ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

INVESTIGATION OF SLUDGE REDUCTION MECHANISM IN OSA PROCESS BY RESPIROMETRIC ANALYSIS

M.Sc. THESIS

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Department of Environmental Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

OSA PROSESİ İLE ÇAMUR AZALTMA MEKANİZMASININ RESPİROMETRİK ANALİZLERLE İNCELENMESİ

YÜKSEK LİSANS TEZİ

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To my mother and father with endless supports,

FOREWORD

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ABBREVIATIONS

ADP	**:** Adenosine Diphosphate
ASM1	**:**Activated Sludge Model 1
ASP	**:** Activated Sludge Process
ATP	**:** Adenosine Triphosphate
COD	**:** Chemical Oxygen Demand
e-CFR	**:** The Electronic Code of Federal Regulations
F/M	**:** Food to Microorganism Ratio
HRT	**:** Hydraulic Retention Time
IAWPRC	**:** International Association on Water Pollution Research and Control
IAWQ	**:** International Association on Water Quality
MBR	**:** Membrane Bioreactor
MLSS	**:** Mixed Liquor Suspended Solids
MLVSS	**:** Mixed Liquor Volatile Suspended Solids
ORP	**:** Oxidation Reduction Potential
OSA	**:** Oxic-Settling-Anoxic
OUR	**:** Oxygen Uptake Rate
SBR	**:** Sequencing Batch Reactor
SCOD	**:** Soluble Chemical Oxygen Demand
SRT	**:** Sludge Retention Time
SS	**:** Suspended Solids
SVI	**:** Sludge Volume Index
THMs	**:** Trihalomethanes
TKN	**:** Total Kjeldahl Nitrogen
TOC	**:** Total Organic Carbon
TS	**:** Total Solids
TVS	**:** Total Volatile Solids
VSS	**:** Volatile Suspended Solids
WWTPs	**:** Wastewater Treatment Plants

LIST OF SYMBOLS

b_H	: Endogenous decay rate for X_H
C_I	: Total inert COD
C_S	: Total biodegradable COD
C_{SI}	: Initial amount of biodegradable COD
C_T	: Total influent COD
f_{ES}	: Fraction of biomass converted to S_P
f_{EX}	: Fraction of biomass converted to X_P
i_{XB}	: Nitrogen fraction in biomass
K_S	: Half saturation constant for growth of X_H
k_h	: Maximum hydrolysis rate for S_{HI}
k_{hx}	: Maximum hydrolysis rate for X_{HI}
K_{OH}	: Heterotrophic half saturation coefficient for oxygen
K_X	: Hydrolysis half saturation constant for S_{SI}
K_{XX}	: Hydrolysis half saturation constant for X_{SI}
P_i	: Inorganic phosphate
S_0	: Initial subsrate concentration
S_{Alk}	: Alkalinity of the wastewater
S_H	: Rapidly hydrolyzable COD
S_{HI}	: Initial amount of readily hydrolyzable COD
S_I	: Soluble inert COD
S_{NH}	: Ammonia and ammonium
S_{NO}	: Nitrite and nitrate
S_P	: Soluble microbial products
S_S	: Readily biodegradable COD
S_{SI}	: Initial amount of readily biodegradable COD
X_0	: Initial biomass concentration
X_A	: Nitrifying organisms
X_H	: Heterotrophic biomass
X_{HI}	: Initial active biomass
X_I	: Particulate inert COD
X_P	: Particulate microbial products
X_S	: Slowly hydrolyzable COD
X_{SI}	: Initial amount of hydrolyzable COD
Y_H	: Yield coefficient of X_H
$\hat{\mu}_H$	: Maximum growth rate for X_H

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INVESTIGATION OF SLUDGE REDUCTION MECHANISM IN OSA PROCESS BY RESPIROMETRIC ANALYSIS

SUMMARY

Activated sludge is the most widely used biological wastewater treatment process for the degradation of organic matter and removal of nutrients from both domestic and industrial wastewaters. However, these processes lead to excess sludge production and restricted regulations cause the increase of sludge generation. All these reasons, the wastewater treatment has become to be difficult more and more. The treatment of excess sludge can account for up to 60% of a plant’s total operating cost and also adds to the capital cost of the facility (Wei ve diğ., 2003). Besides, restricted regulations have been increased about diposing of excess sludge to the landfills and the capacity of landfills is insufficient day by day. Therefore, the reduction of sludge generation in the activated sludge system could be a rational strategy for the sludge problem.

One of the most widely used sludge minimization strategies is OSA (oxic/settling/anaerobic) process which consists of an integrated anaerobic reactor to the activated system and the interchange unit. Basically, OSA process comprises of certain amount of sludge interchange between aerobic and anaerobic phases. 60% of sludge reduction have reported in full-scale operated and lab-scale operated systems with OSA system.

Several approaches have been exposed from studies which try to understand the mechanisms of sludge minimization in OSA process. Therefore, currently these approaches do not generate an agreement. According to the literature, OSA sludge reduction system is thought to be achieved for these reasons; a) most of microbial population in the system is slow growers and consequently the system has low sludge yields, b) the energy uncoupling theory, and c) acceleration of sludge decay in the sludge holding tank.

In this study, a control reactor was operated in a sequencing batch reactor and a reactor was operated with OSA process to determine sludge reduction. In order to understand the sludge minimization mechanism, the data of microbial activity were evaluated with determination of oxygen uptake rates. Profile of oxygen uptake rate was observed for both control reactor and reactor operated as OSA process. After obtained results, profiles of two systems were compared to determine the differences and the effects of anaerobic reactor to the system.

Experimental study was carried out by two parallel systems which were fed with synthetic wastewater. The sequencing batch reactors were used for operation flexibility and monitoring of dynamic behavior in interchange.

In this study, the OSA (oxic/settling/anaerobic) system had consisted of an oxic completely mixed tank, followed by a continuous anaerobic bioreactor which had been connected with oxic tank. Besides, there was a control reactor which did not

have an interchange line is used to determine the sludge minimization. This control reactor had been carried out in same conditions with OSA reactor. Hence, there was a regular sludge disposal which had been sent to the anaerobic digester. The experimental studies were performed by oxygen uptake rate (OUR) experiments with stable sludge having same food/microorganism concentration. These experiments had been performed and compared for both control and OSA systems. Respirometric experiments were conducted in order to evaluate endogenous oxygen uptake rate level of biomass. Firstly, respirometric tests were performed for control and SBRs to observe the differences between them. Thereafter, respirometric tests were carried out to understand the role of anaerobic reactor in the system. It had been observed whether anaerobic reactor was biomass or substrate source for SBRs.

During the experimental studies, solids (suspended solids, volatile suspended solids and total solids), chemical oxygen demand (COD), ammonia, nitrate, nitrite and phosphorus parameters had been monitored to determine daily system efficiency as well as oxygen uptake rates.

The AQUASIM software package (Reichert, 1998) was used for simulations and parameter estimation using OUR data for determination of kinetic and stoichiometric coefficients. The ASM1 (Henze M. et al., 2000) model was used for respirometric data interpretation.

Based on experimental results, steady state conditions were observed in each system (control and OSA) and 60% of sludge reduction was observed in OSA system. This is concluded as reduction of sludge production in the wastewater treatment is possible by application of OSA process to solve sludge associated problems. The obtained result verifys the literature studies. In addition to, microorganism activity in the sludge was observed with the achieved respirometric analysis.

It is also observed that higher nitrogen and phosphorus concentration in the effluent of OSA system. During anaerobic exposure, soluble chemical oxygen demand (COD), nitrogen, and phosphorus are released which is also support literature findings on OSA process.

Using experimental data obtained from respirometric experiments, parameter estimation study revealed that consistent values of kinetic and stoichiometric coefficients with literature for control system were obtained: lower maximum growth rate, slower hydrolysis rate and lower microbial activity for OSA sludge. This could show us that insertion of an anaerobic sludge tank in an OSA system may affect the biomass activity and bacteria population and slow growers may become the dominant species in an OSA system.

Respirometric experiment with OSA sludge and peptone as C source with F/M ratio of the operating system revealed that the activity of OSA sludge was found as 75 % which indicates that the activity in OSA sludge is almost same with the activity in sludge operated with SRT 10 d given in the literature. COD removal was achieved around 89% in this experiment.

Respirometric experiment with control sludge where peptone was used as C source, the activity of control sludge was found as 71% which shows that the activity in control sludge is almost same with the activity in sludge operated with SRT 10 d given in the literature. COD removal was achieved around 78.7%. Kinetic and stoichiometric parameter values were remained almost the same as the literature study.

Respirometric experiment with OSA sludge and anaerobic sludge from bioreactor with F/M ratio of actual system showed that the activity of OSA sludge was reduced when the anaerobic sludge was used as C source. Nevertheles, it can be said that the interchange sludge was consumed as a substrate by microorganisms. COD removal was achieved around 61.5% in this experiment.

From the parameter estimation study of respirometric experiment with anaerobic sludge with pepton as C source exhibited that interchange reactor contains active biomass but with a lower activity (47%). This is concluded that, because of this, biomass activity in OSA reactor appears higher (75%) compared to control system (71%). COD removal was achieved around 90.2 %.

Finally, respirometric experiment had been carried out with OSA sludge. For this experiment, peptone and anaerobic sludge had been added at the same time to the OSA sludge. The respirometric results and model were fitted each other reasonably. According to these results, the activity of OSA sludge was found as 71% which indicates that the activity in OSA sludge is almost same with the activity in sludge operated with SRT 10 d given in the literature. COD removal was achieved around 90.2 % in this experiment. Lastly, it can be said that the activity of sludge and the COD removal efficiency are same with respirometric experiment with OSA sludge and interchange sludge was consumed as substrate.

From the findings of this study, it is assumed that interchange sludge consist of X_H, X_P, S_P, S_H and X_S. The OUR profiles and parameter estimation study showed that X_H could be converted into X_S under stress conditions where external C is not available and than consumed by OSA sludge (*Run-6: OSA sludge + Interchange sludge only; no external C source*).

For better understanding of sludge reduction mechanism and microbial dynamics in OSA systems, it is recommended that dynamic modelling of OSA processes, supporting data with molecular analysis and monitoring gas production and gas composition in digester reactor should be investigated in further studies.

OSA PROSESİ İLE ÇAMUR AZALTMA MEKANİZMASININ RESPİROMETRİK ANALİZZLERLE İNCELENMESİ

ÖZET

Biyolojik arıtma prosesleri, evsel ve endüstriyel atıksuların arıtılmasında yaygın olarak kullanılan, ancak yüksek miktarda çamur üreten proseslerdir. Sıkılaşan çıkış standartlarını sağlamak üzere arıtma proseslerinde yapılan yeni düzenlemeler oluşan çamur miktarının daha da artmasına ve çamur özelliklerinden dolayı arıtımının zorlaşmasına sebep olmaktadır. Çamur arıtımı ve uzaklaştırılması, bir atıksu arıtma tesisinde işletme giderlerinin yaklaşık %60'ını oluşturmaktadır (Wei ve diğ., 2003). Bunun yanısıra, bir yandan arıtılmış çamurların katı atık sahalarında uzaklaştırılması ile ilgili sınırlamalar artmakta, diğer yandan ise depo sahaları için yer bulma sorunları giderek büyümektedir. Dolayısıyla, gelecek açısından baktığımızda, oluşacak çamur miktarının azaltılması önemli bir konu olarak karşımıza çıkmaktadır.

Çamur azaltma stratejilerinden birisi olan ve son yıllarda kullanımı yaygınlaşan OSA (havalandırma/çökelme/havasız) prosesi, bir aktif çamur sistemine entegre edilmiş yan akım anaerobik reaktörden ve çevrim ünitesinden meydana gelmektedir. Temel olarak proses aerobik ve anaerobik fazlar arasında belirli bir miktar çamurun karşılıklı olarak çevriminden/gidiş-gelişinden oluşmaktadır. Bu şekilde işletilen tam ölçekli ve laboratuvar ölçekli sistemlerde çamur miktarlarında %60, hatta daha yüksek, azalma rapor edilmektedir.

OSA prosesinde çamur azalmasını sağlayan mekanizma veya mekanizmaları anlamak üzere yapılan çalışmalardan çeşitli yaklaşımlar ortaya konmuştur. Ancak, halen bu yaklaşımlar ile ilgili bir görüş birliği oluşmamıştır. Literatürde sunulan hipotezlere göre OSA sisteminde çamur azalması a) sistemde bulunan mikrobiyal topluluğun çoğunun yavaş çoğalan organizmalarından oluştuğu ve bu nedenle sistemin düşük dönüşüm oranlarına sahip olduğu, b) sistemdeki mikrobiyal topluluğun metabolizma faaliyetleri sırasında oluşan ve kullanılan enerjinin anabolik ve katabolik reaksiyonlar arasında paylaşımının farklılığı, c) anaerobik (havasız) tankta çamur ölüm hızının normalin üstünde olması ile açıklanmaya çalışılmıştır.

Bu çalışma kapsamında, ardışık kesikli reaktör düzeninde işletilen bir kontrol reaktörü ile OSA prosesi düzeninde çalıştırılan bir reaktörde çamur azalması belirlenmiş ve çamur azaltma mekanizmasının anlaşılabilmesi için oksijen tüketim hızlarının belirlenmesi yoluyla mikrobiyal aktivite ile ilgili veri elde edilmiştir.

Deneysel çalışma, sistemde sentetik atıksu kullanılarak paralel iki sistem ile yürütülmüştür. Deneysel düzenekte işletme esnekliği ve çevrim içindeki dinamik davranışın izlenebilme özelliği nedeniyle ardışık kesikli reaktörler kullanılmıştır.

Deneysel çalışmada, aerobik (havalı) fazdan oluşacak bir işletme düzeni ile işletilen bir ardışık kesikli reaktör ve buna bağlı havasız işletilen bir sürekli biyoreaktörden oluşan bir OSA (havalandırma/çökelme/anaerobik) sistemi işletilmiştir. Ayrıca, çamur azalmasının belirlemek üzere aynı koşullarda çalışan ancak OSA sisteminde

olduğu gibi gidiş-gelişli akım devri olmadan klasik aktif çamur sistemi düzeninde işletilen, dolayısıyla düzenli çamur atılan, atılan çamurun da bir anaerobik çürütücüye verildiği bir kontrol sistemi işletilmiştir. Deneysel çalışma, kararlı dengeye gelmiş reaktörlerden alınan çamurun aynı besi maddesi/mikroorganizma konsantrasyonu (F/M) oranında gerçekleştirilen oksijen tüketim hızı deneylerinden oluşmaktadır. Bu deneyler hem kontrol hem de OSA sistemi için gerçekleştirilmiştir ve sonuçlar karşılaştırılmıştır. Buna ilave olarak, OSA sisteminin ardışık kesikli reaktöründen alınan çamura anaerobik biyoreaktör çamurunun belirlenmesi durumu, yine aynı çamura hem giriş atıksuyu hem de anaerobik biyoreaktör çamurunun birlikte beslenmesi durumlarında oksijen tüketim hızları ölçülmüştür. Son olarak, anaerobik biyoreaktöründen alınan çamurlara ilave edilen atıksu ile bu çamurun davranışı ve aktivitesi belirlenmeye çalışılmıştır.

Deneysel çalışma süresince, oksijen tüketim hızlarının yanısıra günlük sistem verimini belirlemek üzere katı madde (askıda katı madde, uçucu askıda katı madde ve toplam katı madde), kimyasal oksijen ihtiyacı (KOİ), amonyak, nitrat, nitrit ve fosfor parametreleri izlenmiştir.

Elde edilen oksijen tüketim hızı verileri, seçilen aktif çamur modeli No1 kullanılarak kinetik ve stokiyometrik katsayılar belirlenmiştir. Modelleme çalışmasında Aquasim 2.0 programı kullanılmıştır.

Bu sonuçlar doğrultusunda, kararlı halher iki sistem için de (kontrol ve OSA) elde edilmiştir ve OSA sisteminde %60 oranında çamur azalması gözlemlenmiştir. Atıksu arıtımında çamur üretiminin azaltılması, OSA prosesin uygulanarak çamur ile alakalı problemlerin çözümünü mümkün kılmaktadır. Elde edilen sonuç literatür çalışmalarını doğrulamaktadır. Buna ek olarak, yapılan her bir respirometrik analizlerden çamurdaki mikroorganizma aktivitesi gözlemlenmiştir.

