, volatile/suspended solid (MLSS/MLVSS), sludge viscosity, bound EPS and SMP are vary with SRT (Le Clech et al., 2006; Ahmed et al., 2007; G. Laera et al.,2009).

Many studies are made to find the correlation between effluent quality and membrane fouling resulting from different sludge ages and most of the studies stated results for SRTs longer than 10 days (Pollice et al., 2008) and infinite SRTs (Jinhua et al., 2006;Gao et al., 2004; Liu et al., 2005; Nuengjamnong et al., 2005). According to these studies, membrane fouling was not decrease with longer SRTs, however operation flux or aeration could affect fouling tendency. Another disturbance with the membrane operation at long SRTs was the aeration efficiency. Mixed liquor viscosity that increased by the long SRTs lead to decrease the aeration efficiency.

In MBR systems, long SRTs are preferred. Long SRTs allow the growth of slow-growing microorganisms which utilize specific organic pollutants such as polysaccharides, carbohydrates and proteins as substrates. The allowance of the growth of slow-growing microorganisms increases the MLSS concentration in the reactor and hence decreases the amount of sludge to be wasted which leads a reduction in the required volume (R. Van den Broeck et al., 2012). Many studies indicated that MBRs at high SRTs longer than 10 days show efficient performances.

Pollice et al. (2008); reported COD removal efficiency range from 85 to 95 % and complete nitrification with a lab-scale submerged MBR operated at SRT of 20 days with a zero sludge wastage. Jinsong et al. (2006) studied with a submerged MBR system having a flat-frame microfiltration module and reported 93 to 97 % TOC removal which was operated at SRT of 10 days and 30 days. Ahmed et al. (2007) studied with four sequential anoxic/anaerobic MBR operated at SRT between 20 days and 100 days and found that the COD removal efficiency is 98 % and higher. Tan et al. (2008) who investigated the effect of SRT on treatment of municipal wastewater with 4 bench-scale pre-denitrification submerged MBR systems reported excellent COD removal efficiencies (over 95 %) that operated at SRTs of 5, 8.3, 16.7, and 33.3 days.

After the investigation of long SRTs in organic matter removal efficiencies, nitrogen removal has gained attention. According to Hocaoglu et al. (2011), longer sludge ages exploit a significant impact on the efficiency of simultaneous nitrification and denitrification.

In the literature very limited studies, which evaluate the MBR performance at short SRTs are exist. Ng et al. (2005) whose study is the first study that investigated short SRTs in MBR systems operated a lab-scale submerged MBR using hollow fiber membranes and sequencing batch reactor (SBR) system at SRT between 0.25 and 5 days feeding with synthetic wastewater. According to the study they observed outstanding COD removal efficiency ranging between 97.3 and 98.4 % with the MBR system.

Harper et al. (2006), studied the biomass characteristics and microbial yield with a lab-scale MBR system and a SBR system operated at SRT between 0.5 and 3 days. The study of Harper et al. (2006) confirmed the results of Ng et al. (2005).

After these studies, L. Duan et al. (2009) conducted a study on the effects of short solids retention time (SRT = 3, 5 and 10 d) in reactor performance and microbial community composition with operating a lab-scale nitrifying membrane bioreactor. According to the study, the process was capable of achieving over 87% removal of ammonia and 95% removal of COD.

On the other hand, membrane fouling is another operational parameter that must be controlled during operations in MBR systems with long and short sludge ages. The studies have reported conflicting results considering the correlation between long and short SRT effect and membrane fouling. The fouling of membrane at long SRTs is explained by lower production of EPS and SMP. This is supported by Jinsong et al. (2006) who has operated a MBR system at SRT of 10, 20, and 30 days and observed serious fouling at SRT 10 days compared to SRT 30 days; Al-Halbouni et al. (2008) observed more EPS and fouling layers at SRT 23 days than 40 days and Ahmed et al. (2007) explained the high TMP level with high EPS concentrations at SRT of 20 days compared to 40, 60 and 100 days. Furthermore, increase of SS concentrations and/or accumulation of non-biodegradable compounds in the reactor leads membrane fouling in MBR systems (Le- Clech et al., 2006).

In contrast to inverse proportion with sludge age and fouling Lee et al. (2003) observed that fouling is increased by the increasing SRT from 20 days to 60 days.

Although many researchers are investigating to find the optimum SRT that results in less fouling, the relation between SMP, SS or bound EPS concentration in the sludge or at the surface of the membrane with membrane fouling has not been clearly described. This also depends on the assumptions of SMP and bound/soluble EPS in these studies and the methodologies used for the analysis (Al-Halbouni et al., 2008).

2.1.4.2 Effect of HRT on MBR performance

The HRT is an important parameter in MBR applications that effects organic loading rate and metabolic activity of the MBR sludge which also affects the treatment processes and membrane fouling.

HRT is related to the organic loading, known as Substrate/Microorganisms (F/M) ratio, which is an important design and operational parameter and it is directly linked to the reactor volume and operating costs (Viero et al., 2008).

While analyzing the effect of HRT on MBR performance, it is important that the system is under steady-state conditions. Otherwise, the results obtained from systems may cause misconstrues (Viero et al., 2008).

The effects of HRT on membrane fouling and biomass are summarized by Meng et al. (2007) as shown in Fig. 2.2.

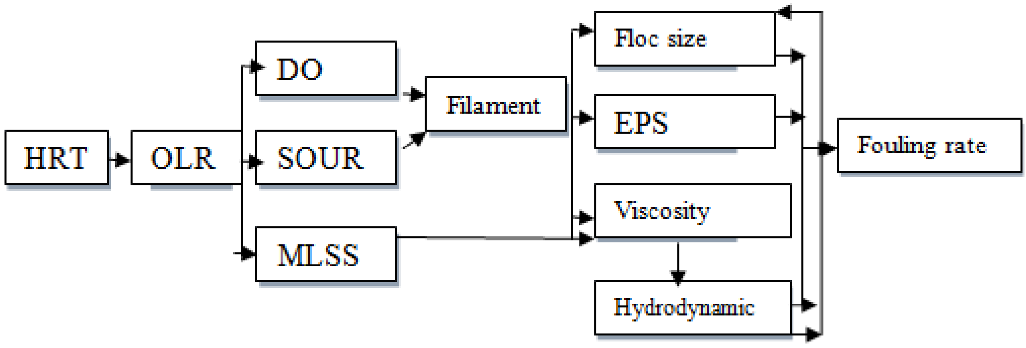


Figure 2.2 Schematic relation of HRT with sludge characteristics and membrane performance (Meng et al., 2007).

Chae et al. (2006) operated a MBR system at SRT of 60 days and observed an increase in fouling rate and membrane resistance related to increased EPS concentrations when HRT reduced to 4 hours from 10 hours. Visvanathan et al. (1997) stated that, due to the rapid formation of a compact layer on the membrane surface less fouling observed at long HRTs.

On the other hand, Nagaoka et al. (1998) worked with a flat-frame type of MBR system and observed that fouling is not affected from the increase of organic loading rate. Ren et al. (2005) indicated that treatment performance is affected from decreasing of HRT to 1 hour from 2 hour. However, Rahman and Al-Malack (2006) operated a MBR system treating industrial wastewater and applied HRT of 17 to 34 hours and observed that COD removal efficiency is not affected.

Viero et al. (2007), operated a MBR system fed with easily biodegradable synthetic wastewater and found that HRT does not affect the COD removal efficiency, however, when the system fed with industrial wastewater the removal efficiency is affected from the slight changes in HRT. Consequently, longer HRTs are desired for treatment of strong wastewaters.

On the other hand, Meng et al. (2007) investigated the short HRT levels. In the study, three submerged MBR systems run at HRT of 10-12 hr, 6-8 hr and 4-5 hr are operated and COD removal efficiency over 94 % in all the systems are observed.

Holler and Trosch (2001) studied with a jet-loop MBR with microfiltration type of membranes and observed a high COD removal efficiency at low organic loading rates (i.e. HRT). Even the organic loading rate was increased to 13 kg COD/m^3.d.; 95-99 % COD removal efficiency was achieved.

In another recent study investigated by Johir et al. (2011), the MBR was operated with different OLRs ranging from 0.5 to 3 kg COD/m^3.d., without changing any hydrodynamic parameters the HRT and SRT were kept at 8 h and 40 d, respectively. According to Johir et al. (2011), the removal efficiency of DOC, COD and NH_4-N decreased with regard to the increase of OLRs from 0.5 to 3 kg COD/m3.d. Ultimately, they stated that higher OLRs resulted in higher transmembrane pressure (TMP).

According to the literature, an increase of MLSS concentration (Chang and Kim., 2005; Cicek et al.,1999), an increase of non-flocculating microorganisms in sludge which is related with increasing of F/M ratio (Ng and Hermanowicz, 2005) and the production of hydrophilic compounds which is attached onto the membrane surface (Pan et al., 2010) are the main reasons of TMP generation. Consequently, the development of TMP is related to the higher levels of OLR.

2.1.5 Membrane Fouling

Membrane fouling in MBR systems causes a reduction in permeate flux and increase the operational and maintenance cost of the system that is why it is the major problem. As mentioned above, there were large number researchers that investigated the membrane fouling and still many of researchers are trying to find best available technology to reduce membrane fouling.

Generally there are two types of fouling; reversible and irreversible fouling. Cake layer formation is a reversible fouling due its easy cleaning from the membrane surface with a physical cleaning. Adsorption of small particles into membrane pores causes internal fouling which is an irreversible fouling and can only be removed by chemical cleaning. In Figure 2.3, fouling mechanisms can be seen.

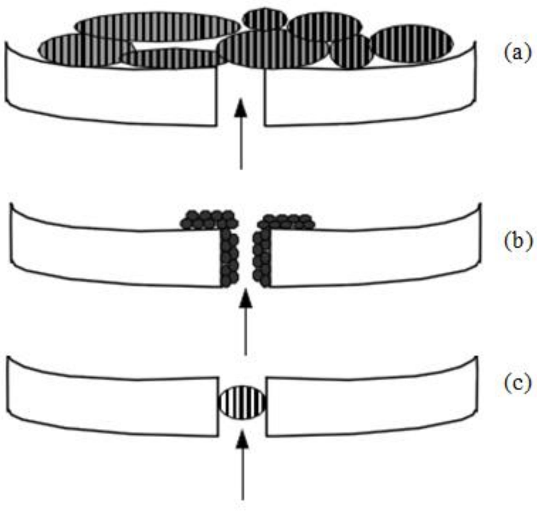


Figure 2.3 Fouling mechanisms (a) Cake layer formation; (b) Pore narrowing; (c)Pore blocking.

However, it is difficult to create a general rule for membrane fouling. The three factors that strongly influence membrane fouling are biomass characteristics, operating conditions and membrane characteristics. Membrane fouling factors are shown in Figure 2.4.

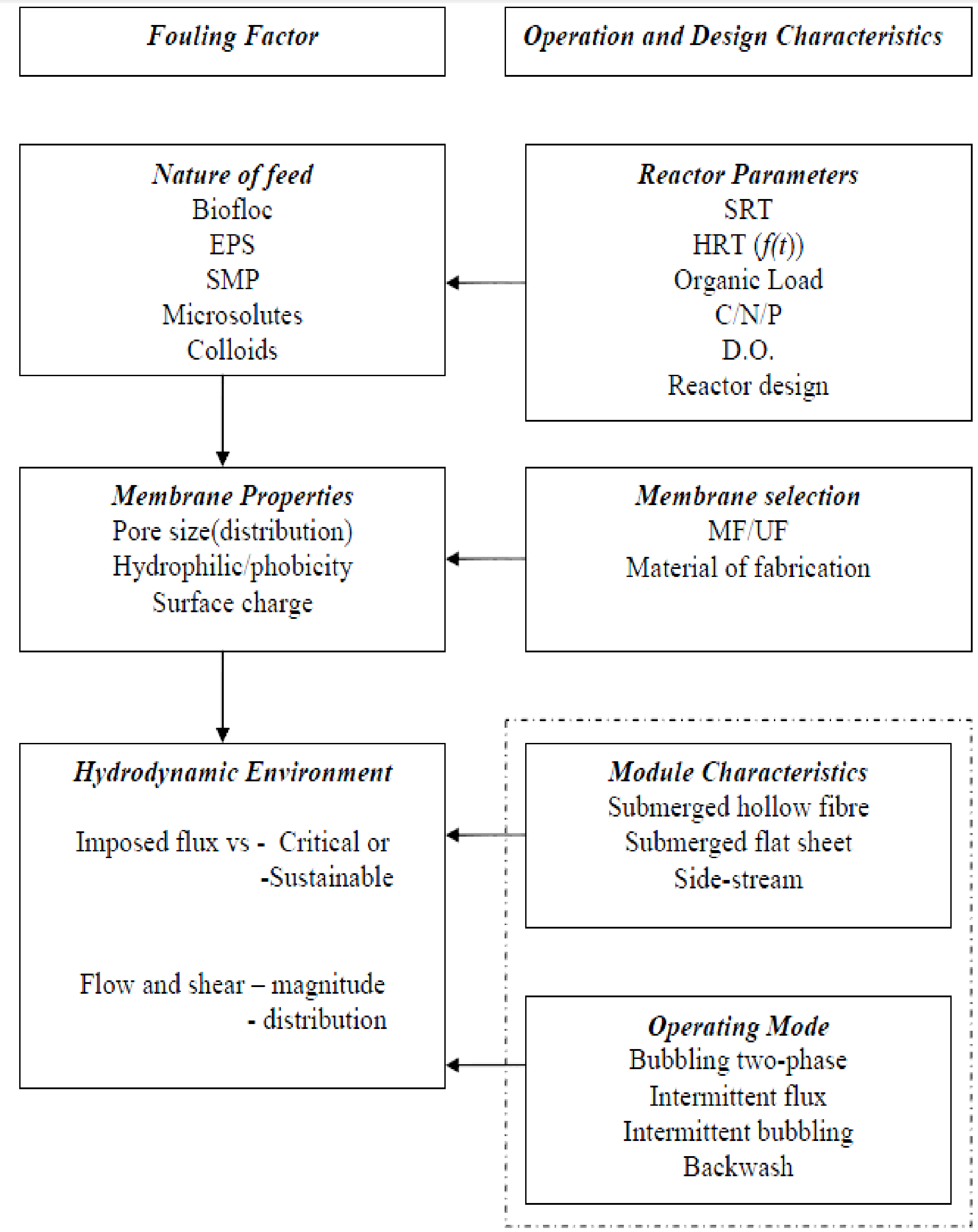


Figure 2.4 Relationship between fouling factors (Zhang et al., 2006).

2.1.5.1 Relationship between EPS/SMP generation and membrane fouling

MLSS, extracellular polymeric substances (EPS), floc structure and size and other dissolved matter are the most discussed fouling factors in literature.