Ayrıca, OSA sisteminin çıkış suyunda yüksek azot ve fosfor konsantrasyonları gözlemlenmiştir. Anaerobik koşullar boyunca , çözünmüş kimyasal oksijen ihtiyacı (KOİ), azot, ve fosfor salınımı, literatürdeki OSA proses ile ilgili bulguları desteklemektedir.

Respirometrik deneylerden elde edilen deneysel verilerin kullanımı, kontrol sistem için literatürden alınan değerler ile değişken tahmin çalışmasınden elde edilen tutarlı kinetik ve stokiyometrik katsayı değerleri şunları elde etmiştir: OSA çamuru için düşük maksimum büyüme hızı, yavaş hidroliz hızı ve düşük mikrobiyal aktivite.

Respirometrik deney, OSA çamuru ve karbon kaynağı olarak sistem ile aynı F/M oranında pepton eklenmesi ile yürütülmüştür. Bu uygulamaya göre, OSA çamurundaki biyokütle aktivitesi %75 olarak bulundu ve bu sonuç ile kontrol çamurunun aktivitesi literatürde verilen ve 10 gün çamur yaşına sahip bir sistemin biyokütle aktivitesiyle yaklaşık olarak aynı olduğu gözlemlenmiştir. Son olarak, bu deneyden %89 KOİ giderimi elde edilmiştir.

Respirometrik deney, kontrol çamuru ve karbon kaynağı olarak sistem ile aynı F/M oranında pepton eklenmesi ile yürütülmüştür. Bu uygulamaya göre, kontrol çamurundaki aktivite %71 olarak bulundu ve bu sonuç ile kontrol çamurunun biyokütle aktivitesi literatürde verilen ve 10 gün çamur yaşına sahip bir sistemin biyokütle aktivitesi ile yaklaşık olarak aynı olduğu gözlemlenmiştir. Bu deneyden %78.7 KOİ giderimi elde edilmiştir. Kinetik ve stokiyometrik parametre değerleri literatür çalışmalarıyla yaklaşık olarak aynı bulunmuştur.

Respirometrik deney, OSA çamuruna belirli F/M oranını sağlayacak şekilde anaerobik çamur eklenerek gerçekleştirilmiştir. Bu uygulamaya göre, OSA çamurundaki biyokütle aktivitesi %56 olarak bulunmuş ve bu sonuç ile OSA çamurun biyokütle aktivitesinin, karbon kaynağı olarak anaerobik çamurun kullanılmasıyla düşmekte olduğu gözlemlenmiştir. Elde edilen verilere göre, anaerobik çamurun mikroorganizmalar tarafından besin kaynağı olarak tüketildiği söylenebilir. Bu deneyden %61.5 KOİ giderimi elde edilmiştir.

Anaerobik çamur ile karbon kaynağı olarak sistem ile aynı F/M oranında pepton eklenmesi ile yürütülmüş respirometrik deneyden elde edilen değişken tahmin çalışması göstermektedir ki; anaerobik sistem düşük aktivite oranına (%47) sahip aktif biyokütle içermektedir. Bu sonuçlara göre, OSA çamurunun biyokütle aktivitesi (%75) kontrol çamurundan (%71) daha yüksektir. Bu deneyden %90.2 KOİ giderimi elde edilmiştir.

Son olarak, respirometrik deney OSA çamuru ile yürütülmüştür. Bu deney, OSA çamuruna aynı zamanda belirli F/M oranını sağlayacak şekilde pepton ve anaerobik çamur eklenerek gerçekleştirilmiştir. Deneyden elde edilen respirometrik sonuçlar model ile uyum sağlamıştır. Bu uygulamaya göre, OSA çamurundaki aktivite %71 olarak bulunmuş ve bu sonuç ile kontrol çamurunun aktivitesi literatürde verilen ve 10 gün çamur yaşına sahip bir sistemin biyokütle aktivitesiyle yaklaşık olarak aynı olduğu gözlemlenmiştir. Bu deneyden %90.2 KOİ giderimi elde edilmiştir. Elde edilen sonuçlara göre sadece OSA çamuru ile gerçekleştirilen respirometrik deney ile aynı KOİ giderimine sahip oldukları ve buna bağlı olarak anaerobik çamurun besin kaynağı olarak tüketildiği söylenebilir.

Çalışmadan elde edilen bulgulara göre, anaerobik çamurun X_H, X_P, S_P, S_H ve X_S içerdiği kabul edilmektedir. Oksijen tüketim hız profili ve değişken tahmin çalışması göstermektedir ki, dışarıdan karbonun eklenmediği ve bu yüzden OSA çamuru tarafından tüketilmesiyle (Set – 6: OSA çamuru + Anaerobik çamur sadece; dışarıdan extra karbon kaynağı yok) oluşan stres koşullarında X_H X_S'e dönüşebilmektedir.

OSA sisteminde çamur azaltma mekanizmasını ve mikrobiyal dinamikleri daha iyi anlamak adına, OSA proseslerin dinamik modellenmesi, bu modellemeyi desteklemek için moleküler analizlerin yapılması ve anaerobik sistemde oluşan gaz üretimi ve gaz bileşiminin takip edilmesi gelecek çalışmalar için tavsiye edilmektedir.

1. INTRODUCTION

The activated sludge system has been the most widely used in biological wastewater treatment plants to degrade the organic matter and remove the nutrients from both domestic and industrial wastewaters. The conventional activated sludge process consists of primary sedimentation, biological treatment in an aeration basin, secondary sedimentation, sludge recycling and sludge wastage. Figure 1.1 shows the conventional activated sludge process. The activated sludge process has become the most current process because of its facile operation mechanism and high efficiency of the treatment. Besides, the activated sludge processes has been becoming the excess sludge producing system, which is undesirable outcome from the wastewater treatment plants (WWTPs). Treatment and disposal of excess sludge accounts for about half, even up to 60%, of the total cost of wastewater treatment (Wei et al., 2003).

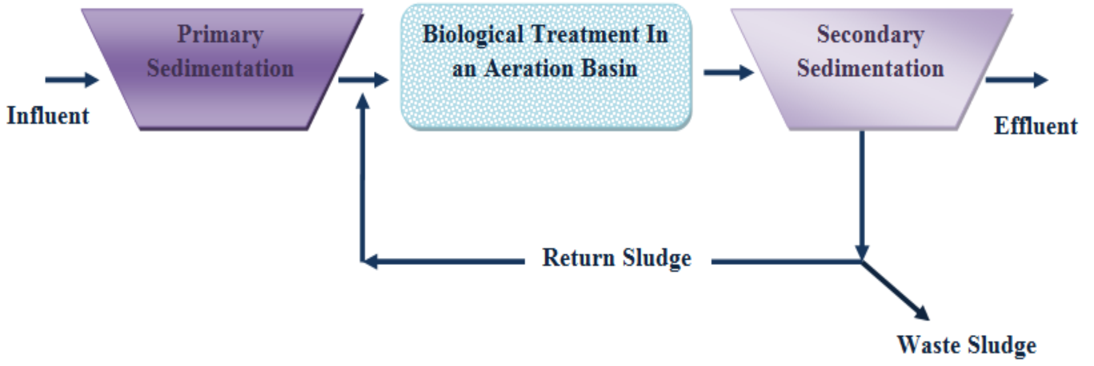

Figure 1.1 : The conventional activated sludge process.

1.1 Problem Statement

The produced excess sludge is the stringent phenomena both to treat unwanted components that remain in from wastewater treatment and to dispose to the environment. The treatment of excess sludge consists of a combination of digestion, chemical treatment, dewatering, and thickening which are hardly operated processes.

Even though the stabilization of sludge is effectively carried out, the impetuses appear to provide the required disposal restrictions.

The main implementation of diposing of sludge comes from WWTPs is the landfilling. 50 – 75% of applied method is landfilling of the excess sludge that is supposed to be treated appropriately according to the regulations. The remaining 25 – 35% of methods is agricultural usage, thermal incineration and recovery to use for other purposes. Thermal incineration is not preferred due to the released combustion emissions and the high cost operation of this system. The sludge transported to the thermal incineration plant is supposed to have advanced calorific value and be dewatered. Generally, produced excess sludge does not have high quality to be incinerated and the applying thermal incineration is not efficient costly (Url-2).

On the other hand, agricultural disposal requires high removal of toxic compounds especially heavy metals from the excess sludge. Due to the environmental issues and human health, this method is not preferable also.

The most used method is landfilling for diposing the excess sludge, but there are many stringent restrictions. Globally, “Electronic Code of Federal Regulations - Title 40: Protection of Environment Part : 503 Standards for The Use or Disposal of Sewage Sludge, (e-CFR) [e-CFR Data is current as of March 20, 2007]” is applied for disposing excess sludge (Url-1). However, in Turkey “Solid Waste Control Regulation, dated 2006, No. 26047” is established within the process of adaptation to the European Union (Url-3). In Europe, disposing to the land is not a solution for this problem due to the limited capacity of landfills and the lack of spaces. In view of these disposal impetuses, reduction of excess sludge has been investigated and focused recently.

1.2 Objective

As mentioned above, many difficulties appear to dispose the excess sludge because of the fact that stringent restrictions, high operation costs and capacity of the landfills. The minimization strategies have been investigated and improved to obtain less than usual amount of sludge from WWTPs with conventional activated sludge processes. The investigated techniques have been supposed to carry out by providing the required effluent quality and settling properties. Additionally, these techniques have been performed by considering in terms of cost.

Minimization of sludge production in the wastewater treatment is better than the post-treatment of the sludge produced in order to solve sludge-associated problems (Yu L. and Joo-Hwa T., 2001). Microbial metabolism releases a portion of the carbon from organic subsrates in respiratory process and digests a portion of biomass. Wastewater processes are supposed to be engineered such that subsrate is diverted from assimilation for the biosynthesis to fuel exothermic, non-growth activities in order to reduce the production of biomass (Low E. W. and Chase H. A., 1998).

The strategies vary with selecting of the specific operation conditions (e.g., high SRT, predation, temperature) or using destruction techniques on the mixed liquor produced (oxidation, thermal, mechanical treatments, enzymatic, etc.) (Etienne P. and Yu L., 2012). The destruction techniques based on these mechanisms, lysis-cryptic growth, uncoupling metabolism, maintenance metabolism and predation on bacteria (Low E. W. and Chase H. A., 1998).

In this study, it has been aimed to understand the minimization mechanism of the sludge production by performing oxic-settling-anaerobic (OSA) process. Respirometric experiments have been conducted in order to compare the response of conventional activated sludge and OSA processes in terms of microbial growth kinetics.

2. LITERATURE REVIEW

2.1 Technologies and Strategies for Sludge Reductionn

Different strategies were proposed and applied for effective minimization of the sludge production. Even as performing these strategies, effluent quality and settling properties are supposed to be almost matching as obtained in the activated sludge process.

In this section, the mechanisms of these strategies and effects on biomass have been focused. As seen in Figure 2.1, this section gives an overview of these strategies investigated and implemented to minimize the sludge production in conventional activated sludge process in order to seek a proper solution.

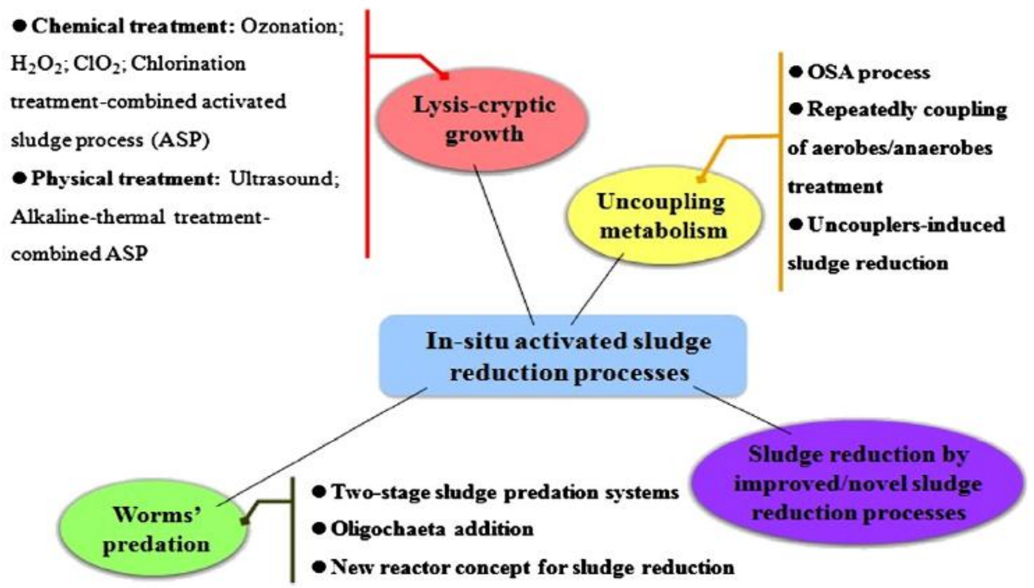

Figure 2.1 : Outline of in-situ activated sludge reduction strategies (Guo W.-Q. et al., 2013).

2.1.1 Lysis-cryptic growth

One of the methods of performing sludge reduction is by lysis-growth of microorganisms, i.e. microbial growth on cell lysates (Liu Y., 2003). The cell lysis releases cell contents into the medium, supplying an autochthonous subsrate that promotes to the organic loading in the system. This autochthonous subsrate is reutilized in microbial metabolism and a portion of carbon is released as a product of respiration resulting in total biomass minimization. “The biomass growth that occurs on autochthonous subsrate is hard to distinguish from the growth on original organic subsrate, and this growth is termed cryptic growth” (Devikarani M. R. and Thiruvenkatachari V., 2005).

There are two phases in lysis-cryptic growth, lysis and biodegradation. The lysis phase is rate-limiting step of lysis-cryptic growth. Therefore, total sludge reduction relates the increment of lysis efficiently. Several methods have been adopted so far to bring about cell disintegration, such as thermal, chemical treatment, advanced oxidation processes such as wet air oxidation using H_2O_2 and ozone, thermo-chemical treatment, combination of alkaline and ultrasonic treatment, freezing and thawing and biological hydrolysis with enzyme addition (Wei et al., 2003).

2.1.1.1 Ozonation

Ozonation is one of the ways to obtain cell lysis. Many investigations have been carried out about minimization of sludge production in the activated sludge process with ozonation. This system contains two phases, an ozonation phase and a biodegradation phase that are illustrated in Figure 2.2. A fraction of sludge is moved through the ozonation unit, in which a part of the sludge is solved due to disintegration of suspended solids, while the other part of the sludge is solved according to the oxidation of soluble organic matter. The solved sludge induces cryptic growth and recycles into the aeration tank (Devikarani M. R. and Thiruvenkatachari V., 2005).

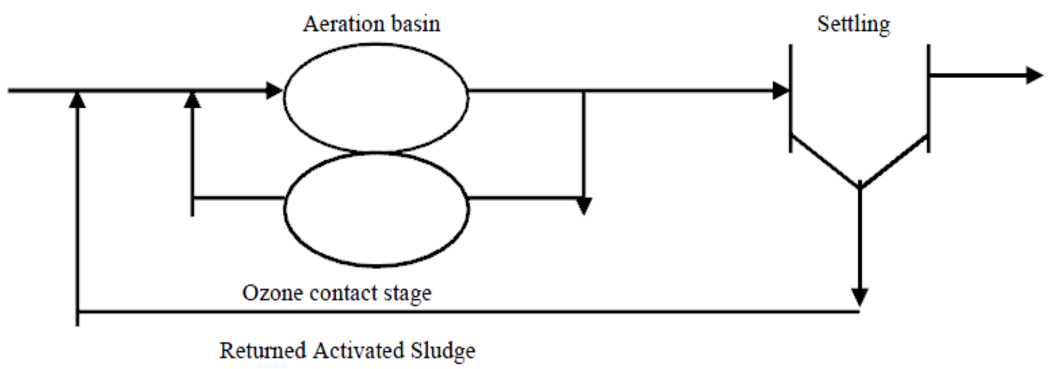

Figure 2.2 : Process flow sheet for the aerobic process with enhanced cell lysis by contacting excess biomass with ozone to form autochthonous subsrate (Devikarani M. R. and Thiruvenkatachari V., 2005).

Despite a sludge minimization of approximately 100% is reported, the integration of ozonation into the activated sludge process comprises a high capital and operating cost, by this way limiting its use (Devikarani M. R. and Thiruvenkatachari V., 2005). In addition to disadvantages, sludge reduction with ozonation caused total organic carbon (TOC) slight increase in the effluent and an investigation showed that the organic matter in the effluent through sludge ozonation was mostly comprised of proteins and sugars moieties, which might be unharmful for the environment. Chlorine was more used instead of ozone because the cost of chlorination is cheaper (Wei et al., 2003).

2.1.1.2 Chlorination

The chlorination activated sludge process is same to the ozonation activated sludge process, i.e., excess sludge is achieved to chlorination and the chlorinated sludge is returned to the aeration basin. In terms of disinfection practice, the cost of operation of chlorination is only 10% of that of ozonation operation. Accordin to the results, "The investigations show that treated the excess sludge at a chlorine dose of 0.066 g Cl_2/g mixed liquor suspended solid (MLSS) and the chlorinated liquor was then returned to the aeration tank" (Devikarani M. R. and Thiruvenkatachari V., 2005). It was observed that 65% of sludge minimization was ontained compared to the control system without chlorination (Devikarani M. R. and Thiruvenkatachari V., 2005).

The main disadvantages of chlorination-combined activated sludge process are the generation trihalomethanes (THMs), bad sludge settleability and significant raising of soluble chemical oxygen demand (SCOD) in the effluent (Wei et al., 2003).

2.1.1.3 Thermal treatment

Most biological wastewater treatment techniques are temperature sensitive, and thus raising process temperature is effective for minimization sludge production. Low temperature operation can lead to the increment of sludge generation, i.e. the sludge generation at 8 ^{0}C in the activated sludge process was raised by about 12-20% compared with that at 20 ^{0}C. The potential interpretation of higher sludge generation at low temperature is a distinct accumulation of cell protoplasm within flocs in the form of COD because the hydrolysis of the organisms is the reaction rate-controlling phase of the endogenous respiration. A side-stream membrane bioreactor (MBR) treating synthetic wastewater by Pseudomonas fluorescens, associated with a continuous sludge thermal treatment process, was operated for minimizing excess sludge generation. About 60% of sludge reduction was achieved when the returned sludge passed through a thermal treatment loop (90 ^{0}C for 3 h) (Wei et al., 2003).

There are number of disadvantages to thermal pretreatment methods that require to be thought:

- There are higher concentrations of refractory compounds that are hard to treat and are recycled to the major biological process in the dewatering supernatant;
- The supernatant also involves high concentrations of nutrients that will impose on the operation of the activated sludge system particularly in plants where nutrient treatment is significant (Riedel, 2009).

2.1.1.4 Alkaline-chemical treatment

Microbial cell lysis can be stabilized by thermal treatment associated with chemical removal process (alkaline or acidic). Sodium hydroxide was considered to be more powerful for obtaining cell lysis in thermal-alkaline hydrolysis. In this method, the sludge was heated to 60 ^{0}C for 20 min and NaOH was added to obtain the pH to 10 for solubilization of the sludge. It was resulted that 75% and 90% of the soluble part of the lysates were biodegraded after 48 and 350 h of incubation, respectively, and 37% sludge minimization was obtained. After all, the treatment of sludge with NaOH was considered to might be toxic to the microorganisms (Devikarani M. R. and Thiruvenkatachari V., 2005).

Applying thermo-chemical treatment corrosion is the main difficulty, thereby high-grade materials are necessary. The costs for auxiliary equipments and maintenance comprise a huge portion of the total operating costs of treatment. Odor issue is another main disadvantage for the thermo treatment process (Wei et al., 2003).

2.1.1.5 Other cell lysis strategies

Mechanical treatment is another strategy to achieve sludge reduction in the activated sludge process. Continuous investigations indicated that the shear force performed lead to a progressive lyse of cells resulting in 20% minimization in sludge generation compared with the control system under the same loading conditions. Returing of mechanically treated sludge to the aeration basin caused a slight raising in effluent total suspended solids. İmportant developments in sludge settling were also obtained. The mechanical lysis of sludge did not lead to any damage to the process operation (Devikarani M. R. and Thiruvenkatachari V., 2005).

In minimizing the sludge, the impact of microbial enzymes was sought. A 50% minimization in wastewater sludge was obtained, when a mixture of industrial cellulose, protease, and lipase was inserted in equal proportion by weight. It was also observed that enzymes have a possible for 80% sludge minimization, when the organic matter in the effluent is more than 60% (Devikarani M. R. and Thiruvenkatachari V., 2005).

Thermophilic aerobic digesters also applied in order to solubilize the sludge. In this method of thermophilic digestion, a part of return sludge was interpenetrated to a thermophilic digester, where solubilization of sludge occured by the action of thermophilic aerobic bacteria. The solubilized sludge was recycled to the aeration tank for more degradation. It was resulted that 93% minimization in total excess sludge generation was obtained with slight rising in the effluent suspended solids and total organic carbon compared to the control system (Devikarani M. R. and Thiruvenkatachari V., 2005).

2.1.2 Uncoupling metabolism

Bacteria have complicated metabolic routes to control growth, replication and other processes. Catabolism is the reaction series that decrease the complicacy of organic compounds generates the free energy. Anabolic routes comprise the utilization of free energy to constitute the molecules needed by cell. Energy transfer between these routes is in the formation of adenosine triphosphate (ATP). For many of aerobic bacteria, ATP is produced by oxidative phosphorylation, in which process electrons are transferred through the electron transport mechanism (Figure 2.3) from an electron donor (subsrate) to a final electron acceptor (O_2). Bacterial anabolism is combined to catabolism of subsrate by means of rate limiting respiration. After all, uncoupled metabolism would take place if respiratory control did not obtain and in place of the biosynthetic activities were rate limiting. Thus, excess free energy would be oriented away from anabolism so that the generation of biomass can be decreased (Wei et al., 2003).

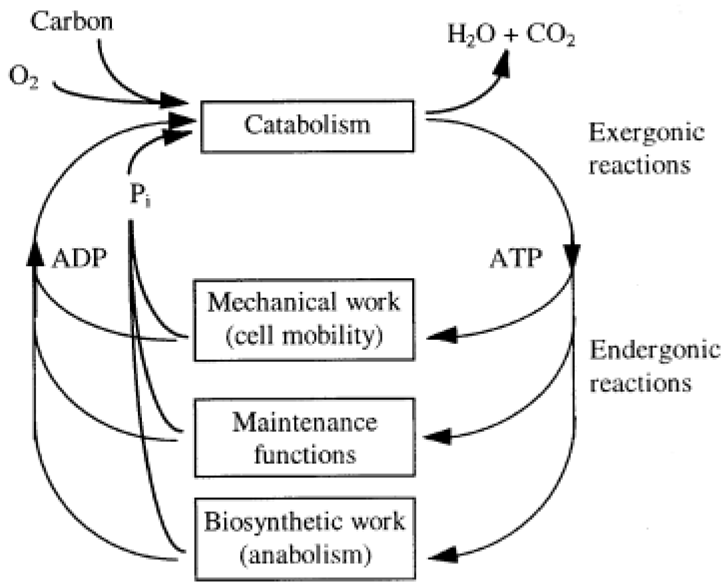

Figure 2.3 : The role of the ATP-ADP cycle in cell metabolism (Low E. W. and Chase H. A., 1998).

Uncoupling metabolism can be achieved by varies methods, which are chemical uncoupling, high S_0/X_0, and oxic-settling-anaerobic (OSA) process. In section 2.2, OSA will be mentioned because of it is the main subject of this study.

Uncoupled metabolism has been obtained with these conditions:

- In the availability of inhibitory compounds
- In the availability of excees energy source
- At undesirable temperatures
- In smallest media, and
- Throughout the transition times, in which the cells arrange to modifications in their environment (Devikarani M. R. and Thiruvenkatachari V., 2005).

The uncoupling approximation is to raise the distinctness of energy (ATP) level between catabolism and anabolism so that energy provide to anabolism is restricted. It was resulted that the obtained growth yield of biomass is decreased therefore when the energy uncoupling takes place. Consumption energy for anabolism without decreasing the removal efficiency of organic pollutants in biological wastewater treatment may accordingly supply a direct method for minimizing sludge generation (Wei et al., 2003).

Despite significant percentage minimization is obtained in sludge generation, the uncoupling metabolism has the following drawbacks:

- Total subsrate removal yield is declined in many of the cases, and
- The metabolism uncouplers used for the dissipation of energy require to be removed from the water prior to dispose, which can transform to toxic
- The implementation of chemical uncouplers for sludge minimization may lead to abatement of COD, but increases the oxygen depletion and deteriorates activated sludge qualities, such as settling and dewatering (Devikarani M. R. and Thiruvenkatachari V., 2005).

2.1.3 Maintenance metabolism

Microorganisms perform their maintenance energy necessities favourably generating supplement biomass, and this recognition has released potential strategies for sludge minimization throughout biological wastewater treatment. It is well known which scaling sludge retention time (SRT)/declining sludge loading rate can minimize sludge generation in aerobic wastewater treatment mechanisms. The existence energy to microorganisms is stated by the providing of subsrate. By raising biomass concentration it would be probable to attain a case in which amount of energy supplied equals the maintenance request. A connection was mentioned to represent subsrate usage for maintenance and biomass generation in subsrate-limited continuous microbial cultures. Consequences indicated that the biomass minimization consisted, i.e. biomass minimization by 12% and 44%, respectively, when the biomass concentration was escalated from 3 to 6 g/L and from 1.7 to 10.3 g/L, respectively (Wei et al., 2003).

2.1.3.1 Membrane bioreactor

MBR can be runned in long SRT in fact complete sludge retention time because SRT can be operated completely from hydraulic retention time (HRT) by membrane in place of clarifiers in order to separate of sludge and effluent. The MBR operation at much higher sludge concentration can be achieved with the long/complete sludge retention. Hence, the higher the sludge concentration leads to the lower the sludge loading rate. Consequently, the microorganisms use a growing part of feed for maintenance intention and ultimately less for growth. When the sludge loading rate to be low enough, minimal or any excess sludge is generated no longer.

Despite MBR has been achieved in full-scale WWTPs, the cost evaluations indicate that the costs of sludge treatment and disposal will be the principal consideration of total plant operation costs since 2004 rather than the costs of membrane module replacement (Wei et al., 2003).

2.1.4 Predation on bacteria

The biological wastewater treatment mechanism can be qualified as a man-made ecosystem, and the activated sludge is a proper habitat for various organisms other than bacteria. One of the methods to minimize sludge generation that is to utilize higher organisms, such as protozoa and metazoa, in the activated sludge mechanisms that predates on the microorganism without inhibiting the degrading of subsrate. Throughout the energy conversion from low to high trophic levels, energy is consumed because of unsatisfying biomass transformation. With proper conditions, the total consumed energy will be high and, thus, the total biomass generation will be less. The Table 2.1 indicates data on awaited biomass minimization by several predators (Devikarani M. R. and Thiruvenkatachari V., 2005).

Table 2.1 : Various predators used for excess biomass reduction (Devikarani M. R. and Thiruvenkatachari V., 2005).

Predator	Prey	Expected Biomass Reduction	Reference
Tetrahymena pyriformis	Ciliated *Pseudomonas fluorescens*	12-43%	(Ratsak et al., 1994 and Ratsak et al., 1996)
Protozoa and Metazoa	Bacteria	60-80%	(Lee et al., 1996 and Welander et al., 1994)
Oligochaete worm	Bacteria	25-50%	(Ratsak and C. H., 2001)
Bdelloid Rotifers	See note below	10-25%	(Lapinski et al., 2003)

Note: They graze on suspended solids, thereby total biomass gets reduced by ~ 10%, and they form as facilitators of floc, in turn reducing 10-25% of the total biomass in suspension.

The method of bacteriovoric metabolism is implemented in low sludge generation process, an aerobic biological treatment process in which the effluent is treated in two sequence phases. The first phase is the bacterial phase, which is operated to control the growth of disordered bacteria, which deplete much of the soluble organic matter in effluent. The second phase is the predator pahse, which is operated and optimized for the growth of filter-feeding micro-animals, which deplete the bacteria from the prior phase. The first tank is run at a high food to microorganism (F/M) ratio to make sure the disordered bacterial growth and the second tank is run at a lower F/M. Operating at a low F/M ratio enhances the endogenous respiration and induces growth of higher life forms. These higher life forms deplete disordered bacteria, consequently participation of the total sludge minimization takes place (Devikarani M. R. and Thiruvenkatachari V., 2005).

The main problem of this method is an augmentation in nitrate and phosphate concentrations in the predator phase (Devikarani M. R. and Thiruvenkatachari V., 2005).

2.2 Description of OSA Process

The OSA process is a variance of conventional activated sludge process in which an anaerobic sludge holding tank is added in the sludge recycling line between the aeration tank and the secondary clarifier, as shown in Figure 2.4 (Etienne P. and Yu L., 2012). It was reported that the adding of a period of anaerobiosis in the high-rate activated sludge process could minimize the rate of excess sludge generation by half with respect to conventional activated sludge treatment without anaerobic reactor. Since then, an option fasting/feasting approximation further to anaerobic and oxic cycling has been qualified as one of the methods for reducing excess sludge generation in the activated sludge treatment (Devikarani M. R. and Thiruvenkatachari V., 2005).

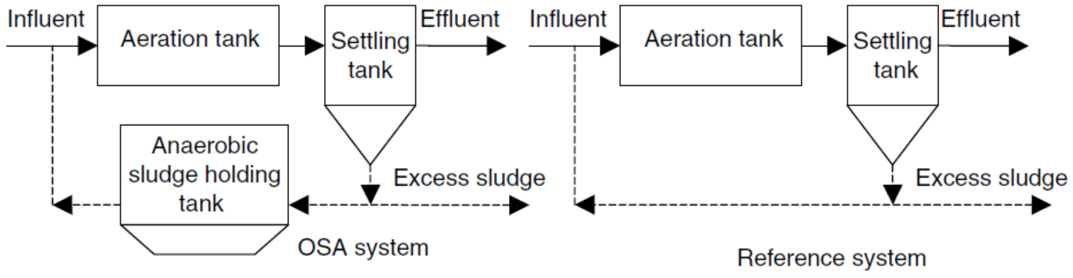

Figure 2.4 : Schematic diagram of an OSA system and a reference system (Etienne P. and Yu L., 2012).

The sludge fasting attributes to reveal of precipitated sludge to an anoxic environment, where subsrate is inefficient. Microorganisms are ravenous under this tense condition causing the consumption of cell energy in the form of ATP or subsrate storage. In sludge feasting the fasted microorganisms are sent back to oxic conditions with enough subsrate, where they attain a spare of cell energy eventuating in ATP storage and, thus, restricting the growth of microorganisms.

Despite the certain reason of sludge minimization in an OSA process is unknown, several statements about the potential reason of excess sludge minimization were recommended. They were as follows:

- Control of slow growers throughout the complete microbial culture that might eventuate in low sludge growth yield
- Toxicity of soluble microbial outputs to microbes that might induce intensive utilization of energy to regulate metabolic activity thus restricting sludge growth
- Declining of sludge decay in the sludge holding tank, and
- The uncoupling energy hypothesis (Devikarani M. R. and Thiruvenkatachari V., 2005).

Despite comprehensively investigating the mechanisms of sludge minimization in an OSA process, the effects of energy uncoupling, control of slow growers, and soluble microbial outputs on sludge minimization could not be considered (Wei et al., 2003).

Excess sludge minimization in an OSA could be performed with a low oxidation-reduction potential (ORP) degree in the sludge holding tank. The studies approved this by running the OSA process at various ORP degrees using synthetic wastewater for a period of nine months and obtained the sludge minimization yield was high with low ORP degrees. When the ORP degree was reduced from +100 mv to -250 mv, the sludge removal yield was raised from 23% to 58%. This minimization was possible by means of increasing of sludge decay coefficient in the anaerobic sludge zone in the OSA process, when the ORP was resumed at -100 mv. The sludge generation in an OSA process was contrasted with conventional activated sludge generation process and indicate that in the OSA process, the specific sludge generation was decreased by 20-65% compared with the conventional process, but the cause for minimization was found to uncoupling energy theory between catabolism and anabolism. In addition, the impact of anaerobic stabilization of recycled activated sludge in a continuous system on biomass generation at various S_0/X_0 ratio was observed and it was attributed that obtaining less biomass yield with high S_0/X_0 ratio (Devikarani M. R. and Thiruvenkatachari V., 2005).