The polymeric structure in activated sludge floc which is a mixture of microorganisms and different types of microbial products, keeps other components in place and it is called as EPS. EPS was observed to be a significant factor in sludge liquors due to its high molecular weight components (Sanin and Vesilind, 2000; Liao et al., 2001). Proteins, polysaccharides, lipids, nucleic acids and other minor components are found in EPS (Bura et al., 1998; Nielson and Jahn, 1999).

EPS is divided into two groups; bound EPS and soluble or colloidal EPS (Nielson and Jahn, 1999). Le Clech et al. (2006), observed that bound EPS concentrations less than 20 and higher than 80 mg EPS/MLVSS were not effective in membrane fouling.

Recently, many researchers are investigating the correlation between EPS generation and membrane fouling. Chang and Lee (1998) found a linear proportion between EPS and membrane fouling. Drews et al. (2008), found no relation between the polysaccharide concentration and fouling and confirmed the literature findings that said the effect of SMP is less related to fouling and filtration resistance at longer SRT. The results showed that SMP affects fouling only at short SRT and large pore sizes. According to Tao (2008), majority of SMP has a slowly biodegradable character and it is accumulated as it is retained by the membrane. The high fouling potential of SMP is explained by their small particle size, which allows their deposition on membrane surfaces which clog the pores and form a sludge cake.

3. MATERIALS AND METHODS

3.1 Experimental Set-up and Operation of Laboratory Scale Submerged MBR System

The study was carried out by operating a lab-scale submerged MBR, which consisted of a Plexiglas reactor with an operating volume of 3 L. The system was equipped with hallow fiber Zee Weed*1 (GE) membrane module with a nominal pore size of 0.04 μm and total membrane surface area of 0.1 m^2. The technical properties of Zee Weed*1 ultra filtration membrane is listed in Table 3.1.

Table 3.1 : Technical properties of Zee Weed*1 ultra filtration membrane.

Module Type	
Nominal Membrane Surface Area	1 ft^2(0.1 m^2)
Module Dimensions	
Height	175mm
Diameter	56 mm
Membrane Properties	
Material	PVDF
Nominal Pore Size	0.04 micron
Surface Properties	Non-Ionic& Hydrophilic
Fiber Diameter	1.9 mm OD/ 0.8 mm ID
Flow Path	Outside-In
Operating Specifications	
TMP Range	-55 to 55 kPa (-8 to 8 psi)
Max. Operating Temperature	40◦C (104 F)
Operating pH Range	5.0- 9.5
Cleaning Specifications	
Max. Cleaning Temperature	40C (104 F)
Cleaning pH Range	2.0- 10.5
Max. CI_2 Concentration	1.000 ppm

In order to control and measure the fundamental operational variables such as dissolved oxygen (DO), trans membrane pressure (TMP), pH and temperature, submerged MBR was automatically controlled by means of a Programmable Logic Controller (PLC) as shown in Figure 3.1.

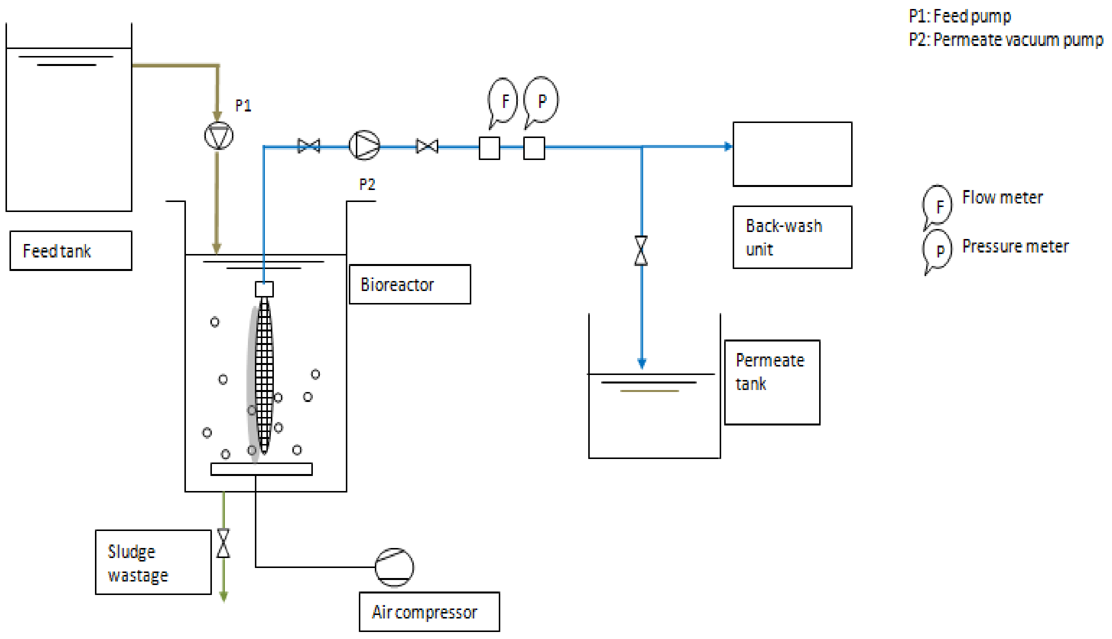


Figure 3.1 Process flow scheme of the lab-scale MBR.

As seen from the Figure 3.1, the wastewater was pumped (P1, Watson Marlow SciQ323, UK) into the bioreactor (3 L, Pexiglas) from the feed tank (30 L, PES). In order to provide aeration and mixing, the bioreactor was regularly aerated and stirred via magnetic stirrer (Velp Scientifica, Italy). To obtain the desired SRT, a peristaltic pump (P3, SISDOZ PRS-1, Italy) was operated every hour for a certain time duration for the discharge of waste sludge.

The MBR system was operated under constant flux conditions where permeate is withdrawn at a constant flow by operating a permeate pump (P2, Watson Marlow SciQ323, UK). The flow rate of the permeate is calculated by the speed of the peristaltic pump (P2). The liquid level set point adjusted to 18.4 cm which refers to 3 L volume and controlled by the operation of the wastewater feed pump (P1).

Every 19 minutes filtration, the membrane was backwashed by air for 1 min. Chemical cleaning of membrane is applied when TMP exceeded 550 mbar or/and every beginning of the new run. Chemical cleaning is applied by approximately 30 min contact with a pH=12 NaOH solution followed by 1 cycle of normal operation and 30 min contact with a pH=2.5 H_2SO_4 solution.

3.2 Characteristics of Synthetic Wastewater and Domestic Wastewater

The system was operated under the HRT of 8 hours with SRT ranging from 0.5 d – 2.0 d. The selected HRT reflects the lowest applicable HRT that used in MBR system for long term operation.

Two different feeds are tested in order to investigate the treatment efficiency of complex substrates in submerged MBR systems; which are peptone mixture and domestic wastewater.

First feed of the study was peptone mixture which was a stock substrate and prepared by dissolving 16 g peptone, 11 g meat extract, 3 g urea, 0.7 g NaCl, 0.4 g $CaCl_2.2H_2O$, 0.2 g $MgSO_4.7H_2O$ and 2.8 g K_2HPO_4 in 1 L distilled water.

Peptone mixture was selected due to the similarity between domestic sewage in terms of biodegradation characteristics as it contains a similar balance between readily biodegradable COD and slowly biodegradable COD fraction (Insel et al., 2006).

Second and last feed of the study was domestic wastewater which is obtained from ISKI Baltalimanı Wastewater Pre-Treatment Plant. Characteristics of domestic wastewater is given in Table 3.2. Pre-treated wastewater (after fine and coarse screens and grit chamber) taken from the parshall flume after the grit chambers. After settling, upper phase of the domestic wastewater was used as a feed in this study.

Table 3.2 Characterization of Domestic Wastewater.

Parameter	Unit	Domestic Wastewater
Biochemical Oxygen Demand (BOD_5)	mg/L	113
Chemical Oxygen Demand (COD)	mg/L	250
Total Suspended Solids (TSS)	mg/L	166
Total Phosphate (TP)	mg/L	4,2
Ammonia Nitrogen (NH_3-N)	mg/L	21,9
pH	-	7,72

Peptone mixture was prepared by diluting stock solution in water to reach total influent COD of 200 mg/L. The nutrient limitation was prevented by adding inorganic salts (10 ml for 1 gCOD/L) concentrated in solutions A and B the contents of which are shown in Table 3.3.

Table 3.3 Solution A and B ingredients.

Solution A	g/L	Solution B	g/L
NH_4Cl	120	$MgSO_4.7H_2O$	15
KH_2PO_4	160	$CaCl_2.7H_2O$	2
K_2HPO	320	$FeSO_4.7H_2O$	0.5
		$ZnSO_4.7H_2O$	0.5
		$MnSO_4.H_2O$	0.5

3.3 Analytical Procedures

The samples taken from bioreactor and permeare for COD measurements are filtered through 0.45µm PVDF syringe filters and preserved with H_2SO_4 and H_3PO_4, respectively. COD samples were analayzed as decribed in the ISO 6060 methodology (ISO 6060, 1986). Mixed liquor suspended solids (MLSS) and volatile suspenden solids (MLVSS) concentrations were analyzed as described in Standard Methods (AWWA, 2005). TOC was analyzed with TOC analyzer and DOC measurements were carried out by filtering TOC samples from 0.45 µm syringe filters.

For measuring the PHA content of the samples, formaldehyde was added to prevent biological activity. Samples biomass was washed with K-P buffer solution and freeze-dried. Extraction, hydrolysation and estrerification processes in mixture of hydrochloric acid, 1-propanol and dichloroethane at 100°C were performed as described by Beun et al. (2000). After extraction with water to remove free acids, organaic phase was analyzed by gas chromatograph (Agilent 6890 N). Benzoic acid was used as internal standard in the analyses.

3.4 Respirometry

Dissolved oxygen (DO) is a significant model component that assists the basic understanding and explanation of complex biochemical reactions in the activated sludge processes. DO is not only important for modeling design but also used as an operational parameter. Furthermore, DO sets the electron balance between biodegradable COD, biomass and electron acceptor for aerobic processes.

Oxygen utilization rate (OUR), is the rate of oxygen utilization in the biochemical processes, which is observed as a change in the dissolved oxygen concentration in time. Thus, it is an overall process rate reflecting the cumulative impact of all oxygen/energy consuming reactions.

OUR is one of the most effective tools for experimental determination of COD fractions in addition to kinetic and stoichiometric model coefficients (Orhon et al., 1999).

The mostly used technique to determine OUR is lab-scale online respirometers. In order to assess the biodegradation kinetics, the OUR profile must be well known and interpreted.

In this study, OUR profiles were obtained by using a respirometer (RA-1000; Manotherm). Respirometric analyses were made using the MBR activated sludge (2L) by applying the same F/M condition with the original MBR bioreactor. The activated sludge from the respirometer chamber is continuously passed through the respiration vessel (0.75 L), where the dissolved oxygen at the inlet and outlet are measured and the sample is returned back to the chamber. The OUR was calculated based on the measurements of a single DO-electrode where the measuring frequency is limited by the response rate of the DO-electrode (Spanjers and Klapwijk, 1990) and is fixed once a minute. The possible interference of ammonia consumption for nitrification is avoided by adding nitrification inhibitor (Formula 2533TM, Hach Co.).

3.5 Sludge Characteristics

3.5.1 TOC based particle size distribution (PSD)

Particle size distribution is important for understanding the wastewater characteristics, evaluation of best convenient treatment technologies and estimation of removal performances (Dulekgurgen et al., 2006).

Particle size distribution analysis was made according to methodology defined by Dülekgürgen et al. (2006). The sequential filtration/ultrafiltration procedure is illustrated in Figure 3.3.

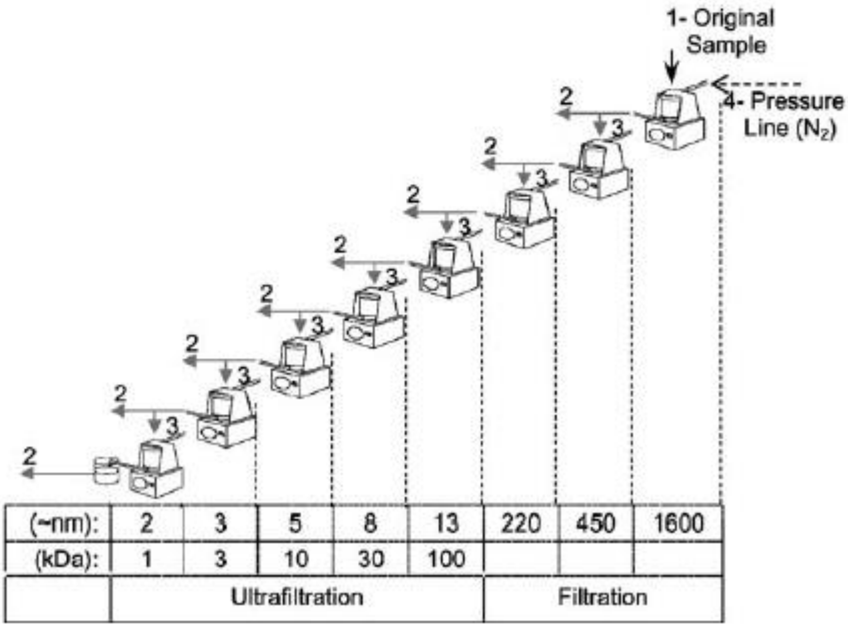


Figure 3.2 : Sequential filtration/ultrafiltration procedure: 1-Non settled, non-filtered but mixed original sample, 2-aliquot of filtrate from the previous step, subjected to COD, 3-aliquot of filtrate from the previous step, subject to subsequent filtration/ultrafiltration procedure, 4-gas line providing positive pressure (Dulekgürhen et al., 2006).

In order to achieve high level of accuracy, it was decided to measure soluable organics as DOC rather than COD. The experiments were analyzed in a 400 ml stirred ultrafiltration cell with an effective membrane area of 41.8 m^2 (Millipore Amicon 8400, USA). Filtration was employed by applying positive pressure (0.6 to 1.2 atm) adjusted according to the filter/membrane characteristics by using inert N_2 gas. Sequential filtration/ultrafiltration tests were run at room temperature however the filtrates were collected in clean flasks which were kept at 4°C in ice baths to avoid sample decomposition.