Methods on the basis of the mechanisms of lysis and cryptic growth, uncoupling metabolism, oxic settling anaerobic process, bacteriovoric metabolism, sludge minimization by the utilization of high purity oxygen and sludge minimization by controlling the sludge retention time were investigated. Table 2.2 indicates a contrast of whole the methods mentioned for minimizing excess sludge generation (Devikarani M. R. and Thiruvenkatachari V., 2005).

Table 2.2 : Comparison of different strategies for reducing excess sludge production (Devikarani M. R. and Thiruvenkatachari V., 2005).

Strategy	Sludge Reduction (%)[a]	Advantages	Disadvantages and Environmental Impact
Lysis-cryptic growth			
Ozonation	40-100	Highly successful in full scale experience, Improved SVI and dewaterability, enhanced nutrient removal in case of MBR	Increase in TOC in the effluent, Involve high cost for operation, Increace in inorganic solids content in MLSS
Chlorination	65	Cheaper compared to Ozonation	Poor settleability and increased soluble COD, Formation of THM's
Alkaline chemical treatment	37	Relatively simpler	NaOH can be toxic to microorganisms
Uncoupling metabolism	40-87	Relatively simpler	Subsrate removal efficiency is decreased, the protonophores if not removed prior to discharge can become toxic, reduced COD removal efficiency and increased oxygen consumption.
OSA	20-65	Only addition of anaerobic tank, improved sludge settleability	
Bacteriovoric metabolism	10 to 80	Improved dewaterability, restively simple	Nutrient release, High costs
High purity oxygen	25-54	Better sludge settling and thickening; lower net sludge production; higher oxygen transfer efficiency per horsepower and more stable operation	High operation and maintenance costs
Sludge retention time		Relatively simple	

[a] values provided are in a broad range

2.3 Activated Sludge Modelling

As mentioned before, increasing of the effluent quality demands in the wastewater treatment induce the increasing of complicacy in the design and operation of the plants (Henze M., 2005).

Models are applied for various goals corresponding with wastewater treatment plants:

- design
- control
- operational optimization
- teaching
- organizing tool

Dynamic models are required to design the plants and optimize and control the operation. Generally, deterministic models, which aim to give a realistic description of the main processes of the plant, are used for wastewater treatment plants today (Henze M., 2005).

"In 1982 the International Association on Water Pollution Research and Control (IAWPRC) established a Task Group on Mathematical Modelling for Design and Operation of Activated Sludge Processes" (Henze M. et al., 2000). The purpose of Task Group was to generate a wide platform that could be utilized for next investigation of models for nitrogen-removal activated sludge systems. The main purpose is the improvement of a model with a minimum of complexity. As a result, they create the Activated Sludge Model No. 1, which is today known under several names: IAWPRC model, ASM1, IAWQ model, and so on (Henze M. et al., 2000).

2.3.1 Wastewater characterization

Several determinants affect models behavior. Hence, the overcoming detailed wastewater composition is significant. Wastewater characterization has an intense impact on real plant behavior as well as on its modeling. Faults in characterization of the wastewater or changes in the composition of the wastewater lead to defective modeling results (Henze M., 2005).

The significant determinant by which a model can be enacted is its capability to estimate real time and space-time related to alterations in the requirement for the electron acceptor. It was due to this that subsrate was partitioned into two fractions: readily and slowly biodegradable (Henze M. et al., 2000). Figure 2.5 shows the distribution of COD fraction in wastewaters, which was imposed on Pala (2012).

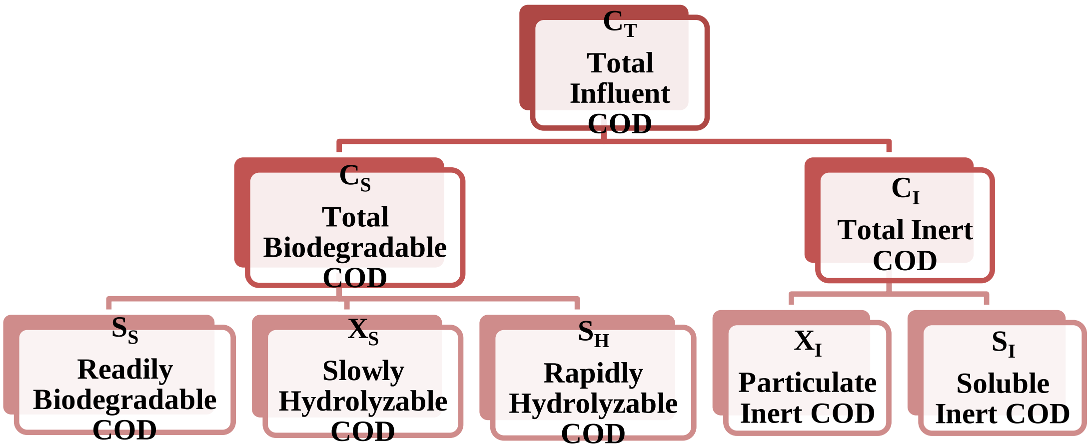

Figure 2.5 : Distribution of COD fraction in wastewaters (Pala Ö. İ., 2012).

2.3.2 Activated sludge model No. 1

The ASM1 model consists of nitrification and denitrification in conventional activated sludge processes (Henze M., 2005). "The ASM1 model only determines reactions by heterotrophic bacteria under aerobic and anoxic conditions consuming carbonaceous subsrates and autotrophic nitrifying bacteria oxidizing ammonia to nitrate" (Metcalf and Eddy, 2003). The ASM1 model becomes a straight determination of the processes, as long as the wastewater has been qualified in depth and is of domestic or municipal source (Henze M., 2005).

The ASM1 can figure up many problems in the plant:

- oxygen depletion in the tanks
- concentration of ammonia and nitrate in the tanks and in the effluent
- concentration of COD in the tanks and in the effluent
- MLSS in the tanks
- solids retention time
- sludge generation

As with all models, ASM1 can cause insufficient results if the model has been established defectively. Table 2.3 gives the process matrix for accurate ASM1. The matrix comprises all processes, reaction kinetics, mass balances and stoichiometry. Figure 2.6 indicates incorporated organic matter removal and nitrification processes in the ASM1 (Henze M., 2005).

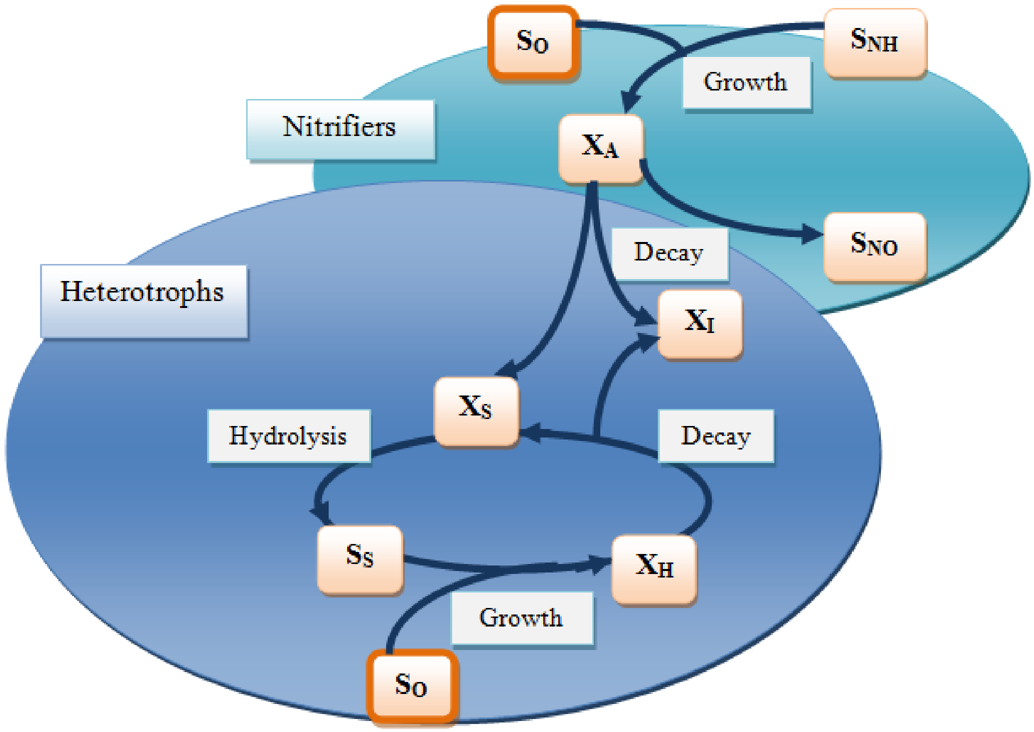

Figure 2.6 : Processes for heterotrophic and nitrifying bacteria in the Activated Sludge Model No. 1 (ASM1) (Henze M., 2005).

Table 2.3 : The process matrix for ASM1 (Pala Ö. İ., 2012).

Components→ Processes↓	S_O	S_S	S_H	X_S	X_H	X_P	S_P	S_{NH}	S_{Alk}	Rate Equations
Growth of X_H	$-\frac{1-Y_H}{Y_H}$	$-\frac{1}{Y_H}$			1			$-i_{XB}$	$-\frac{i_{XB}}{14}$	$\mu_H^{'}\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{S_O}{K_{OH}+S_O}\right)X_H$
Hyrolysis of S_H		1	-1							$k_h\left(\frac{S_H/X_H}{K_X+\left(S_H/X_H\right)}\right)\left(\frac{S_O}{K_{OH}+S_O}\right)X_H$
Hydrolysis of X_S		1		-1						$k_{hX}\left(\frac{X_S/X_H}{K_{XX}+\left(X_S/X_H\right)}\right)\left(\frac{S_O}{K_{OH}+S_O}\right)X_H$
Decay of X_H	$-(1-f_E)$				-1	f_{EX}	f_{ES}	$i_{XB}(1-f_{EX})$		$b_H X_H\left(\frac{S_O}{K_{OH}+S_O}\right)$
Parameters	O_2	COD	COD	COD	cell COD	COD	COD	NH_3-N		

3. MATERIALS AND METHODS

In this study, sludge minimization for the biological treatment of domestic wastewater was evaluated by using two parallel laboratory scale OSA systems. In addition to, oxygen uptake rates was evaluated by using respirometer after achieved steady-state conditions of the system.

3.1 Experimental Set-Up

OSA system consisted of a sequencing batch reactor (SBR) and an anaerobic bioreactor. SBRs were cylindrical glass reactors with an inner-diameter of 120 mm and height of 270 mm. Anaerobic bioreactors were completely closed and continuously mixed glass reactors with an inner-diameter of 57 mm and height of 160 mm. In addition to, there were blankets for anaerobic reactors and water-bath for SBRs to fix the temperature around 20- 22 ^{0}C. Two parallel OSA systems were operated for the study. The volume of each SBR was 1.5 liters.

The initial volume of the SBRs was 1 liter. A U shaped glass pipe was used for discharge to avoid escaping sludge by vacuum effect of pump. Discharge was performed by flexible silicon pipe attached to the glass pipe. There was no sludge waste from the system.

Once per day of the operation scheme of each SBR, a 5 min of mixing period was devoted to provide complete mixing before feeding of settled sludge from SBR to anaerobic bioreactors following the withdrawal phase. Then, same volume of sludge was interchanged between SBR and anaerobic bioreactor to provide 10 days of hydraulic retention time in the anaerobic bioreactor. For this purpose, 100 mL of biological sludge from the mixed liquor was pumped into anaerobic bioreactor after discharge phase of SBR and this was followed by pumping same amount of sludge from anaerobic bioreactor to the SBR on a daily basis. Thus, the interchange ratio of sludge was achieved as 1/10 which is recommended by Easwaran (2006) as optimum interchange rate for maximum solids destruction, and the hydraulic retention time

(HRT) and sludge age were maintained at 10 days in the anaerobic bioreactors. Two separate pumps were used for these operations.

Feeding, discharge and sludge interchange between SBRs and anaerobic bioreactors were conducted by Pump Drive 5201 and Pump Drive 5006 model peristaltic pumps with adjustable flow rate. Timers were used to control the operation duration of pumps.

The operation cycle of each SBR consisted of 5 hours of reaction (only aerobic) phase and 30 min of settling phase, 15 min of decanting phase, 5 min of interchange phase and 10 min of idle phase. Simultaneous feeding, mixing and aeration were initiated at the beginning of reaction phase of each sequence.

Mixing and aeration phases on SBRs were provided by airstones connected to aerators in SBRs. Duration of aeration was controlled by timers. Figure 3.1 shows the experimental set-up used in the laboratory and Figure 3.2 illustrates the flow diagram of reactors.

Figure 3.1 : Experimental set-up used in the laboratory.

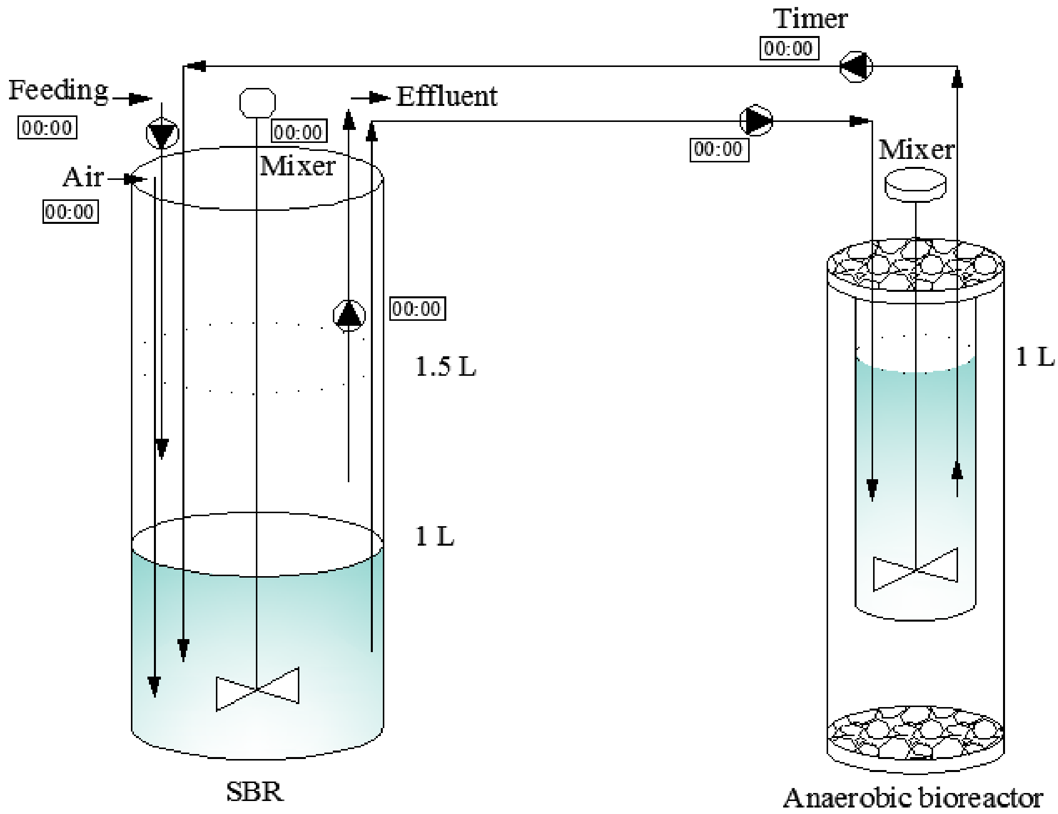

Figure 3.2 : Flow diagram of reactors.

3.2 Operation of Laboratory Scale OSA Systems

In this study, a control reactor was operated in a sequencing batch reactor and a reactor was operated with OSA process to determine sludge reduction. In order to understand the sludge minimization mechanism, the data of microbial activity were evaluated with determination of oxygen uptake rates. Profile of oxygen uptake rate was observed for both control reactor and reactor operated as OSA process. After obtained results, profiles of two systems were compared to determine the differences and the effects of anaerobic reactor to the system.

3.3 Respirometric Experiments

When the concentrations of solids were stable, the measurements were obtained on steady-state system. Respirometric experiments were conducted in order to evaluate endogenous oxygen uptake rate (OUR) level of biomass. Firstly, respirometric tests were performed for control and SBRs to observe the differences between them. Thereafter, respirometric tests were carried out to understand the role of anaerobic reactor in the system. It had been observed whether anaerobic reactor was biomass or substrate source for SBRs.

The OUR experiments were performed with a Ra-Combo (AppliTek Co.) continuous respirometer. Batch OUR experiments were conducted at required Food/Microorganism (S_0/X_0) ratio. In the experiments, 1 g of nitrification inhibitor (Formula 2533, Hach) was added to the sludge to prevent potential attempt by nitrifiers. The wastewater mixture was aerated during the experiment without any oxygen limitation. Figure 3.2 shows the respirometric experiment set-up.

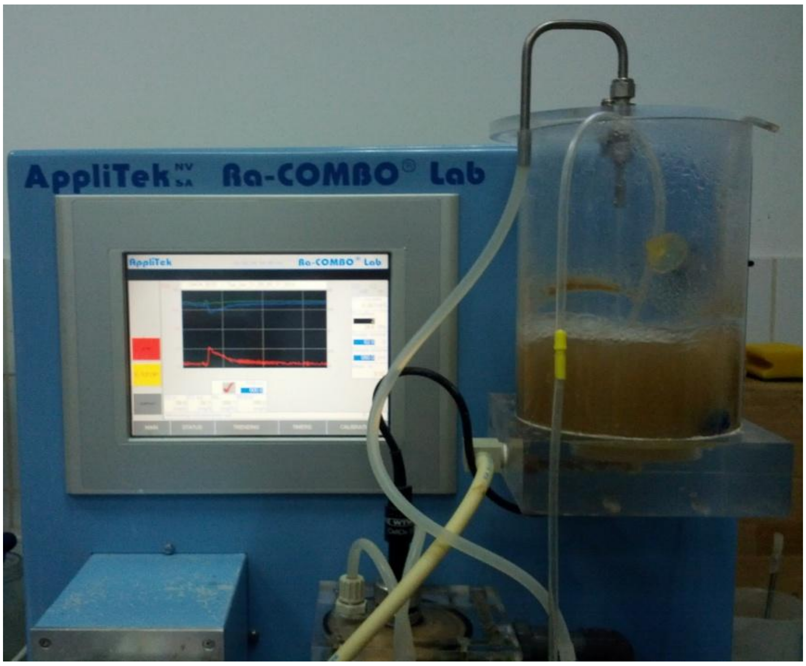

Figure 3.3 : Respirometric experiment set-up.

The OUR experiments were organized as given in Table 3.1. In this table, F/M refers to microorganism/substrate (VSS/COD) ratio of systems operated in this study. Additionally, 1/4th of F/M ratio was also applied to see the response of OUR profiles under lower F/M ratios. Additional sludge from interchange reactor was used as both sludge source and substrate source while interchange sludge was served as biomass and C source, respectively. The volumetric ratio was kept as it is in the original system between OSA sludge and interchange sludge mixture while used as biomass. On the other hand, F/M ratio was calculated by using total COD of interchange sludge when it was used as C source.

Table 3.1 : List of respirometric experiments.

Runs	Source of Sludge	Additional Sludge	Source of Substrate
Run-1	OSA	-	Peptone + Sol B (Low F/M)
Run-2	Control	-	Peptone + Sol B (Low F/M)
Run-3	OSA	Interchange	Peptone + Sol B (Low F/M)
Run-4	OSA	-	Peptone + Sol B (F/M))
Run-5	Control	-	Peptone + Sol B (F/M))
Run-6	OSA	-	Interchange sludge (F/M))
Run-7	Interchange	-	Peptone + Sol B (F/M))
Run-8	OSA	Interchange	Peptone + Sol B (F/M))

During the experiments, COD samples were taken to observe the reaction of sludge in OUR tests.

The AQUASIM software package (Reichert, 1998) was used for simulations and parameter estimation using OUR data for determination of kinetic and stoichiometric coefficients. The ASM1 (Henze M. et al., 2000) model was used for respirometric data interpretation.

3.4 Estimation of Sludge Yield Observation

The observed biomass yield values were determined for and SBRs by using the mixed liquor solids data collected in the systems. The observed yield values were calculated based upon the cumulative increase in solids (in term of VSS) divided by the corresponding removal of COD. The amount of cumulative solids were estimated by the sum of the solids increased in the SBRs, the solids lost in the effluent and the solids removed from the reactors for sampling.

3.5 Wastewater Characteristics

Synthetic wastewater containing a mixture of Peptone mixture and Solution B prepared by ISO 8192 procedure was used in order to obtain domestic wastewater characterization. The synthetic wastewater was prepared with tap water. The composition of peptone mixture for the synthetic wastewater is given in Table 3.2.

Table 3.2 : Composition of peptone mixture.

Chemical	Formula	Amount (g/L)
Peptone	-	16
Meat Extract	-	11
Urea	$H_2N\text{-}CO\text{-}NH_2$	3
Sodium Chloride	$NaCl$	0.7
Calcium Chloride Dihydrate	$CaCl_2.2H_2O$	0.4
Magnesium Sulphate Heptahydrate	$MgSO_4.H_2O$	0.2
Potassium Phosphate	K_2HPO_4	2.8
Potassium Dihydrogen Phosphate	KH_2PO_4	1.4

Peptone mixture was prepared weekly for 1 liter and stored at 4 ^{0}C. In ISO 8192 procedure the mixture does not include potassium dihydrogen phosphate. Due to the domestic wastewater characteristics, sufficient amounts of potassium dihydrogen phosphate was added to the synthetic wastewater.

Solution B was also added to the synthetic wastewater. The micronutrients, which are necessary for the biological growth, were provided from Solution B. The composition of Solution B is given in Table 3.3. Solution was stored in dark colored, glass bottle in appropriate conditions.

Table 3.3 : Composition of Solution B.

Chemical	Formula	Amount (g/L)
Magnesium Sulphate Heptahydrate	$MgSO_4.H_2O$	15
Iron Sulphate Heptahydrate	$FeSO_4.7H_2O$	0.5
Zinc Sulphate Heptahydrate	$ZnSO_4.7H_2O$	0.5
Manganese Sulphate	$MnSO_4.H_2O$	0.7
Calcium Chloride Dihydrate	$CaCl_2.2H_2O$	0.4

The synthetic wastewater for the feed was prepared to have 18 mL of peptone mixture and 4.5 mL of Solution B with tap water. It was analyzed at certain times and its characteristics were observed as 455 mgCOD /L and 60 mgTKN /L.

3.6 Monitoring

In the applied operating condition was given before consists of 4 cycles on a daily basis. Daily and detailed in-cycle analyses were carried out only on the last cycle. This cycle represents the other cycles. Sludge interchange was taken place during this cycle between SBRs and anaerobic bioreactors.

The system was monitored until the parameters (SS, VSS, ions and COD) were steady-state and then analyzed in detail by taking samples from discharge phase of

SBRs at the last cycle as a daily and during the respirometric experiments. Thus, the efficiency of the system was monitored on daily basis.

COD and anion analyses were conducted on the samples taken from effluents of SBRs. Samples for Suspended Solids (SS), Volatile Suspended Solids (VSS), Total Solids (TS), and Total Volatile Solids (TVS) analysis were taken from the mixed liquor at the end of the reaction phase.

The characterization of synthetic wastewater was also monitored every week as the stock solutions were prepared weekly.

Samples from the interchange bioreactor were taken from pipe-line coming from the bioreactor without opening the reactor to ensure anaerobic conditions within the interchange reactor.

Throughout the study, the sample points and the analyses are given in Table 3.4.

Table 3.4 : Analyses according to the sample points.

Sample Point Parameters	Feed	SBR*	Effluent**	Interchange Bioreactor***
Total COD	x			x
Soluble COD	x	x	x	x
TKN	x			
Anions	x		x	
TS, SS, VSS		x	x	x

*Before the last cycle starts
**Discharge phase
*** Sludge interchanges line from bioreactor to SBR

3.7 Analytical Methods

In this study, used analytical methods were; COD, Total Kjeldahl Nitrogen (TKN), SS, VSS, TS and TVS. These analyses were performed according to the procedures given in Standard Methods. (APHA, 2005) COD analyses were performed with closed reflux method. For the COD analyses, samples were filtered from Whatman GF/C fiberglass filters (O.45 µm).

The anion analyses (chloride, floride, nitrite, nitrate, phosphate and sulphate) were performed with Dionex ICS-1500 model ion chromatograph (Figure 3.3). For the ion chromatograph analyses, samples were filtered from 0.22 µm filters.

Figure 3.4 : Dionex ICS-1500 model ion chromatograph.

4. RESULTS AND DISCUSSION

4.1 Monitoring COD and Anions in Influent and Effluent

In the scope of this study, chemical oxygen demand and anion concentrations of synthetic wastewater, control system and OSA system were monitored on daily basis. These daily results are given in Appendix A. Table 4.1 shows characteristics of synthetic wastewater and effluent in two systems. In this table, an accumulation of nitrite was measured in the effluent of the control system which is not expected in such conventional activated sludge systems. In the OSA system, nitrite concentrations were high after start-up and lowered after 85 days of operation. This was then caused lower nitrate concentration at the effluent of the OSA system. Nitrate and nitrite concentrations were stabilized after this day. In the effluent of both control and OSA systems, effluent phosphate concentrations were observed as high. All these aion results were evaluated as the cummulative accumulation and transformation in the anaerobic bioreactors.

Table 4.1 : Wastewater and effluent characteristics of two systems.

	COD (mg/L)	**Chloride* (mg/L)**	**Sulfate* (mg/L)**	**Nitrite* (mg/L)**	**Nitrate* (mg/L)**	**Phosphate* (mg/L)**
Influent	455±22	35.3±3.5	42.2±1.0	0.1±0.1	0.3±0.3	9.0±0.7
Control system	51±15	76.0±3.3	88.1±5.0	38.8±3.1	2.1±1.0	18.4±2.1
OSA system	59±13	76.4±3.3	128.7±71.1	23.9±5.3	24.3±6.2	19±0.5

*Average value after 86th day

Figure 4.1 and Figure 4.2 show change of NO_3-N and NO_2-N concentration in control system and OSA system respectively.

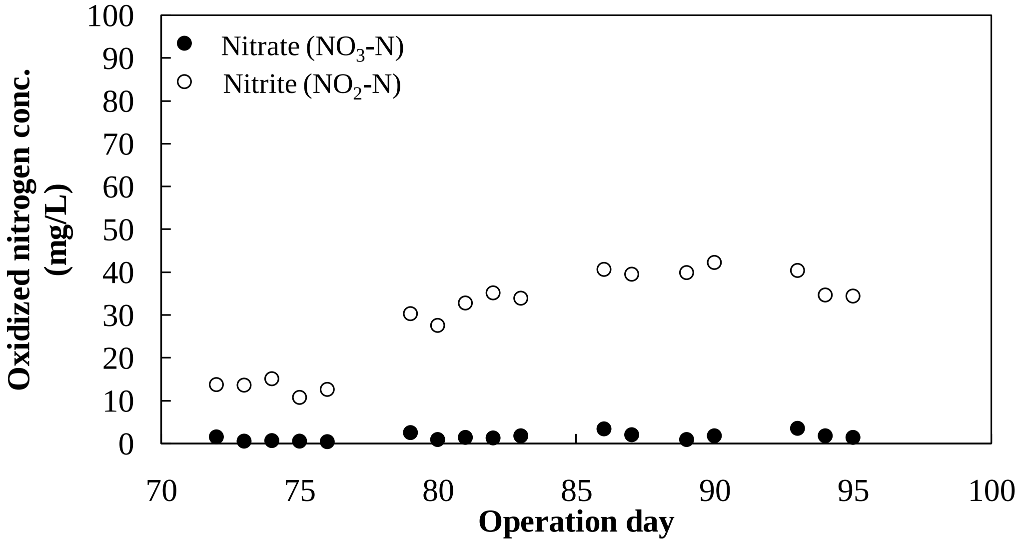

Figure 4.1 : NO_3-N and NO_2-N concentration changes in control system.

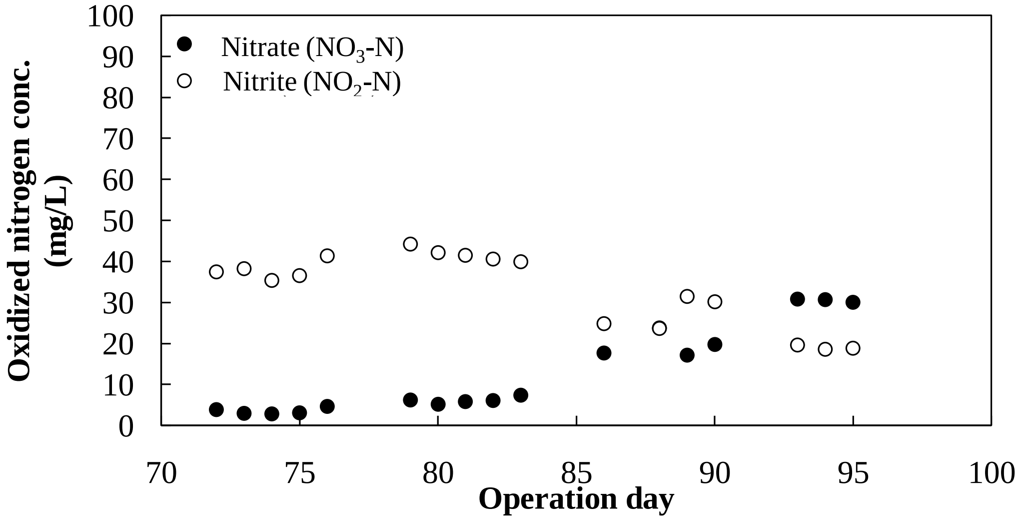

Figure 4.2 : NO_3-N and NO_2-N concentration changes in OSA system.

4.2 The Fate of Solids in OSA Process and Conventional Activated Sludge Process

The performance of OSA and control systems in terms of sludge reduction were firstly evaluated based on suspended solids concentrations. The solid concentrations were increased in time during initial phases of both systems. The low variability of total suspended solids in the SBRs was used as an evidence of steady operation conditions. Thus, it is decided that control and OSA systems were attained steady state on day 40 and 60, respectively. The mixed liquor suspended solids concentration (MLSS) and volatile suspended solid concentration (MLVSS) for control and OSA system were monitored in the SBRs, anaerobic digester connected to the control SBR and interchange bioreactor connected to the OSA SBR. All raw data and calculations for yield estimation were given in Appendix A.

Figure 4.3 and Figure 4.4 show changes of MLSS and MLVSS concentrations and MLVSS/MLSS ratio in Control-SBR respectively.

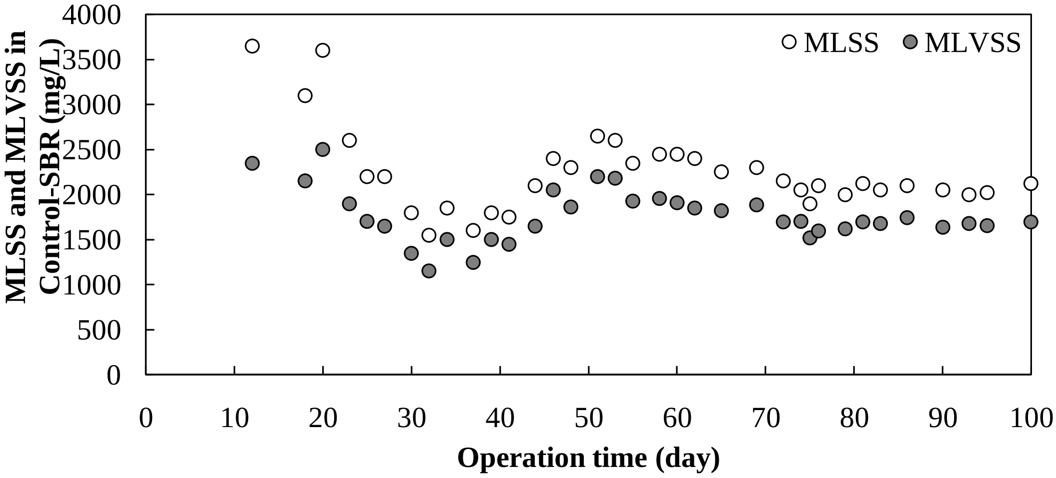

Figure 4.3 : MLSS and MLVSS concentration changes in control-SBR.