The filtration/ultrafiltration sequence was initiated by passing samples with a final volume of 100 ml permeate through membranes with pore sizes of 450 nm (Durapore HV, PVDF), 220 nm (Durapore GV, PVDF). Filtration was performed at 0.35 atm working pressure and below the maximum temperature limit of 85 °C for Durapore disposable filters. Permeates from membrane filter with size 220 nm were filtered through ultrafiltration membranes with nominal molecular weight cut-off (MWCO) values of 100, 30, 10, 3 and 1 kDa (PL series, Millipore, MA). The working pressure was 0.6 atm (0.7 atm recommended) for the 100 kDa membrane and 1.2 atm (3.7 atm recommended) for the remaining sizes of ultrafiltration membranes.

In this study, Filtration from 1600 nm membrane filters was not applied and filtration process was started from 450 nm filter size which is used to separate soluble and particulate fractions.

4. RESULTS AND DISCUSSION

4.1 Carbon Removal Performance of High Rate MBR

4.1.1 Operating conditions

Lab-scale submerged MBR system was operated at three different SRTs; 2.0, 1.0 and 0.5 days, with a same HRT of 8 hours. Runs are sustained at steady-state conditions and as described earlier fed with peptone mixture and domestic wastewater. MBR operating conditions and substrate concentrations are given in Table 4.1.

Table 4.1 MBR system operation conditions.

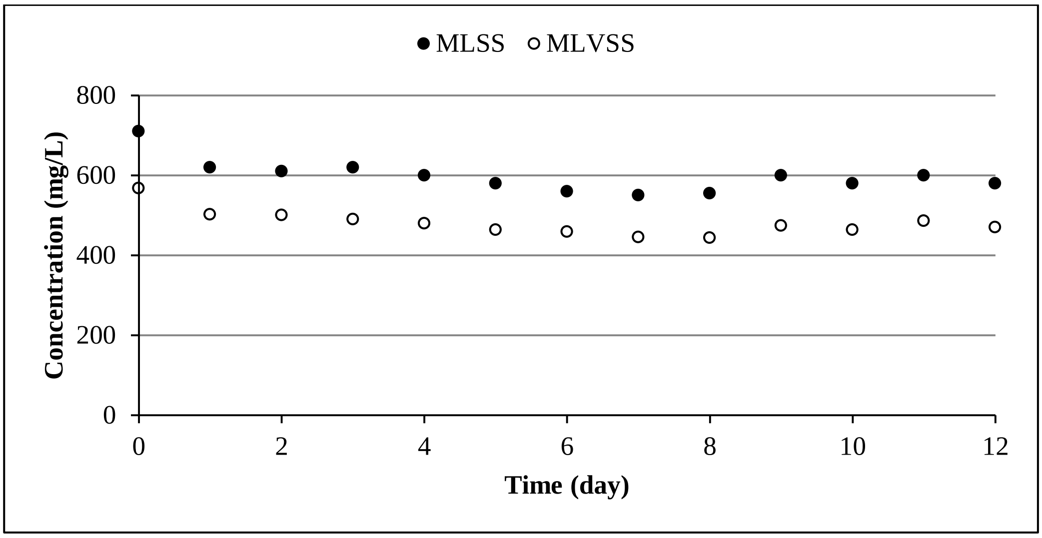
Parameters	Peptone Mixture	Domestic Wastewater
SRT (d)	2.0, 1.0, 0.5	2.0, 1.0, 0.5
Substrate concentration (mg COD/L)	200	250

MBR performance was evaluated in terms of COD (<450 nm) measurements at steady-state from the reactor together with permeate during all operation periods. COD inside the reactor was measured as soluble COD (SCOD-R) which was analyzed by filtering from 0.45µm syringe to adopt the standard size differentiation and assessment of biomass in biological treatment and effluent COD (COD-P) was analyzed as sampled.

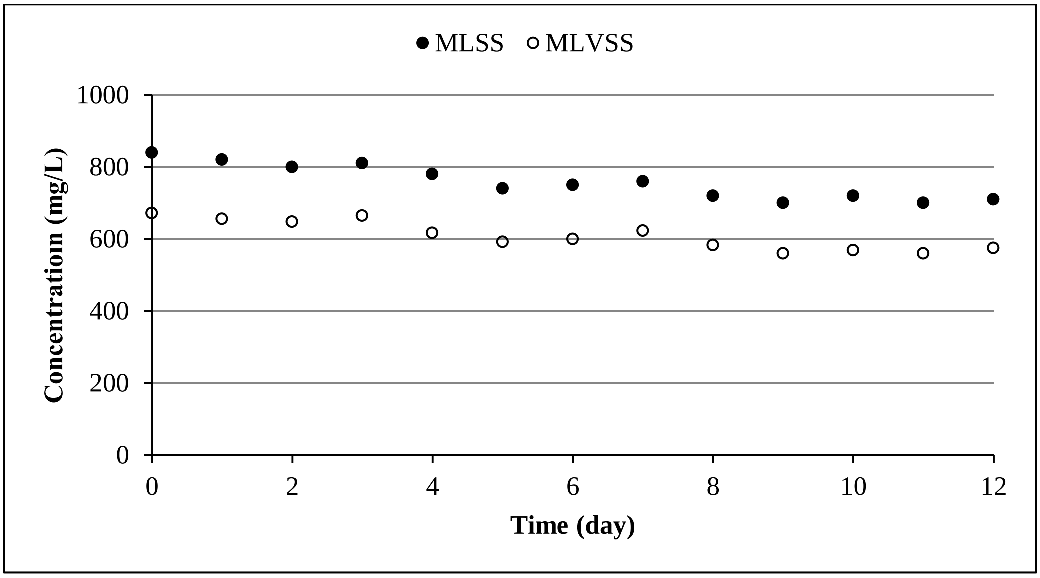
4.1.2 MLSS and MLVSS concentrations

Concentrarion of MLVSS which is considered to be the concentration of biomass in the system is a control parameter for treatment systems. In this study, MLVSS and MLSS concentrations are used as control parameters for attainig steady-state conditions.

After 12 days of monitoring period, steady-state conditions are attained both for system fed with peptone mixture and domestic wastewater. Figure 4.1 shows the steady-state concentraions of MLSS and MLVSS for peptone mixture and domestic wastewater operated at SRT of 2.0d.



(a) Peptone Mixture



(b) Domestic Wastewater

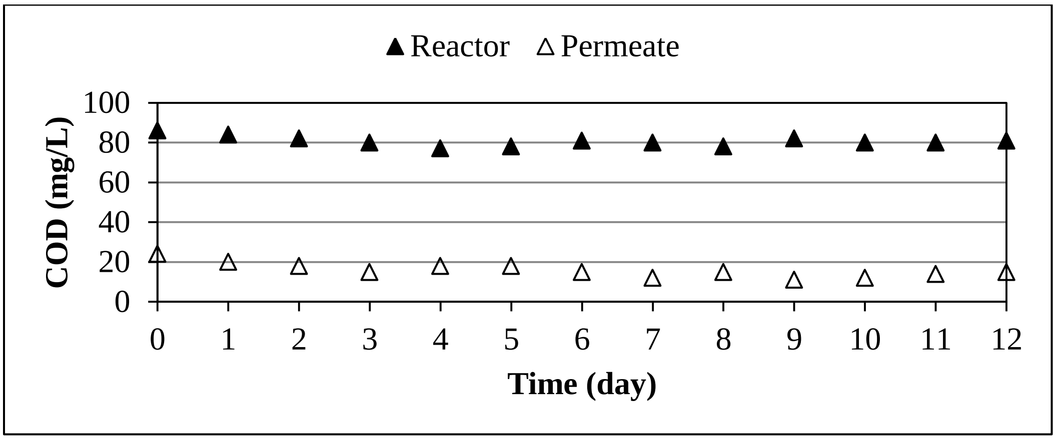
Figure 4.1 Observed MLSS and MLVSS profiles at steady state for (a) Peptone Mixture and (b) Domestic Wastewater at SRT of 2.0d

Average MLVSS concentrations of MBR system fed with domestic wastewater at SRTs of 2.0d, 1.0d and 0.5d are respectively; 470 mg/L, 370 mg/L and 280 mg/L and system fed with domestic wastewater respectively; 560 mg/L, 420 mg/L and 290 mg/L.

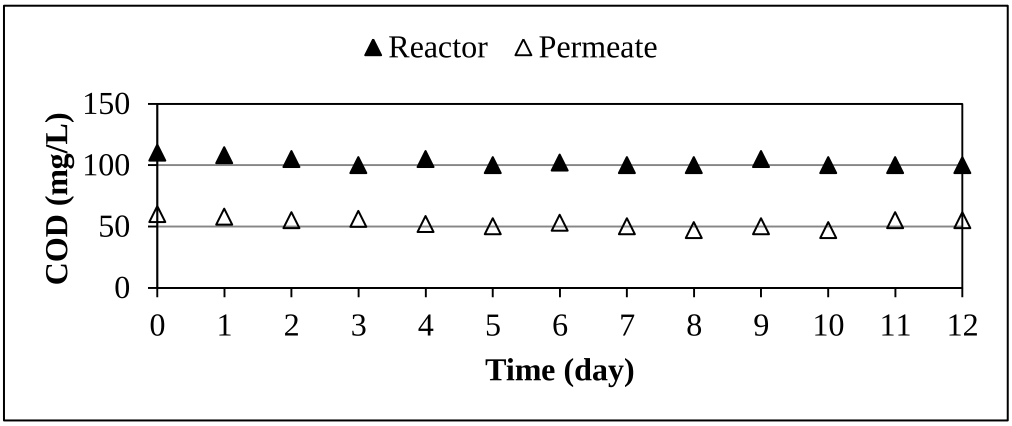
MLVSS profiles obtained for MBR system fed with peptone mixture and domestic wastewater at SRTs of 1.0d and 0.5d are given in Appendix B.

4.1.3 COD profiles

COD measurements are the main operation parameters that reflect the carbon removal performance of the system. As mentioned above, COD measurements are made for reactor bulk and permeate. Figure 4.2 shows the steady-state COD profiles of peptone mixture and domestic wastewater operated at SRT of 2.0 days.



(a) Peptone Mixture



(b) Domestic Wastewater

Figure 4.2 Observed COD profiles at steady state for (a) Peptone Mixture and (b) Domestic Wastewater at SRT of 2.0d.

Average permeate concentrations of MBR system fed with domestic wastewater at SRTs of 2.0d, 1.0d and 0.5d are respectively; 15 mg/L, 30 mg/L and 40 mg/L and system fed with domestic wastewater respectively; 55 mg/L, 60 mg/L and 70 mg/L.

COD profiles obtained for MBR system fed with peptone mixture and domestic wastewater at SRTs of 1.0d and 0.5d are given in Appendix C.

4.1.4 Summary of carbon removal performance

The organic carbon removal performance of MBR operated at SRT range of 0.5 to 2.0 d and HRT of 8.0 h, revealed that despite the extremely limited operating conditions, MBR operation could yield excellent effluent by achieving 85 % COD removal efficiency. In addition, effluent quality increased with the higher SRTs.

According to the European Union, the legally required discharge standards for urban wastewater treatment plants (125 mgCOD/L), the permeate from the MBR operation yielded way more higher quality.

The performance monitoring results are summarized in Table 4.2.

Table 4.2 : Summary of MBR carbon removal performance at SRT of 0.5 to 2d and HRT of 8h for Peptone Mixture and Domestic Wastewater.

Operational Conditions	MLVSS (mg/L)	SCOD-R (mgCOD/L)	SCOD-P (mgCOD/L)	Membrane Rejection (%)
SRT (day)	**Peptone Mixture (200 mgCOD/L)**			
2.0	470	80	15	81
1.0	370	60	30	50
0.5	280	50	40	20
SRT (day)	**Domestic Wastewater (250 mgCOD/L)**			
2.0	560	100	55	45
1.0	420	85	60	29
0.5	290	75	70	7

Difference between the soluble COD in the reactor and soluble COD of permeate gives the membrane rejection. The influence of the membrane rejection to overall COD removal can be clearly seen from the monitored data. Membrane rejection was observed to be between 81-7 % and the ifluence of membrane rejection to overall COD removal increased with the increasing SRT. The reason of the increase is assumed to be the higher MLSS concentrations. Higher MLSS concentration could affect the filtration cake on top of the membrane which acts like an additional filtration media and the cake load tends to rise with MLSS concentration (Le-Clech et al., 2006).

These results are supported by the studies that published in literature. Cicek et al. (2001) operated a MBR system fed with synthetic wastewater at SRT of 2 d and 5 d and observed that average effluent COD increased from 3.5 mg/L at SRT of 5 days to 23 mg/L at SRT of 2 d. Holler and Trosch (2001), operated eMBr with synthetic wastewater and observed that the effluent COD concentrations remained constant around 24 mg/L for SRT greater than 2d. Another study was made by Teussel et al. (2006), treated primary effluent from a munucipal WWTP with a pilot-scale submerged MBR and reduced influent COD (345 mg/L) to a median effluent concentration of 24 mg/L at all SRTs tested from 2 to 10d.

In evaluation of the carbon removal performance in high rate MBR system, two main observations are underlined according to the course of substrate in the system; (i) Soluble COD levels in the reactor (COD-R) always remained higher than the effluent COD (COD-P), (ii) COD-R concentrations are increased significantly, nearly folded double with the increasing SRTs. As a result, the difference between COD-R and COD-P, indicates a membrane rejection due to the membrane filtration, increased with the increasing SRTs. Based on these observations, dissolved organic material remained in the reactor considered as SMP. Respirometric analysis and assesments from the model based on respirometric analysis are essential for verification of this approach and determination of biodegradtion kinetics of peptone and domestic wastewater.

4.2 Determination of Substrate Removal Kinetics

4.2.1 Respirometric analysis

Respirometric measurements and COD monitoring were performed to determine the microbial oxygen utilization rate while the F/M ratio was kept the same as in the reactor at the steady-state conditions in the sMBR. OUR profiles are demonstrated in Figures (4.19- 4.34). Detailed soluble COD profiles during the OUR test is given in Appendix D.

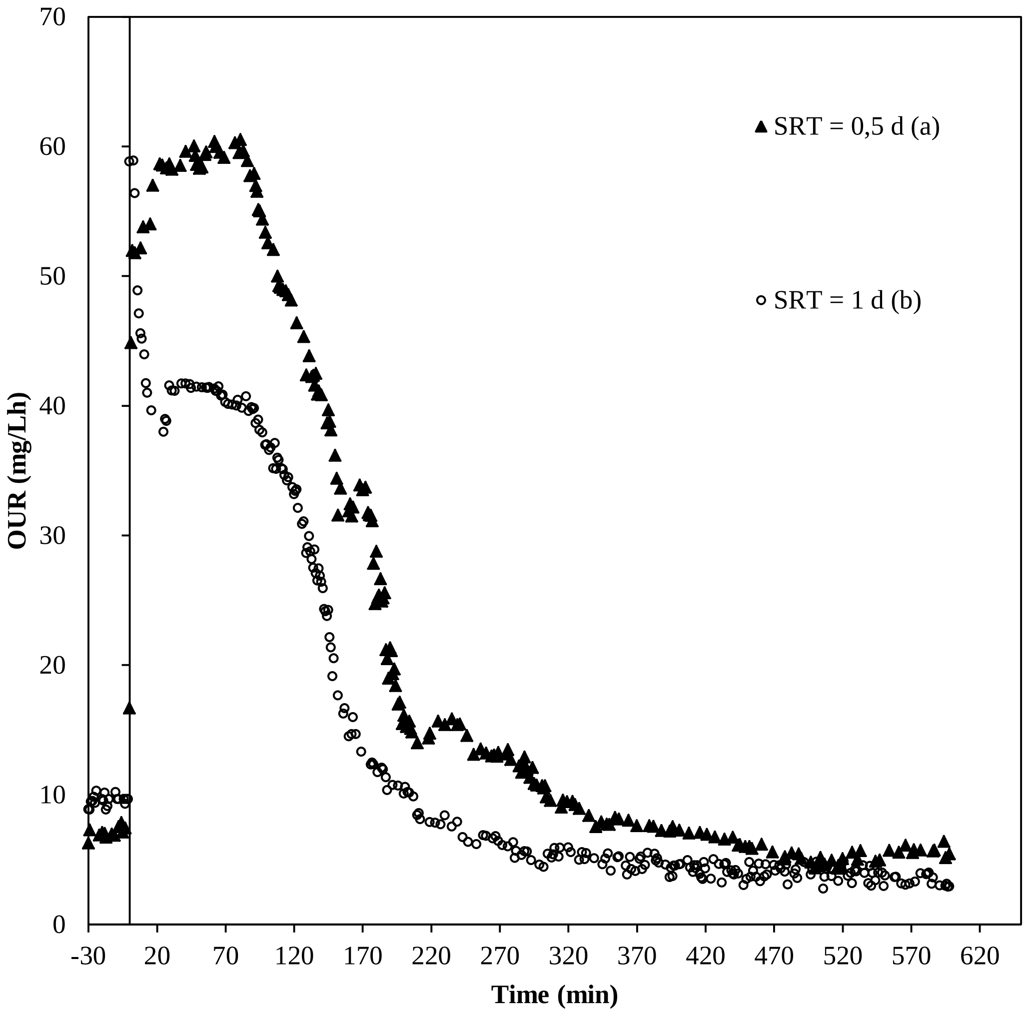


Figure 4.3 OUR profile for Peptone Mixture at (a) SRT= 0.5 d, (b) SRT= 1.0 d.

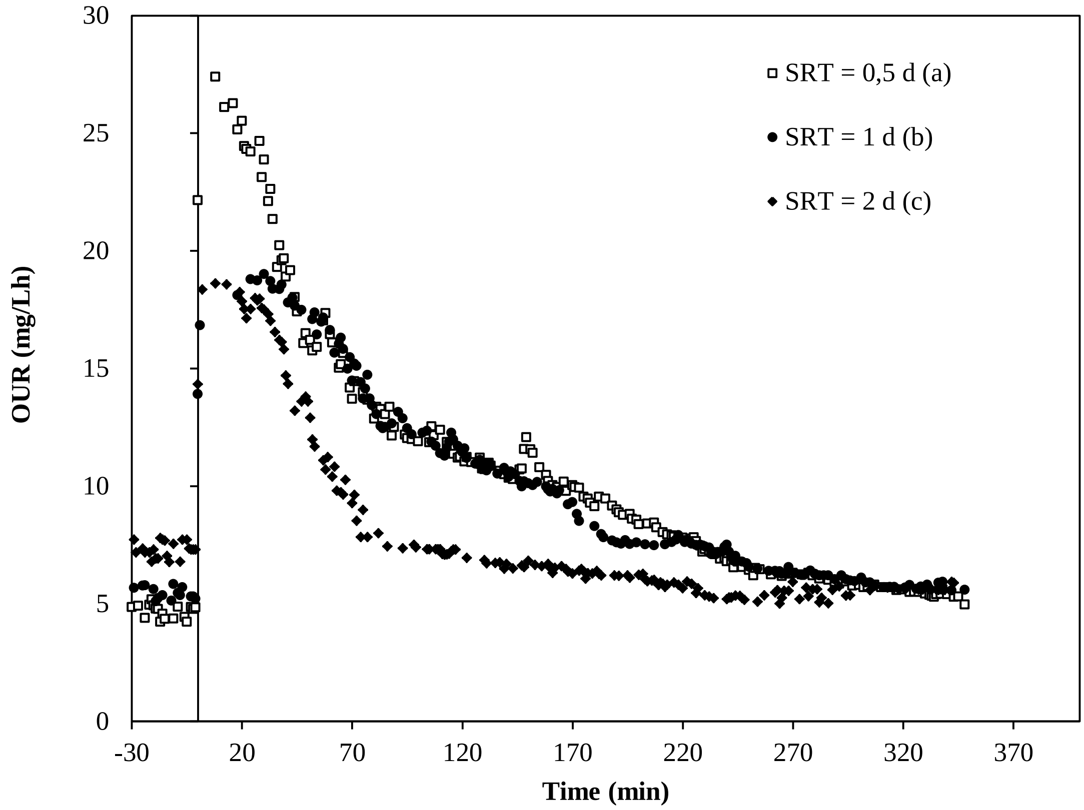


Figure 4.4 OUR profile for Domestic Wastewater at (a) SRT= 0.5 d, (b) SRT= 1.0 d, (c) SRT= 2.0 d.

4.3 Sludge Characteristics

4.3.1 Effective filtration size of the membrane

Soluble COD levels in the reactor (COD-R) always remained higher than the effluent COD (COD-P). The difference between COD-R and COD-P, indicates a significant retention effect due to membrane filtration. Retention of soluble COD in MBR systems depends on effective filtration size generated by the particular biomass rather than membrane pore size. Investigation of this retention effect is made by particle size distribution (PSD) test which involves sequential filtration between 2 – 450 nm.

PSD tests were conducted on samples from reactor volume, characterizing different operating conditions in terms of SRT. PSD was made for only experimental run that treated domestic wastewater.

As mentioned earlier, TOC parameter was selected (rather than COD) in order to represent the organic content in the samples due to volume limitations in the analyses. In the study TOC values are equal to DOC since all the measurements were carried out after filtration through 450 nm filters.

DOC concentrations collected from reactors at steady state from experimental runs treating domestic wastewater at SRT 0.5 d, 1.0 d and 2.0d were 3.94, 4.58 and 4.62 mg/L respectively. Cumulative TOC fractions and differential TOC values are given in table 4.3.

Table 4.3 Cumulative TOC fractions and differantial TOC values.

Separation Technique	**Particle Size (nm)**	**Cumulative TOC (mg/L)**			**Size Category (nm)**	**Differantial TOC (mg/L)**		
		SRT (d)				**SRT (d)**		
		2.0	**1.0**	**0.5**		**2.0**	**1.0**	**0.5**
Filtration								
HV filter	450 nm	16	16	11				
GV filter	220 nm	11	12	9	220-450	5	4	2
Ultrafiltration								
100 kDa	13 nm	5,2	5,48	4,13	13-220	5,8	6,52	4,87
30 kDa	8 nm	4,62	5,16	3,86	8-13	1,22	0,87	1,03
10 kDa	5 nm	4,59	4,81	3,59	5-8	0,4	0,27	0,09
3 kDa	3 nm	3,71	4,53	3,44	3-5	0	0,21	0,1
1 kDa	2 nm	3,53	3,79	3,42	2-3	1,06	0,36	0,06
					<2	2,43	2,88	3,6

PSD tests indicated that, current MBR system with a pore size of 40nm, entrapped organics above the size range of around 8 nm. This may be attributed to cake filtration effect due to biofilm formation on the surface of the membrane.

The size distribution results related to TOC for the experimental runs are plotted in Fig 4.5 and 4.6.

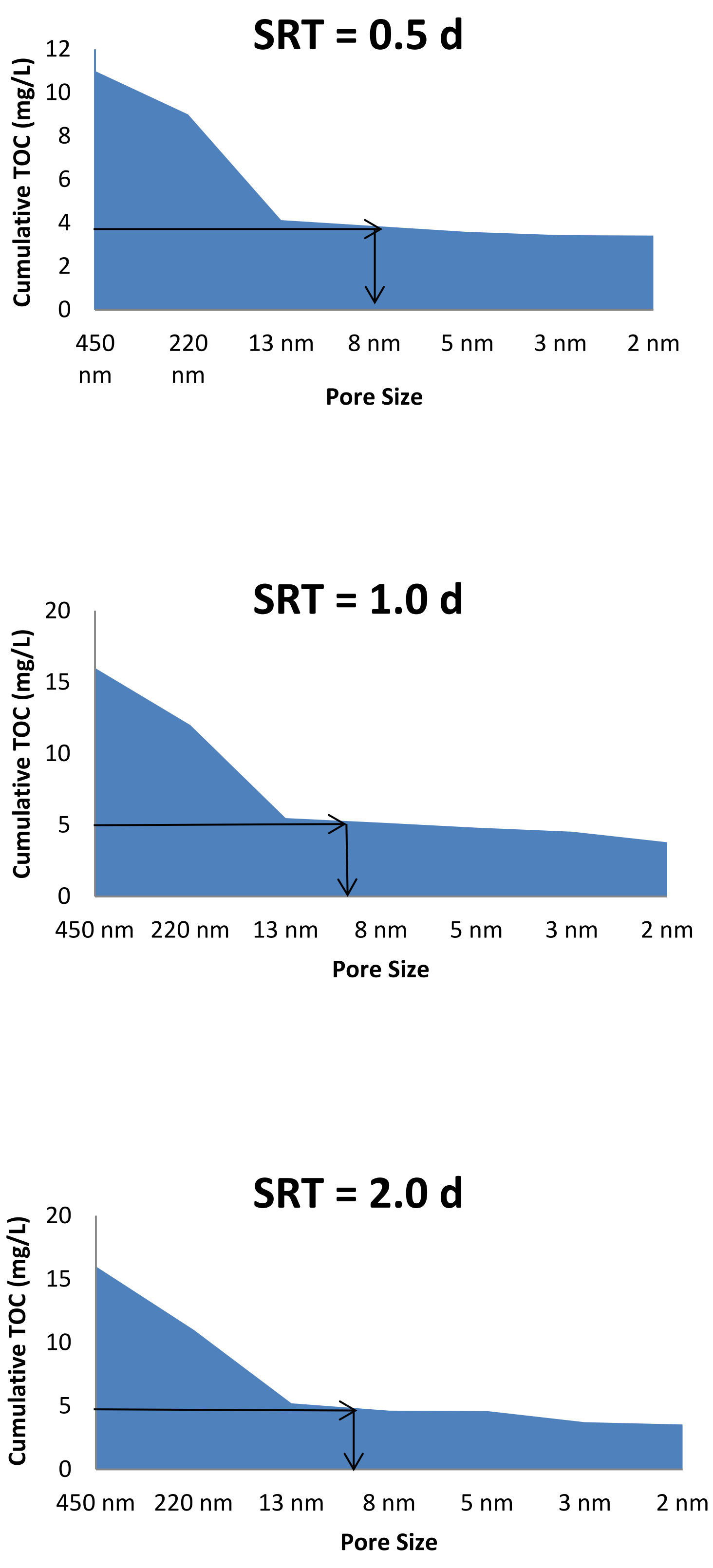


Figure 4.5 Cumulative PSDs for Domestic Wastewater at SRT: 0.5, 1.0 and 2.0d.

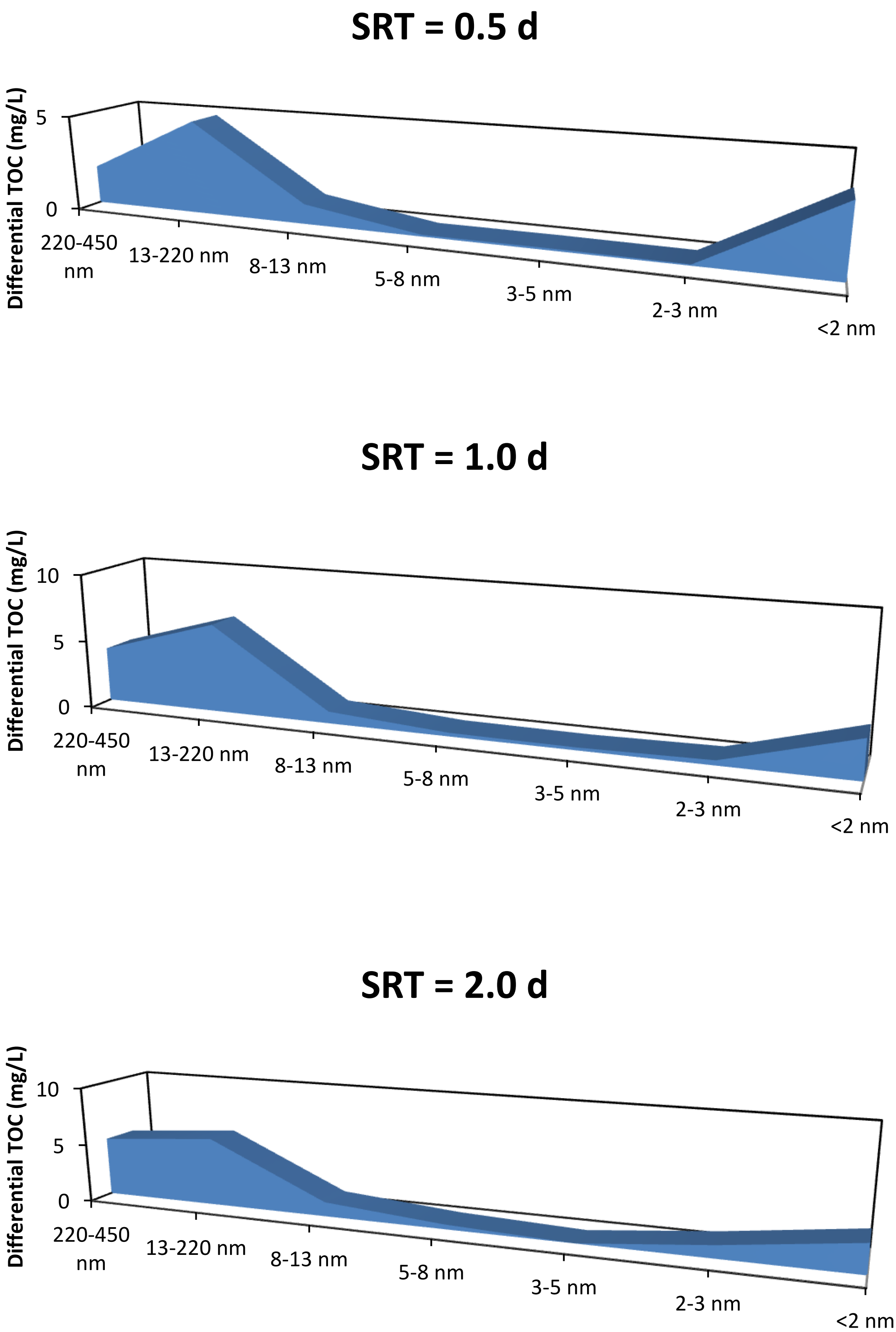


Figure 4.6 Differential PSDs for Domestic Wastewater at SRT 0.5, 1.0 and 2.0d.