During the stable operational period (after 40 days), it was observed that there were no distinct changes in the concentration of MLSS and MLVSS, as it can be seen from the data given in the Figure 4.4. Thus, the average MLSS and MLVSS concentrations were calculated as in the range of 2200±220 mg/L and 1800±190 mg/L, respectively.

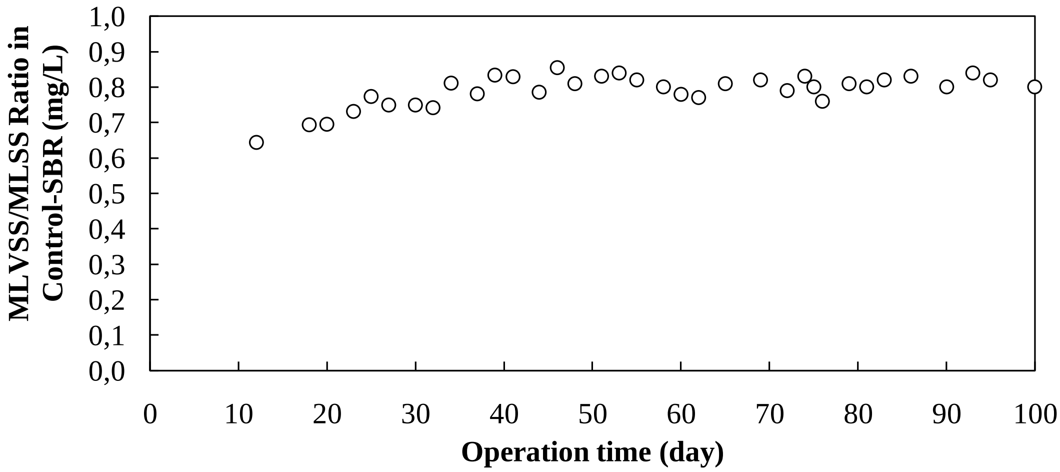

Figure 4.4 : MLVSS/MLSS ratio in control-SBR system.

Control system has been steady state faster than OSA system, which can be observed from MLVSS/MLSS ratio fixed at 40 days.

Figure 4.5 and Figure 4.6 show changes of MLSS and MLVSS concentrations and MLVSS/MLSS ratio in OSA-SBR respectively.

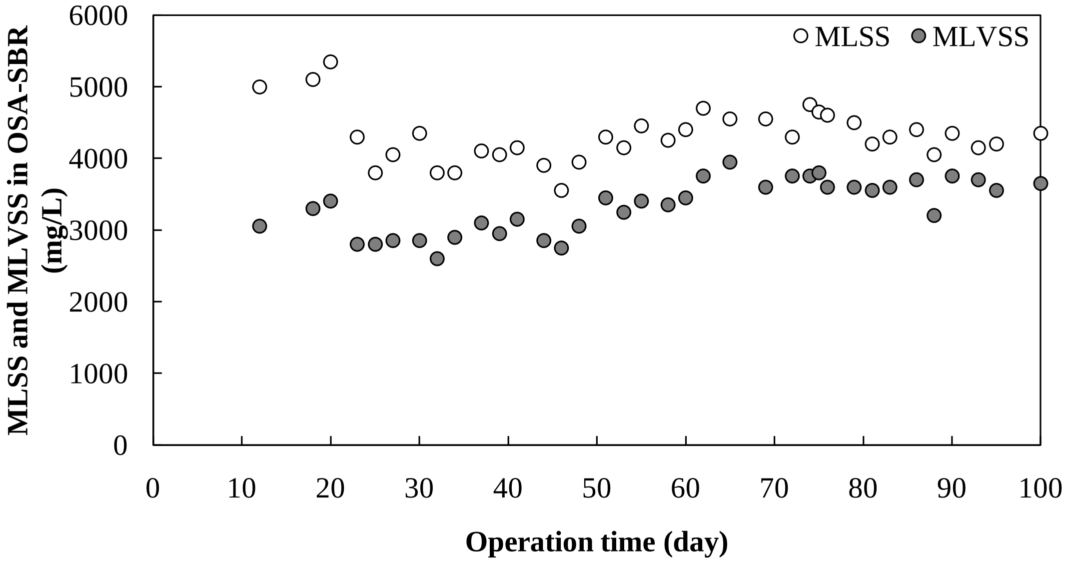

Figure 4.5 : MLSS and MLVSS concentration changes in OSA-SBR.

During the stable operational period (after 60 days) of OSA system, the average MLSS and MLVSS concentrations were calculated as in the range of 4400±200 mg/L and 3650±165 mg/L, respectively.

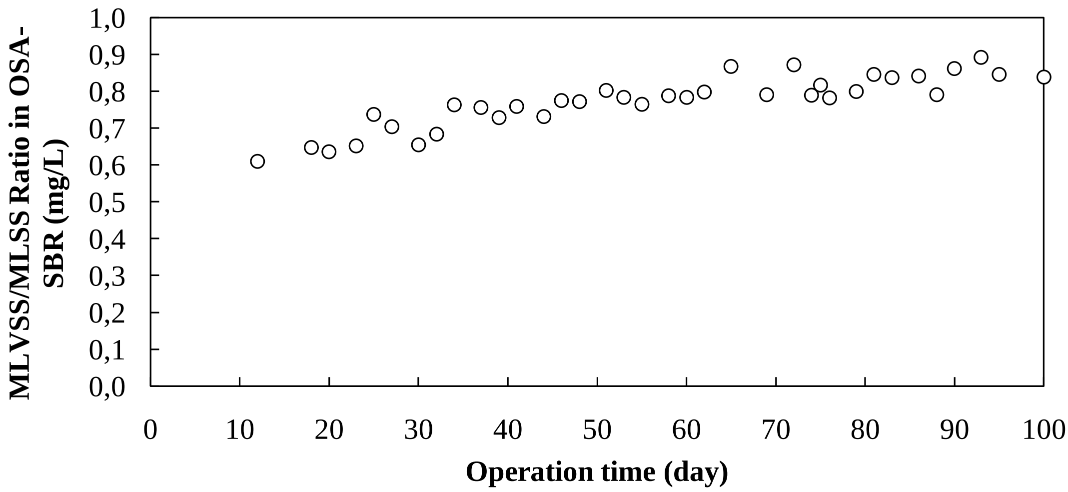

Figure 4.6 : MLVSS/MLSS ratio in control-SBR system.

Figure 4.7 and Figure 4.8 show changes of MLSS and MLVSS concentrations in digester reactor and interchange reactor respectively.

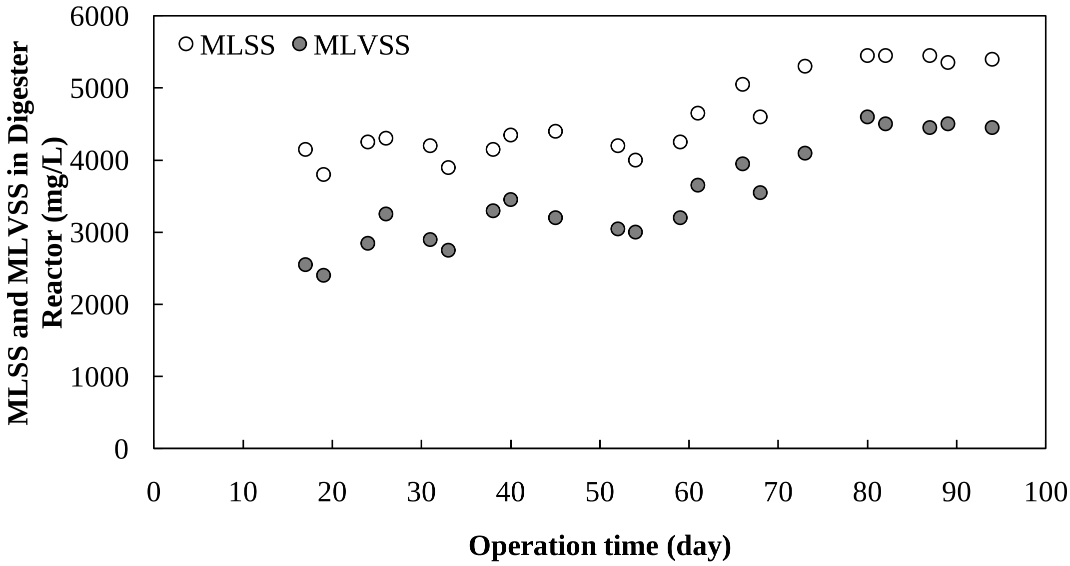

Figure 4.7 : MLSS and MLVSS concentration changes in digester reactor.

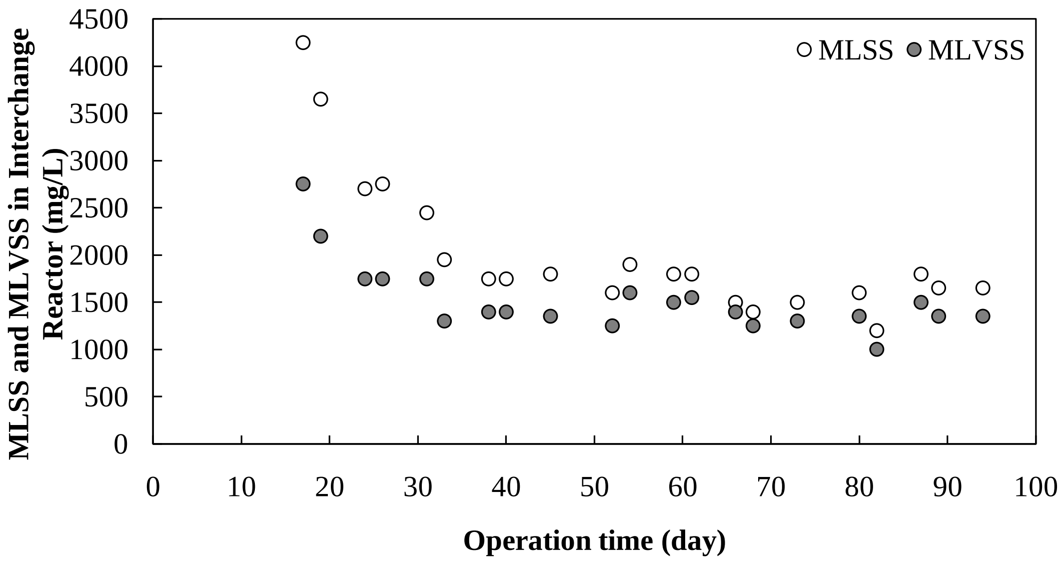

Figure 4.8 : MLSS and MLVSS concentration changes in interchange reactor.

4.3 Sludge Reduction in OSA Process

The accumulated solids were estimated for each system as described in "Materials and Methods" section once steady-state was reached. The observed yield values were calculated by using cumulative solids, which were lost from the effluent and removed for sampling. Figure 4.9 and Figure 4.10 show the variation of cumulative solids (in terms of VSS) for two systems. In order to estimate yield values, the corresponding removals of COD values were calculated considering average influent and average effluent COD concentrations as given in Table 4.2.

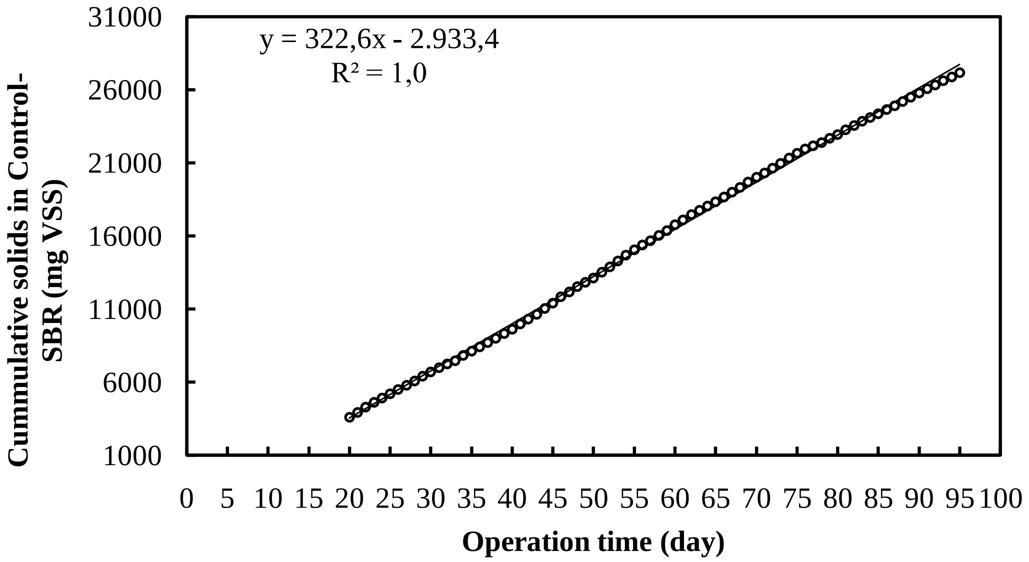

Figure 4.9 : Cumulative solids (in terms of VSS) in control system.

In the control system, daily VSS loss was observed as 322.6 mg VSS with sludge wastage. Experimental yield (Y_H) of Control-SBR was found as 0.58 g cellCOD/gCOD according to the VSS loss.

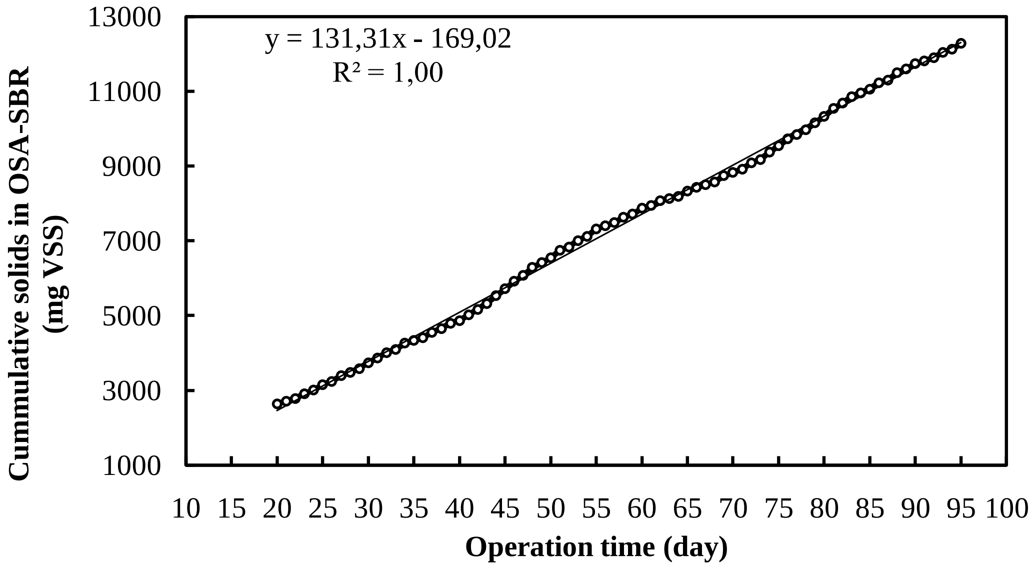

Figure 4.10 : Cumulative solids (in terms of VSS) in OSA system.

In the OSA system, daily VSS loss was observed as 131.3 mg VSS without sludge wastage. Experimental yield (Y_H) of OSA-SBR was found as 0.23 g cellCOD/gCOD according to the VSS loss.

The corresponding removals of COD values, which were calculated considering average influent and average effluent COD concentrations, were used to obtain yield and sludge reduction values. As seen in Table 4.2, yield and sludge reduction values were calculated and summarized for Control-SBR and OSA-SBR.

Table 4.2 : Yield and sludge reduction values in Control-SBR and OSA-SBR.

Parameter	**Value**
Control SBR	
Average Influent COD, mg/L	455
Average Effluent COD, mg/L	60
Daily loss of biomass	322.6
Yield (experimental), gVSS/gCOD	0.41
Yield (experimental), g cellCOD/gCOD	0.58
OSA SBR	
Average Influent COD, mg/L	455
Average Effluent COD, mg/L	50
Daily loss of biomass	131.30
Yield (experimental), gVSS/gCOD	0.16
Yield (experimental), g cellCOD/gCOD	0.23
Sludge Reduction	**0.60**

According to these results, the achieved sludge reduction is 60% considering VSS losses from both control and OSA systems. As seen in Table 2.2 and mentioned before, 20 – 65% and 44% sludge reduction were found by Devikarani and Thiruvenkatachari (2005) and Euan and Howard (1998) respectively, which are considerably close to obtained results in this study.