5. CONCLUSION AND PERSPECTIVES

MBR systems are increasingly preferred for the treatment of domestic and industrial wastewater since they offer significant operational advantages over conventional activated sludge systems such as effective separation, total control of biomass and superior effluent quality. But selection of design parameters still remain conventional, with higher SRTs and increased biomass levels. In this respect, the experimental results should be assessed by different treatment configurations which discards primary and secondary settling and requires designing the high rate MBR system for removal of complex substrate by treatment of domestic wastewater.

The purpose of this study is to investigate the performance of submerged MBR system operated at extremely low SRT in removing complex substrates from wastewater while the larger organics/particulates are retained by the membrane and/or adsorbed into microbial flocs and evaluate the carbon removal performance by treating domestic wastewater. In this context, a laboratory scale submerged MBR was operated at three different SRT of 2.0, 1.0 and 0.5 days. For each level of the selected sludge age, hydraulic retention time (HRT) of the system was adjusted to 8 hours. Two different substrate feedings were tested; (a) peptone mixture, representing the soluble/readily and slowly biodegradable substrate mixture and (b) domestic wastewater. The peptone mixture and domestic wastewater was tested at all SRTs. The synthetic feed, peptone mixture was adjusted to 200 mg COD/L. Domestic wastewater obtained from İSKİ Baltalimanı Wastewater Pre-Treatment Plant had an average COD of 250mg/L.

The experimental works covered monitoring of carbon removal performance and determining the biodegradation kinetics of MBR system treating domestic wastewater and peptone mixture supported with respirometric and sludge characterization tests.

High rate MBR operation at extremely short SRT (0.5 d – 2.0 d) and HRT of 8 h was able to yield high quality effluent treating domestic wastewater. Effluent COD for MBR system treating peptone mixture at SRT of 0.5 d, 1.0 d and 2.0 d are 40 mg/L, 30 mg/L and 15 mg/L respectively and for domestic wastewater is 70 mg/L, 60 mg7L and 55 mg/L respectively. The soluble COD profiles monitored inside the bioreactors tended to be higher than the COD values observed in the effluent streams which was attributed to generation of SMPs during the biological processes as the influent COD was assumed to be totally biodegradable, which was supported with the literature that the SMP generation was increased with the increasing SRT.

System performance was also benefited from effective pore size of the membrane. Sequential filtration and and ultrafiltration test were carried out with soluble fraction of the reactor bulk. The tests revealed that, membrane could sustained the particles larger than 8 nm, which is a smaller size than the actual pore size of 20 nm.

It is important to satisfy sustainable long-term operation of high-raye MBR systems with different wastewater streams. In this respect, future studies should study the treatment performance of different wastewater streams, mainly focusing on industrial wastewaters. This MBR operation approach should also be tested for much lower HRT, i.e. HRT of 0.5 to 2.0 h, in order to prove as a treatment alternative which also saves considerably from the required reactor volumes.

REFERENCES

Ahmed, Z., Cho, J., Lim, B., Song, K., Ahn, K., (2007). Effects of sludge retention time on membrane fouling and microbial community structure in a membrane bioreactor. *Journal of Membrane Science,* **287**, 211-218.

Al-Halbouni, D., Traber, J., Lyko, S., Wintgens, T., Melin, T., Tacke, D., Janot, A., Dott, W., Hollender, J., (2008). Correlation of EPM content in activated sludge with membrane fouling phenomena, Water Res. 42 (6-7)3, 1475-1488.

APHA, (1998). Standard Methods for the Examination of Water and Wastewater (20th ed.), American Public Health Association Inc., *Washington, DC,* USA.

AWWA, (2005). Standard methods for the examination of water and wastewater, 21st ed., American Public Health Association/American Water Works Association/Water Environment Federation, Washington, DC.

Broeck, R.V., Dierdonck, J.V, Nijskens, P., Dotremont, C., Krzeminski, P., Graaf, J.H.J.M., Lier, J.B, Impe, J.F., Smets, M.I.Y., (2012). The influence of solids retention time on activated sludge bioflocculation and membrane fouling in a membrane bioreactor (MBR). *Journal of Membrane Science*, **401-402**, 48-55.

Chang I.S. and Lee, C.H., (1998). Membrane filtration characteristics in membrane-coupled activated sludge system—the effect of physiological states of activated sludge on membrane fouling, Desalination 120, 221–233.

Chech, J. J. and Chudoba, J., 1983**.** Influence of accumulation capacity of activated sludge microorganisms on kinetics of glucose removal. *Wat. Res.*, 17(6), 659-666.

Chen G.W., Lin W.W. ve Lee D.J., (1996). Capillary suction time (CST) as a measure of sludge dewaterability, *Water Sci.and Technology*., **34(3-4),** 443-448

Chen, W., Liu, J., Xie, F. (2012). Identification of the moderate SRT for reliable operation in MBR. *Desalination,* **286**, 263-267.

Claassen, P. A. M., van Lier, J. B., Lopez Contreras, A. M., Niel, E. W. J., Sijtsma, L. , Stams, A. J. M., de Vries, S. S., Weusthuis, R. A. (1999) .Utilisation of biomass for the supply of energy carriers, Appl. Microbiol. Biotechnol. 52, 741 755.

Cokgor, E.U., Insel, G., Aydin, E., Orhon, D., (2009) . Respirometric evaluation of a mixture of organic chemicals with different biodegradation kinetics, J. Hazard. Mater. 161 35–41.

De Wilde, W., Richard, , Lesjean, , Tazi-Pain A. (2008). Towards standardisation of the MBR technology? *Desalination*, **231**, 156-165.

Domínguez, L., Cases, V., Birek, C., Rodríguez,M., Prats, D., (2012). Influence of organic loading rate on the performance of ultrafiltration and microfiltration membrane bioreactors at high sludge retention time. *Chemical Engineering Journal,* **181-182**, 132-143.

Duan, L., Moreno-Andrade, I., Huang, C., Xia, S., Hermanowicz, S., (2009). Effects of short solids retention time on microbial community in a membrane bioreactor, Bioresource Technol. 100 3489–3496.

Dubois, M., Gilles, K.A., Hamilton, J.K., Rebers, P.A. and Smith F., (1956). Colorimetric method for determination of sugars and related substances, *Anal. Chem*. **28 (3),** pp. 350–356.

European Union, Urban Wastewater Treatment Directive, Council Directive 91/271/EEC of 21.05.1991 Concerning Urban Wastewater Treatment, as Amended by Directive 98/15/EC.

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

Hocaoglu, S. M., Insel, G., Ubay-Cokgor, E., Orhon, D., (2011). Effect of sludge age on simultaneous nitrification and denitrification in membrane bioreactor, Bioresource Technol. 102 (12) 6665–6672.

Hocaoglu, S. M., Orhon, D., (2010). Fate of soluble residual organics in membrane bioreactor, J. Mem. Sci. 364 65-74.

Hong, S., Aryal,R., Vigneswaran, S., Johir, M.A.H., Kandasamy, J. (2012). Influence of hydraulic retention time on the nature of foulant organics in a high rate membrane bioreactor. *Desalination*, **287**, 116- 122.

Holler, S., and Trosch, W., (2001). Treatment of urban wastewater in a membrane bioreactor at high organic loading rates, J. Biotechnol. 92, 95-102.

Insel, G., Orhon, D., Vanrolleghem, P.A., (2003). Identification and modelling of aerobic hydrolysis mechanism-application of optimal experimental design, J. Chem. Technol. Biotechnol. 78 437–445.

ISO 6060, (1986). Determination of the Chemical Oxygen Demand. International Standards Organization, Switzerland.

Jefferson, B., Brookes, A., Le-Clech P. and Judd, S.J., (2004). Methods for understanding organic fouling in MBRs, Water Sci. Technol. 49,237–244. Membrane bioreactors, PhD Thesis), Ghent University, Belgium, 241.

Jiang, T., (2007). Characterization and modelling of soluble microbial products in Membrane bioreactors, PhD Thesis), Ghent University, Belgium.

Jinsong, Z., Chuan, C. H., Jiti Z., Fane, A.G., (2006). Effect of sludge retention time on membrane bio-fouling intensity in a submerged membrane bioreactor, Sep. Sci. Technol. 41 (7) 1313 –1329.

Johir, M.A.H., Vigneswaran, S., Sathasivan, A., Kandasamy J., Chang C.Y. (2011). Effect of organic loading rate on organic matter and foulant characteristics in membrane bio-reactor. *Bioresource Technology*, Article in Press.

Kappeler, J., Gujer, W., (1992). Estimation of kinetic parameters of heterotrophic biomass under aerobic conditions and characterization of wastewater for activated sludge modelling, Water Sci. Technol. 25 125–139.

Laera, G., Pollice, A., Saturno ,D., Giordano, C., Sandulli, R. (2009) . Influence of sludge retention time on biomass characteristics and cleaning requirements in a membrane bioreactor for municipal wastewater treatment. *Desalination*, **206**, 104-110.

Laspidou, C. S., Rittmann, B. E., (2002). A unified theory for extracellular polymeric substances, soluble microbial products, and active and inert biomass, Water Research 36, 2711-2720.

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

Lee, N.H., Amy, G., Croue., J.P and Buisson, H. (2004). Identification and understanding of fouling in low-presure membrane (MF/UF) filtration by natural organic matter (NOM). Water Research 38(20), 4511-4523.

Li, T., Bai, R., Liu, J., (2008). Distribution and composition of extracellular polymeric substances in membrane-aerated biofilm, J. Biotechnol. 135 52-57.

Masse, M., Sperandio, C., Cabassud, C., (2006). Comparison of sludge characteristics and performance of a submerged membrane bioreactor and activated sludge process at high solids retention time, Water Res., 40, 2405-2415.

Meng, F., Chae,S., Drews, A., Kraume, M., Shin H., Yang, F. (2009). Recent advances in membrane bioreactors (MBRs): Membrane fouling and membrane material. *Water Research,* **43**, 1489-1512.

Munasinghe, P., (PhD, 2012). Mass Transfer Evaluation and Analytical Modeling Using Composite Hollow Fiber Membrane for Syngas Fermentation toBiofuels.

Ng, H.Y, Hermanowicz S.W. (2005). Membrane bioreactor operation at short solids retention times: performance and biomass characteristics. *Water Research,* **39**, 981-992.

Ng, A.N.L., Kim A.S. (2007). A mini-review of modeling studies on membrane bioreactor (MBR) treatment for municipal wastewaters. *Desalination,* **212**, 261-281.

Orhon, D., (1998). Evaluation of industrial biological treatment design on the basis of process modeling, Water Sci. Technol. 38, 1-8.

Orhon, D., Germirli-Babuna, F., Karahan, O., (2009). Industrial Wastewater Treatment by Activated Sludge, IWA Publishing, London.

Orhon, D., Yildiz, G., Cokgor, E.U., (1995). Respirometric Evaluation of Biodegradability of Confectionary Wastewaters, Water Sci. Technol. 32 11–19.

Pollice, A., Laera, G., Saturno, D., Giordano. C. (2008). Effects of solid retention time on the performance of a membrane bioreactor treating municipal sewage, *Jour. Mem. Sci*. **317**, 65–70.

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

Rosenberger, S,. Evenblij, H., te Poele, S., Wintgens T. and Laabs, C., (2005). The importance of liquid phase analyses to understand fouling in membrane assisted activated sludge processes—six case studies of different European research groups, J. Membr. Sci 263, 113–126.

Sarioglu, M., Insel, G., Artan, N., Orhon, D., (2011). Stoichiometric and kinetic evaluation of simultaneous nitrification and denitrification in a membrane bioreactor at steady state, J. Chem. Technol. Biot, 86 (6) 798–811.

Spanjers, H., Vanrolleghem, P.A., (1995). Respirometry as a tool for rapid characterization of wastewater and activated sludge, Water Sci. Technol. 31105–114.

Stephenson, T., Judd, S., Jefferson B. and Brindle K. (2000) Membrane bioreactors for wastewater treatment, IWA Pub., London, UK.

Tan, T.W., Ng, H.Y., Ong, S.L., (2008). Effect of mean cell residence time on the performance and microbial diversity of pre- denitrification submerged membrane bioreactors, Chemosphere 70 387–396.

Trussell, R.S, Merlo, R.P., Hermanowicz, S.W., Jenkins D. (2006). The effect of organic loading on process performance and membrane fouling in a submerged membrane bioreactortreating municipal wastewater. *Water Research,* **40**, 2675-2683.

van den Eynde, E., Geerts, J., Maes, B., Verachtert, H., (1983). Influence of feeding pattern on the glucose metabolism of *Arthobacter* sp.and *Sphaerotilus natans*, growing in chemostat culture, simulating activated sludge bulking. *Eur. J Appl. Microbiol. Biotechnol.*, 17, 35-43.

Wang, Z., Wu, Z., Mai, S., Yang, C., Wang, X., An, Y., Zhou Z., (2008). Review: Research and applications of membrane bioreactors in China: Progress and prospect, Separation and Purification Technology, 62, 249-263.

Wang Z., Wu, Z., Yin X. and Tian, L, (2008). Membrane fouling in a submerged membrane bioreactor (MBR) under sub-critical flux operation: Membrane foulant and gel layer characterization, Jour. Mem. Sci. 325, 238–244

Yang, W., Cicek N. and Ilg, J., (2006). State-of-the-art of membrane bioreactors: worldwide research and commercial applications in North America, J. Membr. Sci. 270, 201–211.

Zevenhuizen, L. P. T. M., Ebbink, A. G., (1974). Interrelations between glycogen, poly-b- hydroxybutyric acid and lipids during accumulation and subsequent utilization in a Pseudomonas. *Antonie van Leeuwenhoek* 40, 103–120.