4.4 Evaluation of Respirometric Results and Model Results

Kinetic coefficients for SRT – 10 day were applied according to the model when the respirometric data was obtained. Table 4.3 shows reference kinetic coefficients and achieved results for each runs.

Figure 4.11, Figure 4.12, Figure 4.13, Figure 4.14 and Figure 4.15 show the illustration of respirometric and model results for each runs.

Table 4.3 : Stoichiometric and kinetic coefficients from respirometric data.

Model Parameter		Unit	SRT 10d*	Run-4 (OSA w/ pept.)	Run-5 (Control w/ pept.)	Run-6 (OSA w/ Interc. Sl.)	Run-7 (Interc. Sl. w/ pept.)	Run-8 (OSA& Interc. Sl. w/ pept.)
Maximum growth rate for X_H	$\hat{\mu}_H$	1/day	5.2	3	5.2	3	3	3
Half saturation constant for growth of X_H	K_S	mg COD/L	24	24	24	24	24	24
Endogenous decay rate for X_H and	b_H	1/day	0.1	0.1	0.1	0.1	0.1	0.1
Heterotrophic half saturation coefficient for oxygen	K_{OH}	mg O_2/L	0.01	0.01	0.01	0.01	0.01	0.01
Maximum hydrolysis rate for S_{HI}	k_h	1/day	5.2	2.4	5.2	2.4	1.5	2.4
Hydrolysis half saturation constant for S_{HI}	K_X	g COD/g COD	0.15	0.15	0.15	0.15	0.15	0.15
Maximum hydrolysis rate for X_{SI}	k_{hx}	1/day	0.56	0.56	0.56	0.56	0.56	0.56
Hydrolysis half saturation constant for X_{SI}	K_{XX}	g COD/g COD	0.05	0.05	0.05	0.05	0.05	0.05
Yield coefficient of X_H	Y_H	g COD/g COD	0.60	0.60	0.60	0.60	0.60	0.60
Fraction of biomass converted to S_P	f_{ES}	-	0.05	0.05	0.05	0.05	0.05	0.05
Fraction of biomass converted to X_P	f_{EX}	-	0.15	0.15	0.15	0.15	0.15	0.15
Total biomass		mg COD/L	2010	2000	2265	1950	2015	1965
Initial active biomass	X_{HI}	mg COD/L	1450	1500	1600	1100	950	1400
Activity		%	72	75	71	56	47	71
Initial amount of biodegradable COD	C_{SI}	mg COD/L	600	253**	123**	130**	243**	293**
Initial amount of readily biodegradable COD	S_{SI}	mg COD/L	57	22	11	0	22	22
Initial amount of readily hydrolysable COD	S_{HI}	mg COD/L	335	147	70	40***	137	137+15***
Initial amount of hydrolysable COD	X_{SI}	mg COD/L	208	84	42	90***	84	84+35***

* Stoichiometric and kinetic coefficients for Control-SRT 10 days were imposed on (Pala Ö. İ., 2012) PhD thesis.
** Calculated from OUR profiles [$\Delta O_2/(1-Y_H)$] and cross-checked with theoretical COD addition for each run.
*** Soluble biodegradable COD of interchange sludge (30% S_H and 70%X_S)

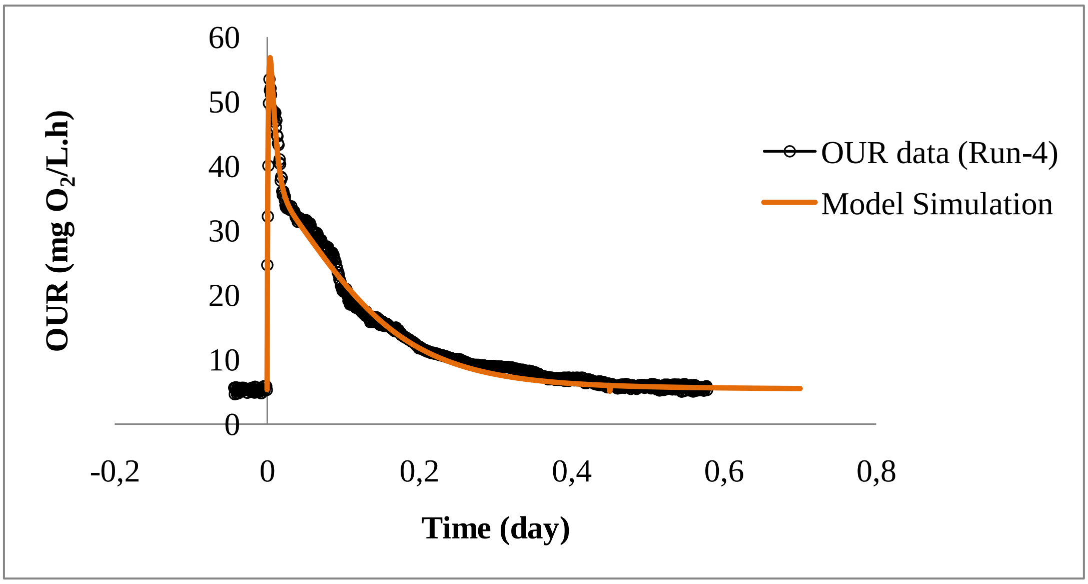

Figure 4.11 : Illustration of respirometric and model results for Run – 4.

In Run – 4 experiment, mixture of the OSA sludge and peptone with certain F/M ratio was performed in respirometry. As seen in Figure 4.11, the respirometric results and model were fitted each other reasonably. Microorganism activity was observed as 75 % and 89 % of COD removal was achieved.

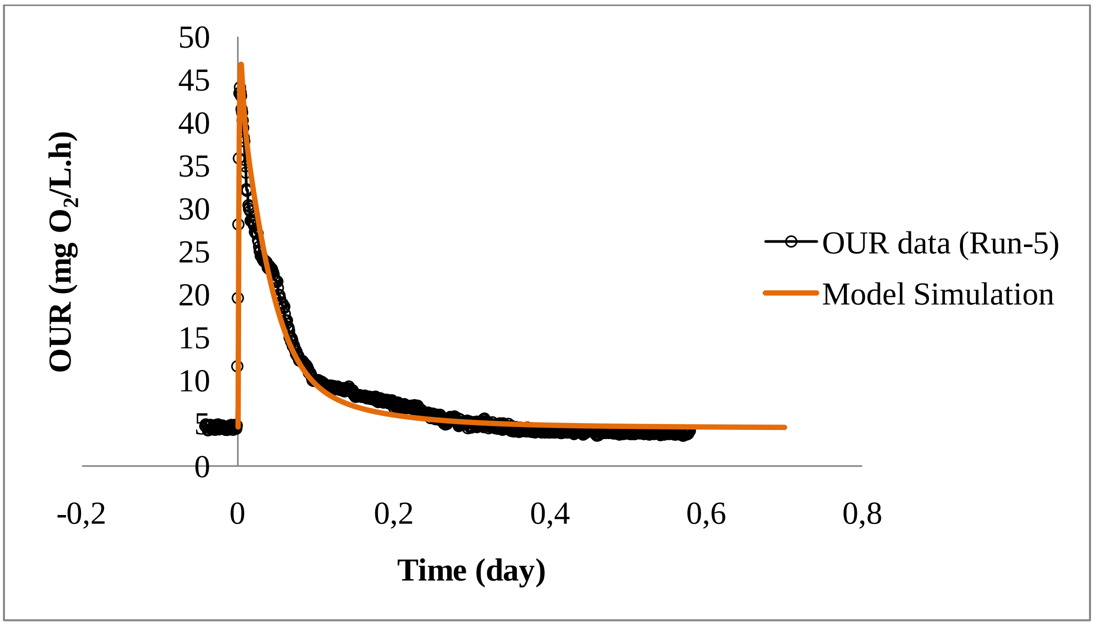

Figure 4.12 : Illustration of respirometric and model results for Run – 5.

In Run – 5 experiment, mixture of the control sludge and peptone with certain F/M ratio was performed in respirometry. As seen in Figure 4.12, the respirometric results and model were fitted each other reasonably. Microorganism activity was observed as 71 % and 78.7 % of COD removal was achieved.

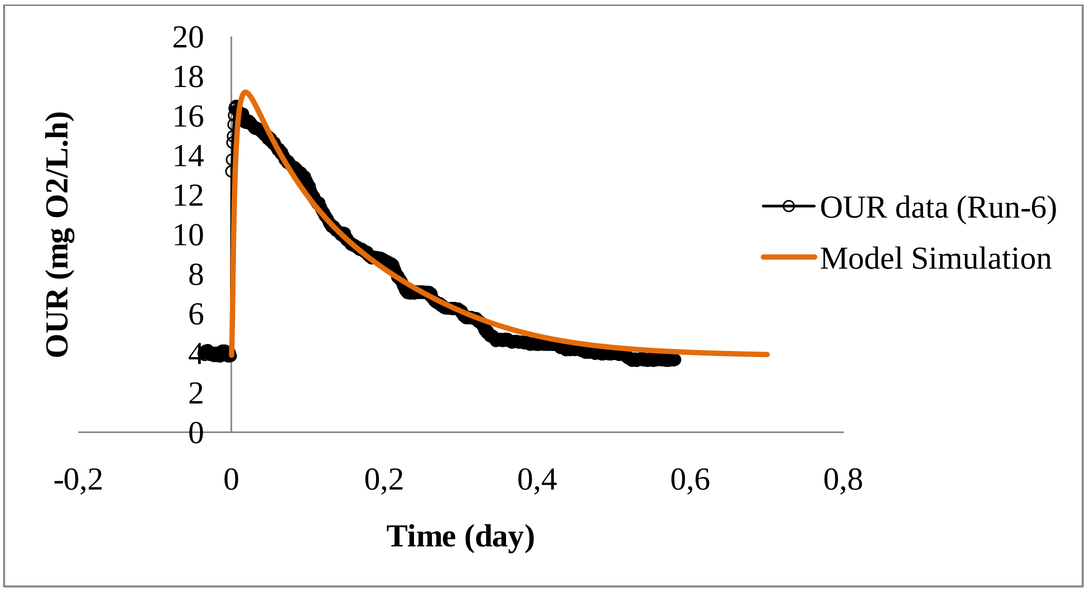

Figure 4.13 : Illustration of respirometric and model results for Run – 6.

In Run – 6 experiment, mixture of the OSA sludge and interchange sludge with certain F/M ratio was performed in respirometry. As seen in Figure 4.13, the respirometric results and model were fitted each other reasonably. Microorganism activity was observed as 56% and 61.5% of COD removal was achieved.

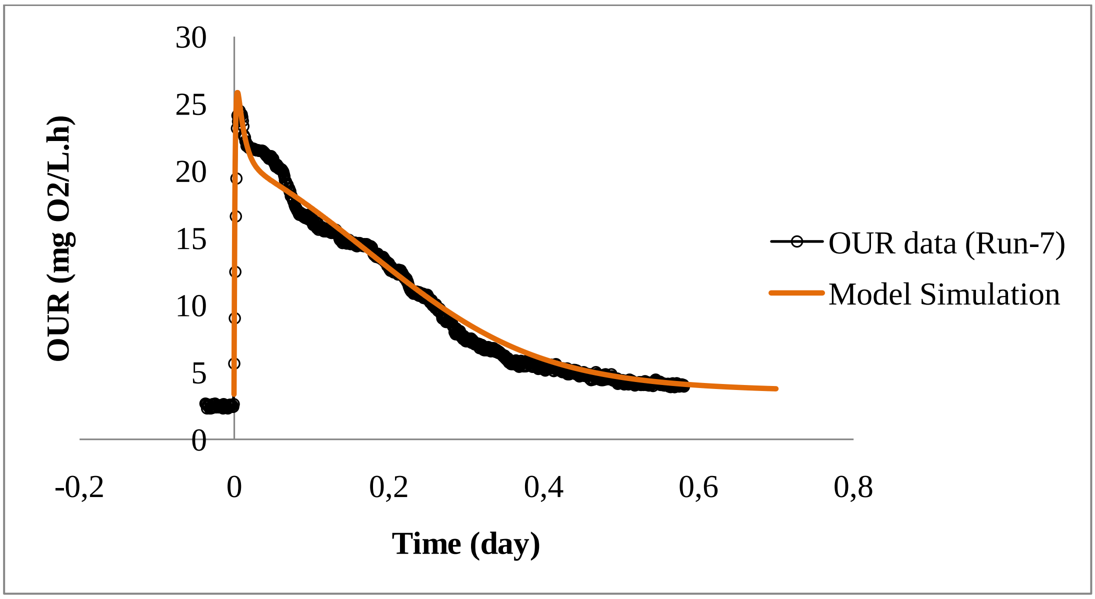

Figure 4.14 : Illustration of respirometric and model results for Run – 7.

In Run – 7 experiment, mixture of the interchange sludge and peptone with certain F/M ratio was performed in respirometry. As seen in Figure 4.14, the respirometric results and model were fitted each other reasonably. Microorganism activity was observed as 47% and 90.2% of COD removal was achieved.

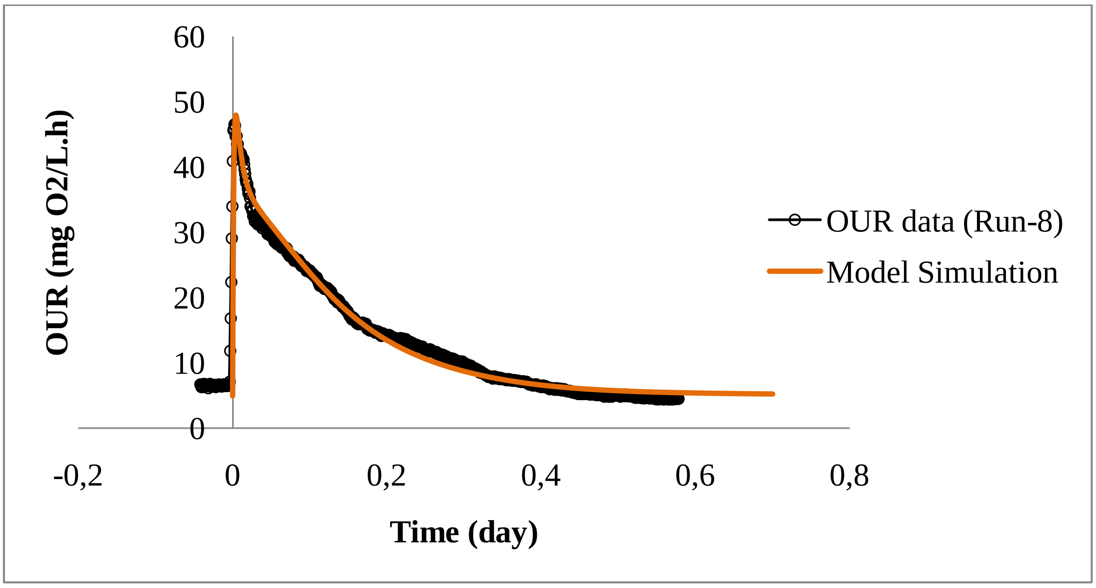

Figure 4.15 : Illustration of respirometric and model results for Run – 8.

In Run – 8 experiment, mixture of the OSA sludge, the interchange sludge and peptone with certain F/M ratio was performed in respirometry. As seen in Figure 4.15, the respirometric results and model were fitted each other reasonably. Microorganism activity was observed as 71% and 90.2% of COD removal was achieved.

5. CONCLUSIONS

The experimental studies were performed by oxygen uptake rate (OUR) experiments with stable sludge having same food/microorganism concentration. These experiments had been performed and compared for both control and OSA systems. Respirometric experiments were conducted in order to evaluate endogenous oxygen uptake rate level of biomass. Firstly, respirometric tests were performed for control and SBRs to observe the differences between them. Thereafter, respirometric tests were carried out to understand the role of anaerobic reactor in the system. It had been observed whether anaerobic reactor was biomass or substrate source for SBRs.