APPENDICES

Appendix A: MLSS and MLVSS monitoring results for sets run with Peptone Mixture

Appendix B: COD profiles for sets run with Peptone Mixture

Appendix C: OUR profiles for sets run with Peptone Mixture

APPENDIX A

A.1 MLSS and MLVSS monitoring results for sets run with Peptone Mixture:

a) SRT = 2.0 d and HRT = 8 h

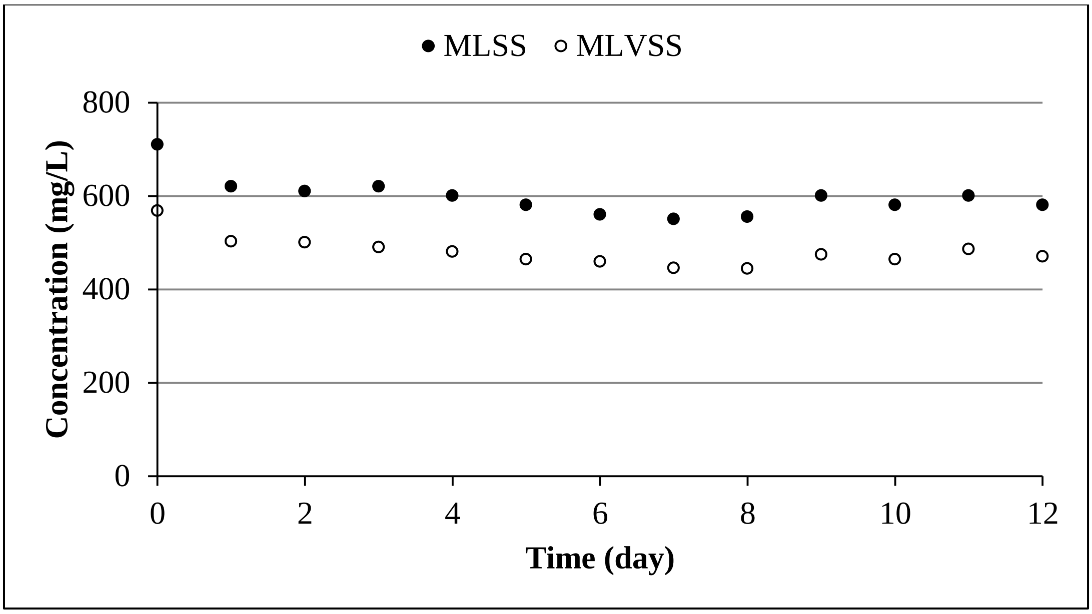


Figure A.1 : MLSS and MLVSS results for sMBR operated at SRT = 2.0 d treating Peptone Mixture

b) SRT = 1.0 d and HRT = 8 h

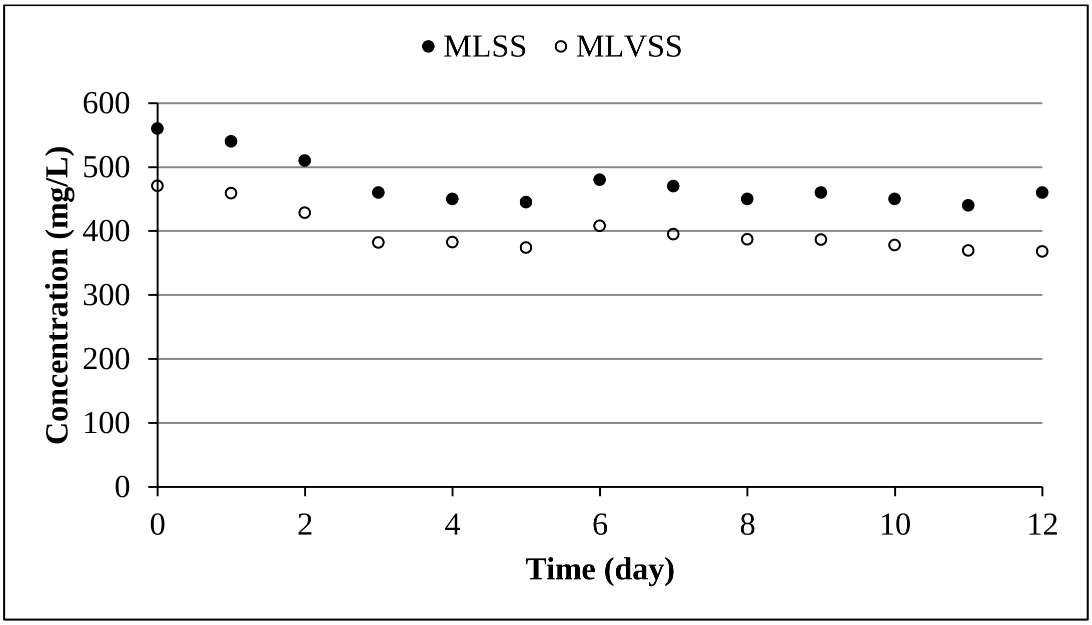


Figure A.2 : MLSS and MLVSS results for sMBR operated at SRT = 1.0 d treating Peptone Mixture

c) SRT = 0.5 d and HRT = 8 h

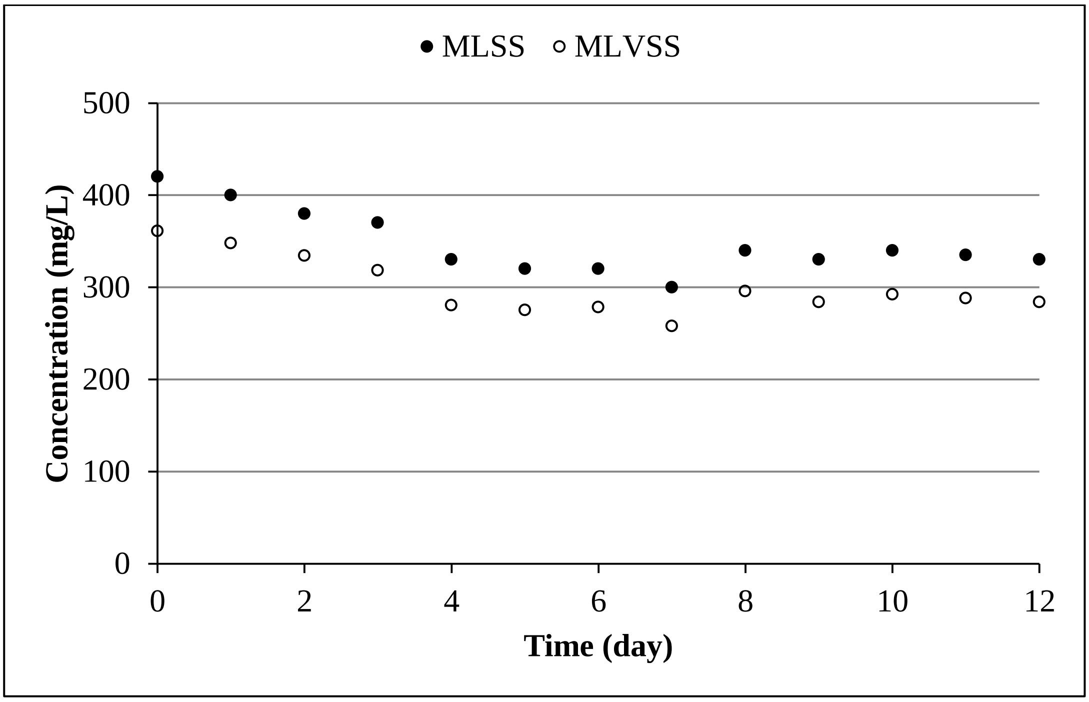


Figure A.3 : MLSS and MLVSS results for sMBR operated at SRT = 0.5 d treating Peptone Mixture

A.2 MLSS and MLVSS monitoring results for sets run with Domestic Wastewater:

a) SRT = 2.0 d and HRT = 8 h

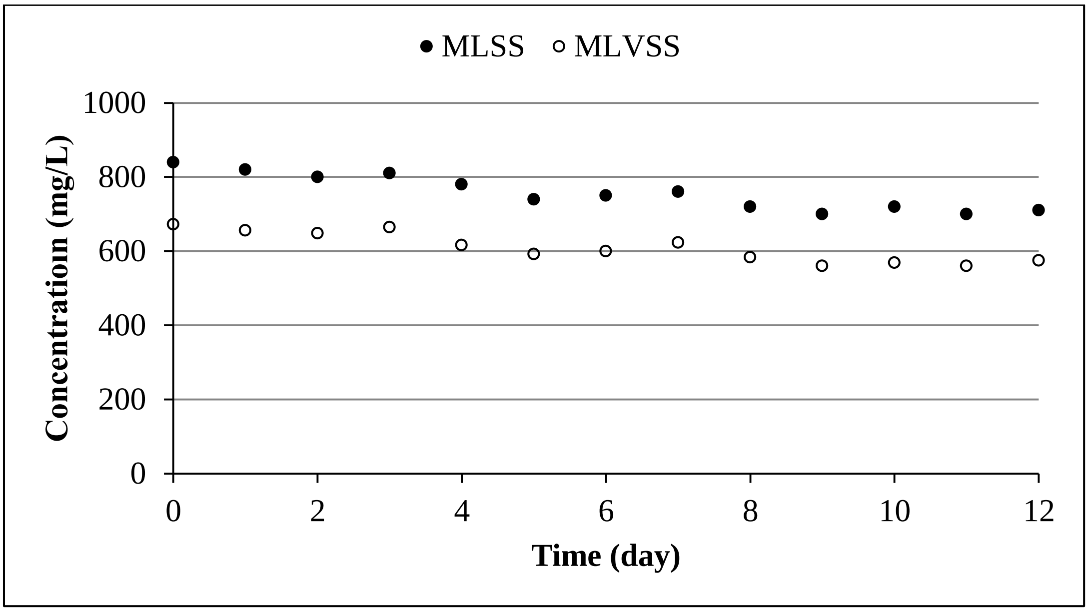


Figure A.4 : MLSS and MLVSS results for sMBR operated at SRT = 2.0 d treating Domestic Wastewater

b) SRT = 1.0 d and HRT = 8 h

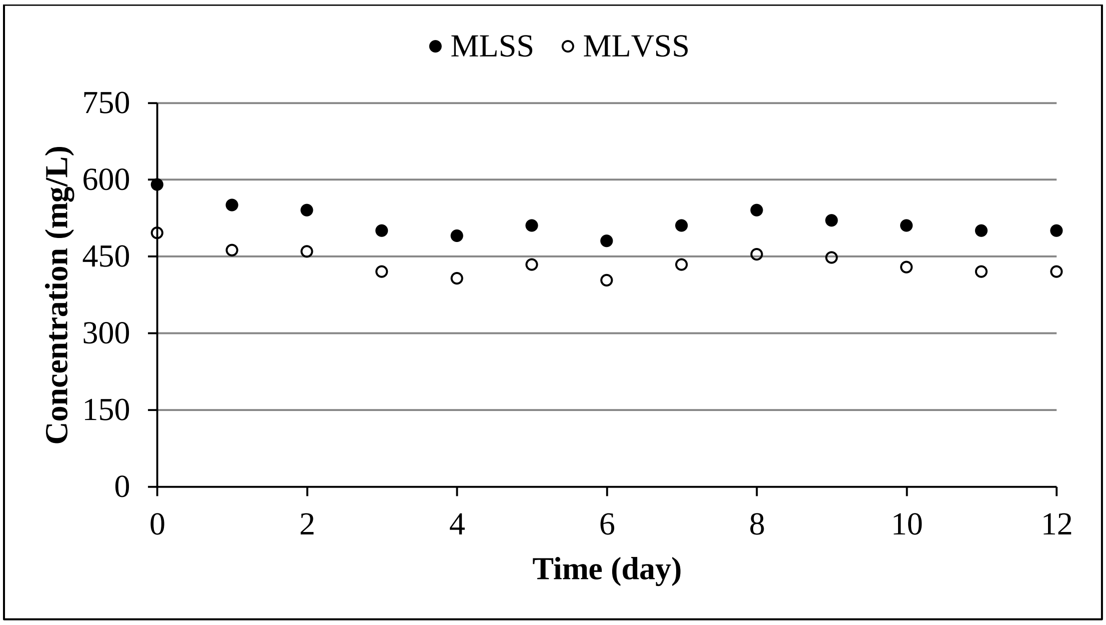


Figure A.5 : MLSS and MLVSS results for sMBR operated at SRT = 1.0 d treating Domestic Wastewater

c) SRT = 0.5 d and HRT = 8 h

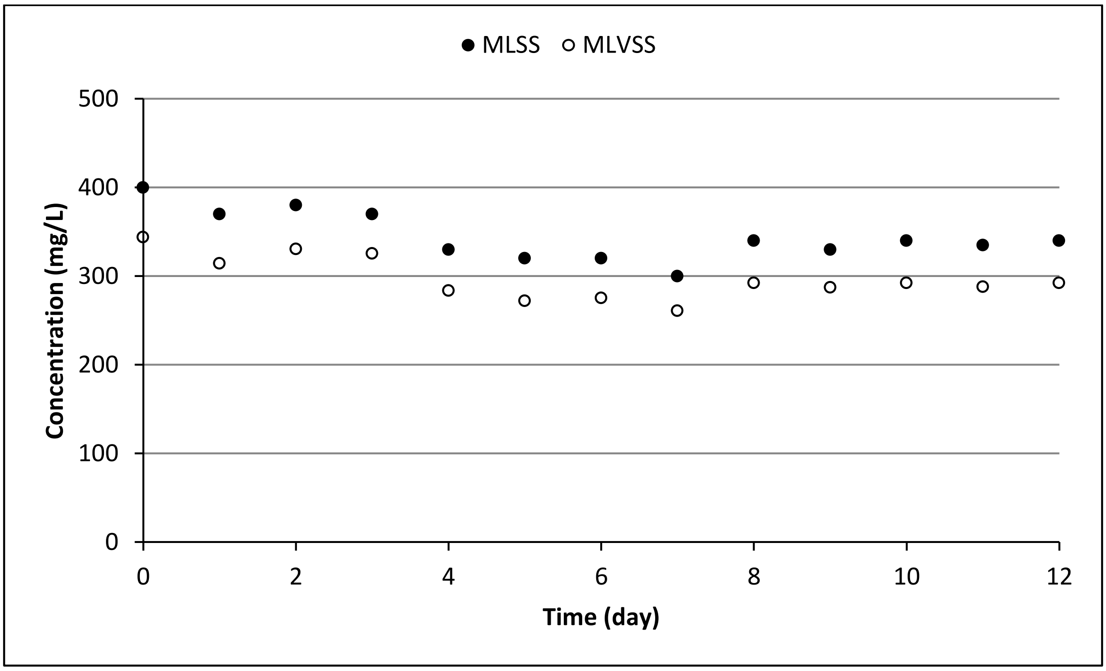


Figure A.6 : MLSS and MLVSS results for sMBR operated at SRT = 0.5 d treating Domestic Wastewater

APPENDIX B

B.1 COD profiles for sets run with Peptone Mixture:

a) SRT = 2.0 d and HRT = 8 h

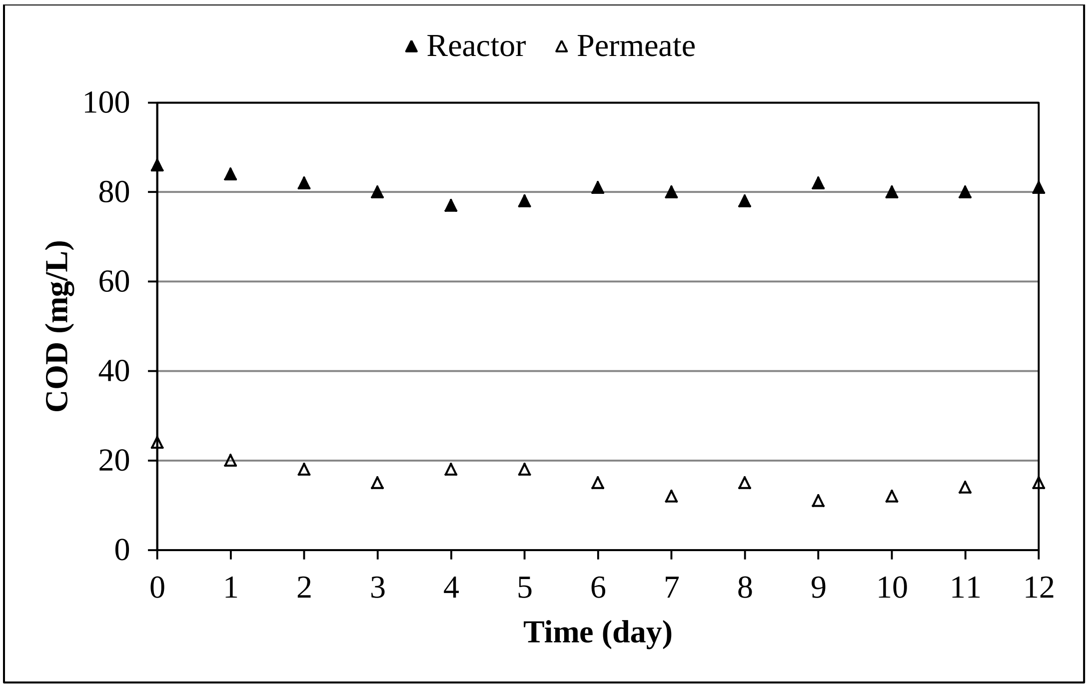


Figure B.1 : COD profiles for sMBR operated at SRT = 2.0 d treating Peptone Mixture

b) SRT = 1.0 d and HRT = 8 h

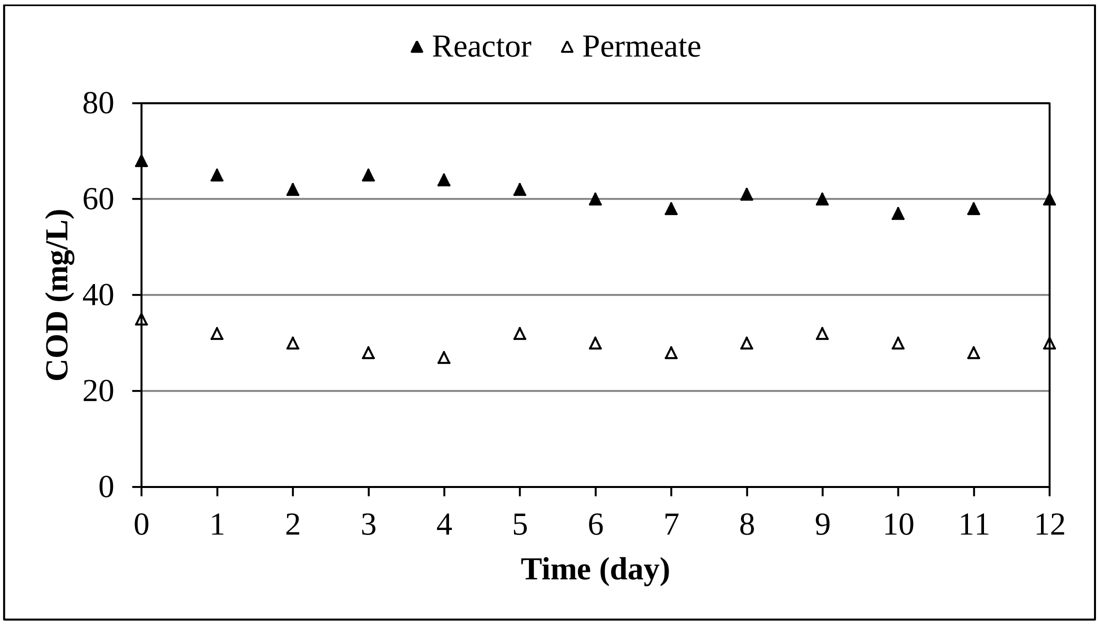


Figure B.2 : COD profiles for sMBR operated at SRT = 1.0 d treating Peptone Mixture

c) SRT = 0.5 d and HRT = 8 h

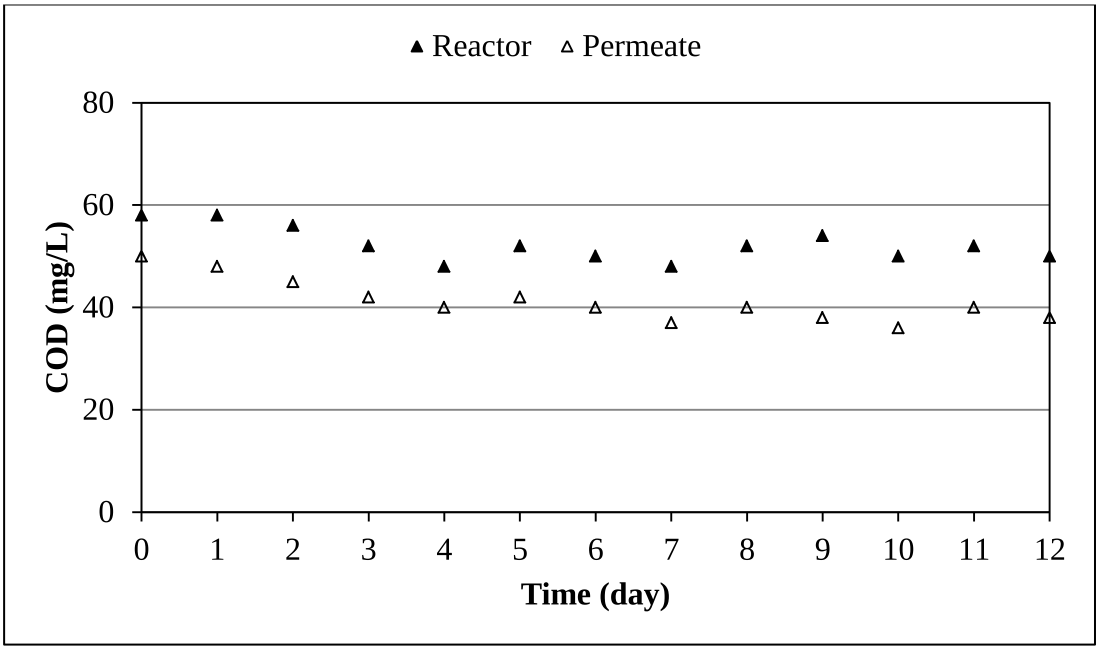


Figure B.3 : COD profiles for sMBR operated at SRT = 0.5 d treating Peptone Mixture

B.2 COD profiles for sets run with Domestic Wastewater:

a) SRT = 2.0 d and HRT = 8 h

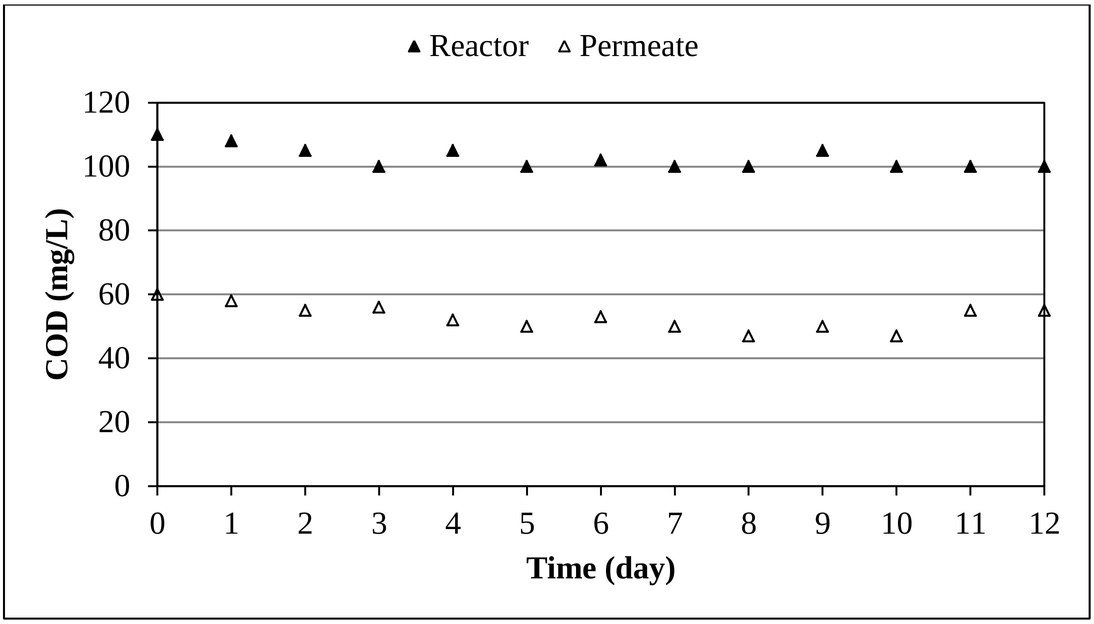


Figure B.4 : COD profiles for sMBR operated at SRT = 2.0 d treating Domestic Wastewater

b) SRT = 1.0 d and HRT = 8 h

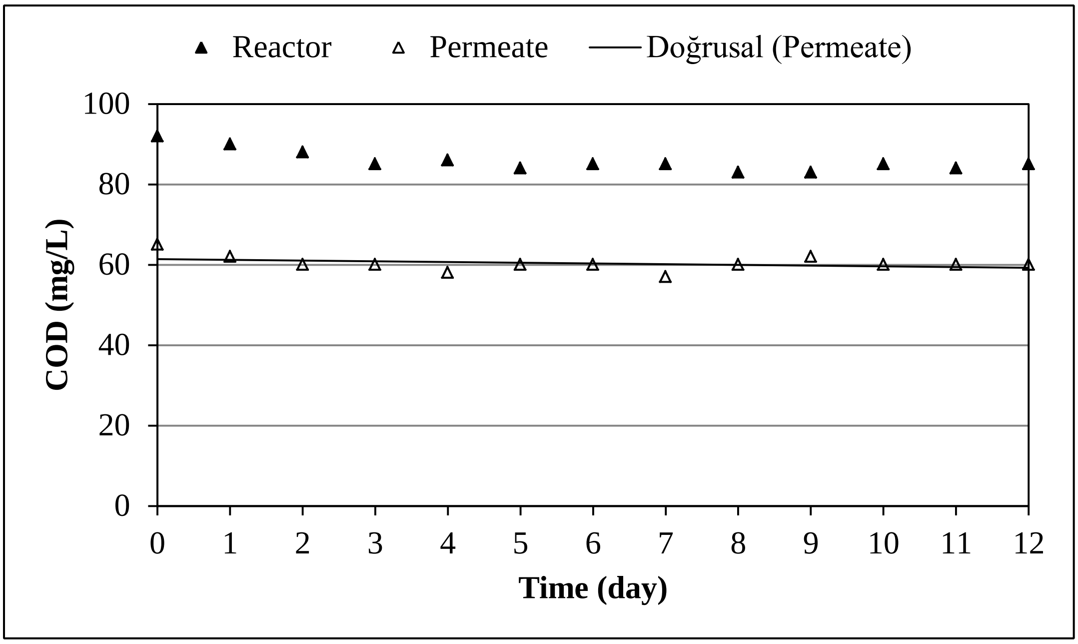


Figure B.5 : COD profiles for sMBR operated at SRT = 1.0 d treating Domestic Wastewater

c) SRT = 0.5 d and HRT = 8 h

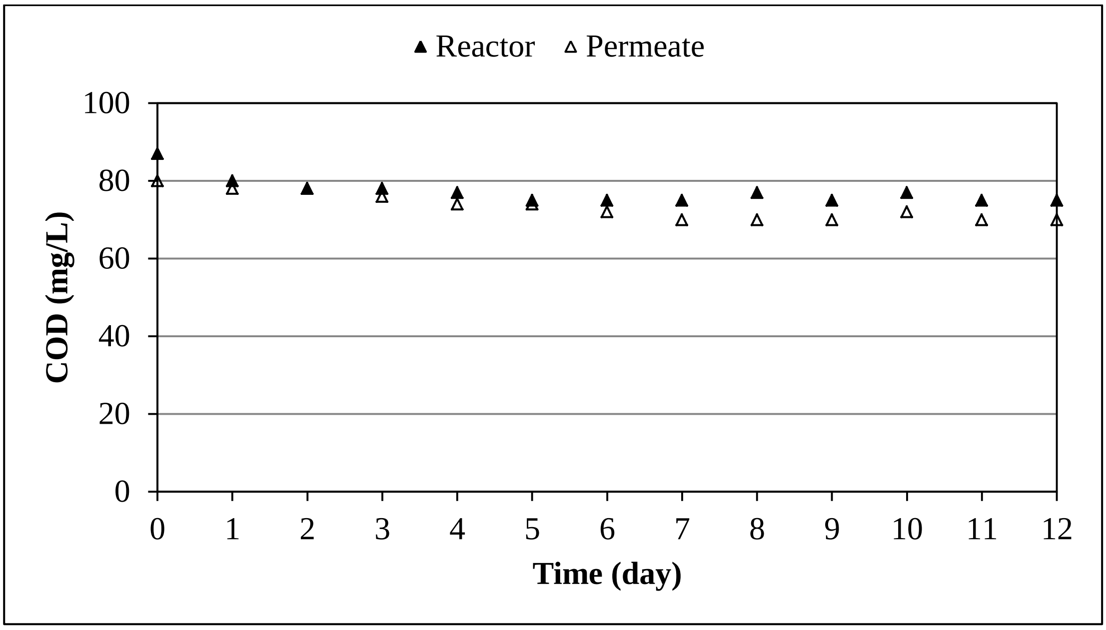


Figure B.6 : COD profiles for sMBR operated at SRT = 0.5 d treating Domestic Wastewater

APPENDIX C

C.1 OUR profiles for sets run with Peptone Mixture:

a) SRT = 1.0 d and HRT = 8 h

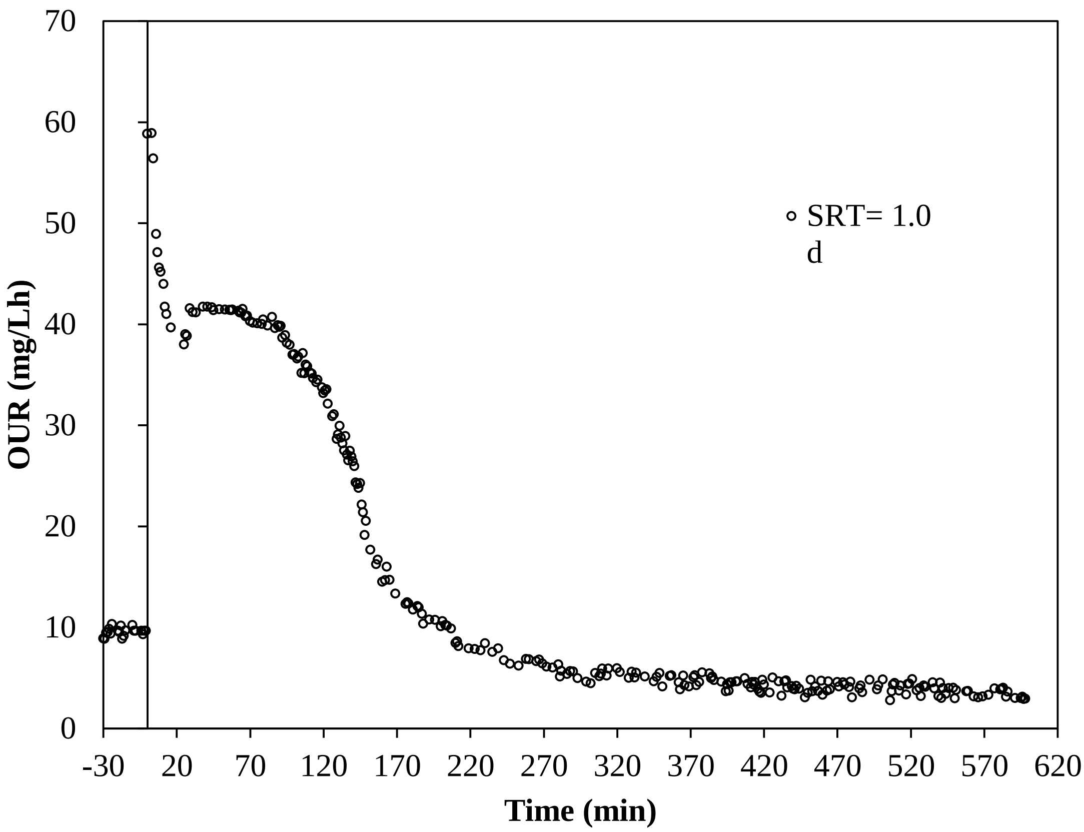


Figure C.1 : OUR profiles for sMBR operated at SRT = 1 d treating Peptone Mixture

b) SRT = 0.5 d and HRT = 8 h

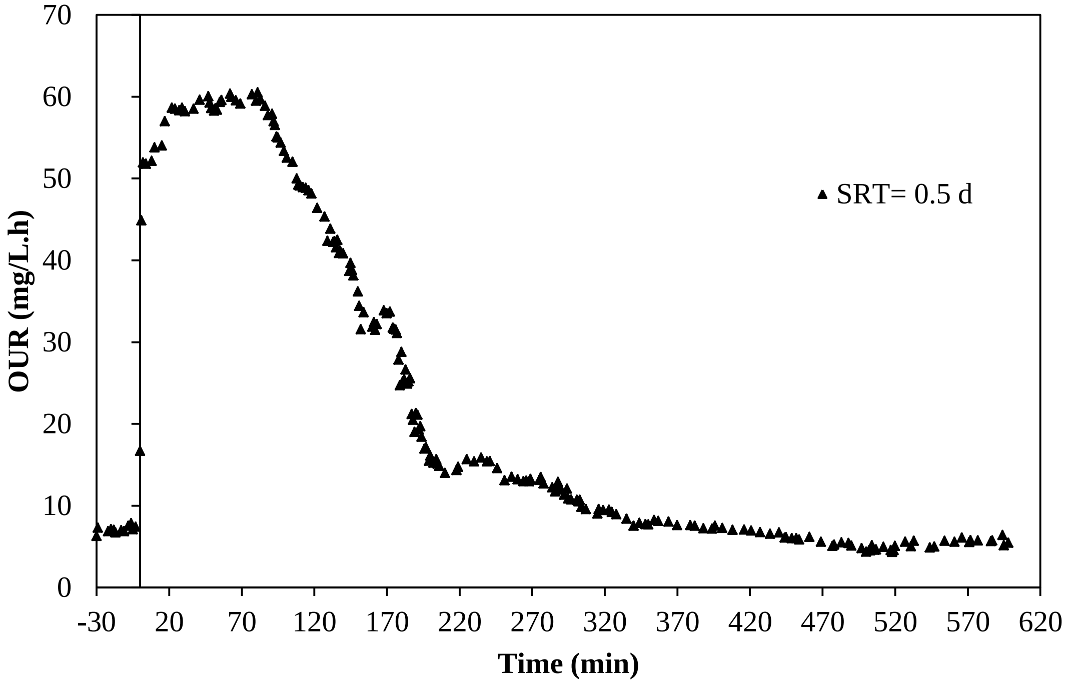


Figure C.2 : OUR profiles for sMBR operated at SRT = 0.5 d treating Peptone Mixture

C.2 OUR profiles for sets run with Domestic Wastewater:

a) SRT = 2.0 d and HRT = 8 h

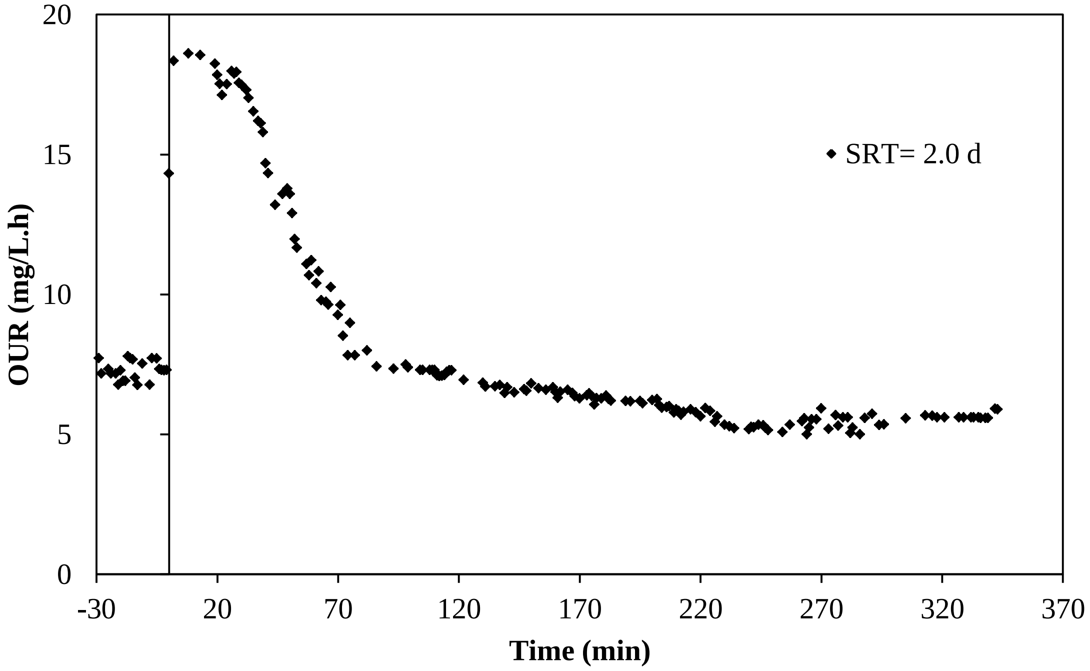


Figure C.3 : OUR profiles for sMBR operated at SRT = 2.0 d treating Domestic Wastewater

b) SRT = 1.0 d and HRT = 8 h

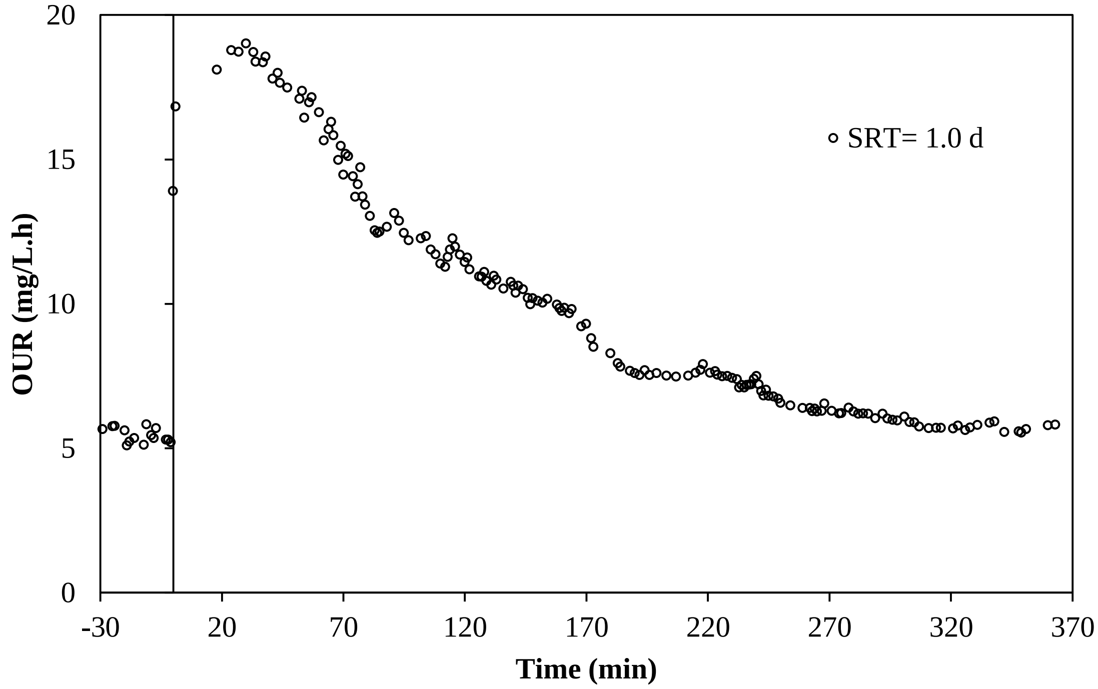


Figure C.4 : OUR profiles for sMBR operated at SRT = 1.0 d treating Domestic Wastewater

c) SRT = 0.5 d and HRT = 8 h

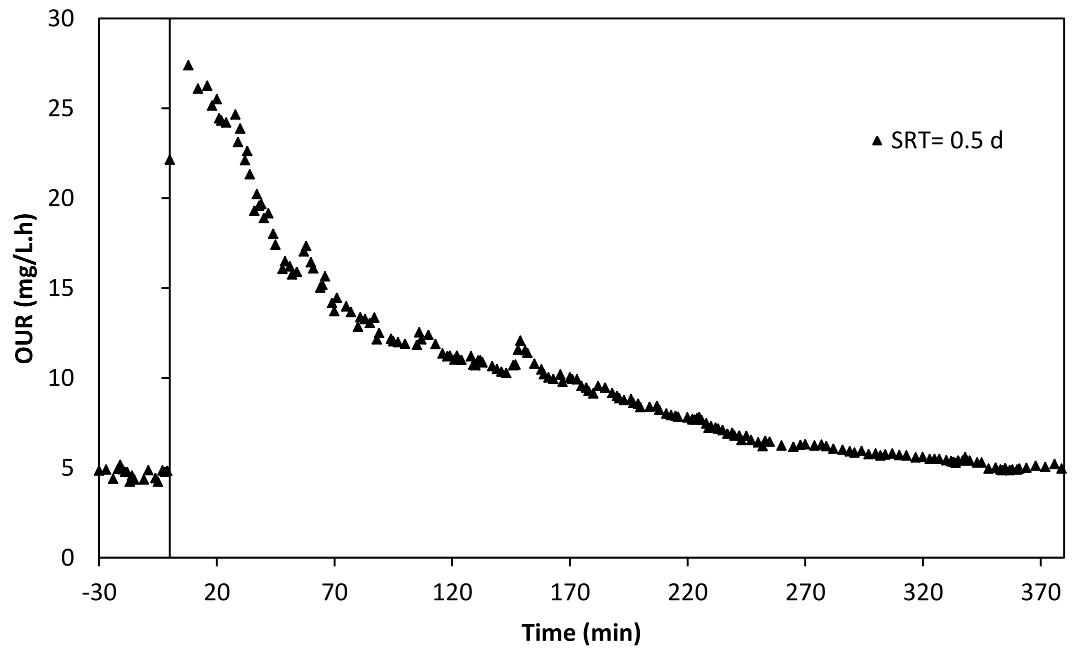


Figure C.5 : OUR profiles for sMBR operated at SRT = 0.5 d treating Domestic Wastewater

CURRICULUM VITAE

Name Surname:	**Cansın Razbonyalı**
Place and Date of Birth:	**İzmir 1989**
Address:	**Mecidiyeköy /İSTANBUL**
E-Mail:	**crazbonyali@gmail.com**
B.Sc.:	**Istanbul Technical University, Environmental Engineering**

Professional Experience and Rewards:

MASS Treatment Systems Construction Industry and Trading Co., Ltd.	3 months, continued- Project Engineer, 2013-now
TUBITAK 109Y261 Project	5 months- Evaluation of Carbon Removal Performance and Characteristics of Produced Sludge as a Fuel in Membrane Bioreactors at Restricted Operating Conditions (Low Hydraulic Retention Time and Low Sludge Retention Time), Scholar, 2011-2012
ENVIS Energy and Environmental Systems Research & Development Ltd.	10 months- Project Implementation / Consulting, Project Assistant, 2011-2012
Optimus Human Resources	3 months- Human Resources -Assistant, 2011
TUBITAK	1 month- Environment Institute, Solid and Hazardous Waste Laboratory - Laboratory Internship, 2009

TUBITAK	1 month- Environment Institute, Business Internship, 2009
Istanbul Technical University	1 month- Environmental Laboratory – Laboratory Internship, 2008
T.C. Maltepe Uni., Press and Public Relations Department	3 months- Assistant of Public Relations Coordinator, 2007

List of Publications and Patents:

PUBLICATIONS/PRESENTATIONS ON THE THESIS