The AQUASIM software package was used for simulations and parameter estimation using OUR data for determination of kinetic and stoichiometric coefficients. The ASM1 models were used for respirometric data interpretation.

Based on experimental results, steady state conditions were observed in each system (control and OSA) and 60% of sludge reduction was observed in OSA system. This is concluded as reduction of sludge production in the wastewater treatment is possible by application of OSA process to solve sludge associated problems. The obtained result verifys the literature studies. In addition to, microorganism activity in the sludge was observed with the achieved respirometric analysis.

It is also observed that higher nitrogen and phosphorus concentration in the effluent of OSA system. During anaerobic exposure, soluble chemical oxygen demand (COD), nitrogen, and phosphorus are released which is also support literature findings on OSA process.

Using experimental data obtained from respirometric experiments, parameter estimation study revealed that consistent values of kinetic and stoichiometric coefficients with literature for control system were obtained: lower maximum growth rate, slower hydrolysis rate and lower microbial activity for OSA sludge. This could show us that insertion of an anaerobic sludge tank in an OSA system may affect the biomass activity and bacteria population and slow growers may become the dominant species in an OSA system.

Respirometric experiment with OSA sludge and peptone as C source with F/M ratio of the operating system revealed that the activity of OSA sludge was found as 75 % which indicates that the activity in OSA sludge is almost same with the activity in sludge operated with SRT 10 d given in the literature. COD removal was achieved around 89% in this experiment.

Respirometric experiment with control sludge where peptone was used as C source, the activity of control sludge was found as 71% which shows that the activity in control sludge is almost same with the activity in sludge operated with SRT 10 d given in the literature. COD removal was achieved around 78.7%. Kinetic and stoichiometric parameter values were remained almost the same as the literature study.

Respirometric experiment with OSA sludge and anaerobic sludge from bioreactor with F/M ratio of actual system showed that the activity of OSA sludge was reduced when the anaerobic sludge was used as C source. Nevertheles, it can be said that the interchange sludge was consumed as a substrate by microorganisms. COD removal was achieved around 61.5% in this experiment.

From the parameter estimation study of respirometric experiment with anaerobic sludge with pepton as C source exhibited that interchange reactor contains active biomass but with a lower activity (47%). This is concluded that, because of this, biomass activity in OSA reactor appears higher (75%) compared to control system (71%). COD removal was achieved around 90.2 %.

Finally, respirometric experiment had been carried out with OSA sludge. For this experiment, peptone and anaerobic sludge had been added at the same time to the OSA sludge. The respirometric results and model were fitted each other reasonably. According to these results, the activity of OSA sludge was found as 71% which indicates that the activity in OSA sludge is almost same with the activity in sludge operated with SRT 10 d given in the literature. COD removal was achieved around 90.2 % in this experiment. Lastly, it can be said that the activity of sludge and the COD removal efficiency are same with respirometric experiment with OSA sludge and interchange sludge was consumed as substrate.

From the findings of this study, it is assumed that interchange sludge consist of X_H, X_P, S_P, S_H and X_S. The OUR profiles and parameter estimation study showed that X_H could be converted into X_S under stress conditions where external C is not available and than consumed by OSA sludge (*Run-6: OSA sludge + Interchange sludge only; no external C source*).

For better understanding of sludge reduction mechanism and microbial dynamics in OSA systems, it is recommended that dynamic modelling of OSA processes, supporting data with molecular analysis and monitoring gas production and gas composition in digester reactor should be investigated in further studies.

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APPENDICES

APPENDIX A: Daily measurement results for Influent, Control-SBR and OSA-SBR

APPENDIX A

Table A.1 : Daily COD and anion measurements in the influent.

Day	Chloride (mg/L)	Sulfate (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	COD (mg/L)
72	31.3	42.2	0.1	0.1	7.8	452
73	30.9	42.2	0.2	0.0	8.5	385
74	31.7	41.9	0.0	0.2	9.3	434
75	32.3	43.7	0.0	0.2	8.8	467
76	32.2	42.4	0.0	0.2	9.6	461
79	32.7	43.3	0.0	0.2	8.5	476
80	33.7	44.7	0.1	0.0	7.1	476
81	33.4	42.6	0.0	0.2	9.3	464
82	34.0	41.7	0.1	0.2	9.5	449
83	34.2	42.9	0.0	0.3	8.7	455
86	37.0	42.7	0.1	0.2	9.5	461
87	37.2	41.9	0.1	0.2	9.5	469
88	37.5	42.0	0.0	0.2	9.4	469
89	37.7	41.4	0.1	0.3	9.3	449
90	37.2	40.9	0.0	0.2	9.4	447
93	40.3	41.4	0.1	0.2	9.5	464
94	40.7	41.3	0.0	0.3	9.7	-
95	42.0	40.6	0.1	1.6	9.3	-

Table A.2 : Daily COD and anion measurements in the effluent of control system.

Day	Chloride (mg/L)	Sulfate (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	COD (mg/L)
72	61.5	84.6	13.7	1.5	14.4	66.7
73	59.3	78.8	13.7	0.5	14.6	57.6
74	60.1	78.8	15.1	0.7	14.2	48.5
75	59.9	75.7	10.7	0.5	15.0	51.5
76	61.7	81.4	12.6	0.4	15.4	54.6
79	64.4	91.4	30.3	2.5	17.4	78.3
80	64.9	86.3	27.5	0.9	17.6	78.3
81	66.3	87.2	32.8	1.4	18.2	72.3
82	66.9	85.4	35.1	1.3	17.6	69.3
83	67.6	84.9	33.9	1.7	17.0	63.7
86	71.8	96.1	40.7	3.4	19.4	63.7
87	72.3	87.5	39.5	2.1	17.7	-
89	77.1	84.8	39.9	0.9	21.8	46.4
90	74.7	90.4	42.2	1.7	15.5	49.3
93	76.5	92.0	40.4	3.5	19.7	45.8
94	78.1	82.8	34.7	1.8	17.4	31.5
95	81.3	83.0	34.4	1.4	17.2	-

Table A.3 : Daily COD and anion measurements in the effluent of OSA system.

Day	Chloride (mg/L)	Sulfate (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	COD (mg/L)
72	61.3	86.0	37.5	3.9	18.4	49
73	59.1	84.1	38.2	2.9	19.1	33
74	59.5	84.8	35.4	2.8	18.9	27
75	59.4	83.1	36.6	3.1	18.8	27
76	64.1	93.8	41.4	4.7	19.9	33
79	66.3	96.8	44.2	6.2	20.8	63
80	65.9	95.1	42.1	5.1	19.8	60
81	67.2	96.8	41.5	5.8	19.2	57
82	67.1	94.2	40.5	6.1	18.7	60
83	68.9	92.4	39.9	7.4	18.5	54
86	71.7	101.4	24.8	17.7	19.5	54
88	79.8	287.5	23.6	23.7	19.3	72
89	73.4	126.9	31.4	17.2	18.7	67
90	73.9	106.2	30.1	19.8	18.8	-
93	77.2	96.3	19.6	30.8	19.7	35
94	78.6	92.0	18.5	30.7	18.8	66
95	80.4	90.6	18.8	30.1	18.2	-

Table A.4 : Daily solid concentrations in the Control-SBR and its effluent, and calculation of cummulative solids.

Days	Effluent of the Control-SBR			In the Control-SBR			TS	TVS	Daily mount of lost MLVSS from the effluent (mg)	Lost VSS from the SBR by sampling (mg)	Daily sludge wastage * (mg)	Total daily loss of MLVSS from the system (mg)	Cumulative solids (mg)
	Ave-MLSS	Ave-MLVSS	Ave-MLVSS /MLSS	Ave-MLSS	Ave-MLVSS	Ave-MLVSS/ MLSS							
12	21	16	0.77	3650	2350	0.64	-	-	97	47	294	438	438
13	18	14	0.74	-	-	-	-	-	82	-	294	376	815
14	19	14	0.74	-	-	-	-	-	85	-	294	379	1194
15	19	14	0.74	-	-	-	-	-	85	-	294	379	1573
16	19	14	0.74	-	-	-	-	-	85	-	294	379	1952
17	27	19	0.70	-	-	-	-	-	114	-	294	408	2360
18	24	18	0.73	3100	2150	0.69	3415	1931	105	4	269	417	2777
19	19	16	0.79	-	-	-	-	-	93	-	269	362	3139
20	15	13	0.86	3600	2500	0.69	3783	2429	77	50	313	439	3578
21	9	7	0.74	-	-	-	-	-	42	-	313	355	3932
22	9	7	0.74	-	-	-	-	-	42	-	313	355	4287
23	9	7	0.74	2600	1900	0.73	2808	1725	42	38	238	318	4604
24	12	11	0.86	-	-	-	-	-	63	-	238	301	4905
25	12	10	0.80	2200	1700	0.77	2807	1851	60	34	212	306	5211
26	13	11	0.86	-	-	-	-	-	66	-	212	278	5490
27	8	7	0.82	2200	1650	0.75	2133	1614	42	33	206	281	5771
28	19	17	0.89	-	-	-	-	-	102	-	206	308	6079
29	19	17	0.89	-	-	-	-	-	102	-	206	308	6387
30	19	17	0.89	1800	1350	0.75	1999	1279	102	27	169	298	6685
31	23	20	0.87	-	-	-	-	-	120	-	169	289	6974

Table A.4 (continued) : Daily solid concentrations in the Control-SBR and its effluent, and calculation of cummulative solids.

Days	Effluent of the Control-SBR			In the Control-SBR			TS	TVS	Daily mount of lost MLVSS from the effluent (mg)	Lost VSS from the SBR by sampling (mg)	Daily sludge wastage * (mg)	Total daily loss of MLVSS from the system (mg)	Cumulative solids (mg)
	Ave-MLSS	Ave-MLVSS	Ave-MLVSS /MLSS	Ave-MLSS	Ave-MLVSS	Ave-MLVSS/ MLSS							
32	16	13	0.84	1550	1150	0.74	1842	1141	81	23	144	248	7222
33	21	18	0.86	-	-	-	-	-	107	-	144	250	7472
34	23	20	0.87	1850	1500	0.81	60	1327	120	30	188	338	7809
35	22	19	0.86	-	-	-	-	-	111	-	188	299	8108
36	22	19	0.86	-	-	-	-	-	111	-	188	299	8406
37	22	19	0.86	1600	1250	0.78	1660	1040	111	25	156	292	8699
38	25	21	0.85	-	-	-	-	-	126	-	156	282	8981
39	23	20	0.87	1800	1500	0.83	1025	1387	119	30	188	336	9317
40	23	20	0.85	-	-	-	-	-	117	-	188	305	9621
41	25	21	0.87	1750	1450	0.83	2032	1474	129	29	181	339	9961
42	29	26	0.87	-	-	-	-	-	155	-	181	336	10296
43	29	26	0.87	-	-	-	-	-	155	-	181	336	10632
44	29	26	0.87	2100	1650	0.79	2101	1606	155	33	206	394	11026
45	34	29	0.86	-	-	-	-	-	174	-	206	380	11406
46	23	20	0.87	2400	2050	0.85	2264	1703	117	41	256	414	11820
47	17	14	0.85	-	-	-	-	-	84	-	256	340	12161
48	17	14	0.85	2300	1863	0.81	2170	1513	84	37.26	233	354	12515
49	16	12	0.77	-	-	-	-	-	72	-	233	305	12820
50	16	12	0.77	-	-	-	-	-	72	-	233	305	13124
51	16	12	0.77	2650	2200	0.83	2859	2174	72	43.99	275	391	13515

Table A.4 (continued) : Daily solid concentrations in the Control-SBR and its effluent, and calculation of cummulative solids.

Days	Effluent of the Control-SBR			In the Control-SBR			TS	TVS	Daily mount of lost MLVSS from the effluent (mg)	Lost VSS from the SBR by sampling (mg)	Daily sludge wastage * (mg)	Total daily loss of MLVSS from the system (mg)	Cumulative solids (mg)
	Ave-MLSS	Ave-MLVSS	Ave-MLVSS /MLSS	Ave-MLSS	Ave-MLVSS	Ave-MLVSS/ MLSS							
52	16	13	0.81	-	-	-	-	-	78	-	275	353	13868
53	20	17	0.85	2600	2184	0.84	2820	2156	102	43.68	273	419	14287
54	20	17	0.85	-	-	-	-	-	102	-	273	375	14662
55	22	17	0.77	2350	1927	0.82	2690	2047	102	38.54	241	381	15043
56	14	12	0.89	-	-	-	-	-	73	-	241	314	15358
57	14	12	0.89	-	-	-	-	-	73	-	241	314	15672
58	14	12	0.89	2450	1960	0.80	2598	1983	73	39.2	245	358	16030
59	17	14	0.82	-	-	-	-	-	84	-	245	329	16359
60	21	18	0.88	2450	1911	0.78	2600	2064	110	38.22	239	387	16745
61	19	16	0.85						96	-	239	335	17080
62	18	15	0.82	2400	1848	0.77	2402	1727	90	36.96	231	358	17438
63	13	10	0.78	-	-	-	-	-	60	-	231	291	17729
64	13	10	0.78	-	-	-	-	-	60	-	231	291	18020
65	13	10	0.78	2250	1822	0.81	2305	1530	60	36.45	228	324	18344
66	17	14	0.81	-	-	-	-	-	84	-	228	312	18656
67	20	16	0.82	-	-	-	-	-	96	-	228	324	18980
68	20	16	0.82	-	-	-	-	-	96	-	228	324	19304
69	18	16	0.88	2300	1886	0.82	2324	1743	96	37.72	236	369	19673
70	14	13	0.93	-	-	-	-	-	81	-	236	317	19990
71	14	13	0.93	-	-	-	-	-	81	-	236	317	20307

Table A.4 (continued) : Daily solid concentrations in the Control-SBR and its effluent, and calculation of cummulative solids.

Days	Effluent of the Control-SBR			In the Control-SBR			TS	TVS	Daily mount of lost MLVSS from the effluent (mg)	Lost VSS from the SBR by sampling (mg)	Daily sludge wastage * (mg)	Total daily loss of MLVSS from the system (mg)	Cumulative solids (mg)
	Ave-MLSS	Ave-MLVSS	Ave-MLVSS /MLSS	Ave-MLSS	Ave-MLVSS	Ave-MLVSS/ MLSS							
72	14	13	0.93	2150	1698	0.79	2048	1551	81	33.97	212	327	20634
73	18	17	0.93	-	-	-	-	-	99	-	212	311	20945
74	22	21	0.93	2050	1702	0.83	2094	1581	123	34.03	213	370	21315
75	18	17	0.92	1900	1520	0.80	2198	1683	101	30.4	190	321	21636
76	12	10	0.87	2100	1596	0.76	2319	1665	60	31.92	200	291	21928
77	6	6	0.85	-	-	-	-	-	33	-	200	233	22160
78	6	6	0.85	-	-	-	-	-	33	-	200	233	22393
79	6	6	0.85	2000	1620	0.81	2108	1552	33	32.4	203	268	22660
80	12	10	0.83	-	-	-	-	-	60	-	203	263	22923
81	14	11	0.81	2120	1696	0.80	2193	1660	66	33.92	212	312	23235
82	19	17	0.92	-	-	-	-		105	-	212	317	23552
83	7	6	0.86	2050	1681	0.82	1978	1503	36	33.62	210	280	23832
84	9	7	0.82	-	-	-	-	-	42	-	210	252	24084
85	9	7	0.82	-	-	-	-	-	42	-	210	252	24336
86	9	7	0.82	2100	1743	0.83	1935	1342	42	34.86	218	295	24631
87	9	8	0.94	-	-	-	-	-	48	-	218	266	24896
88	15	13	0.90	-	-	-	-	-	78	-	218	296	25192
89	14	12	0.86	-	-	-	-	-	72	-	218	290	25482
90	14	11	0.79	2050	1640	0.80	1982	1367	66	32.8	205	304	25786
91	11	9	0.82	-	-	-	-	-	54	-	205	259	26045

Table A.4 (continued) : Daily solid concentrations in the Control-SBR and its effluent, and calculation of cummulative solids.

Days	Effluent of the Control-SBR			In the Control-SBR			TS	TVS	Daily mount of lost MLVSS from the effluent (mg)	Lost VSS from the SBR by sampling (mg)	Daily sludge wastage * (mg)	Total daily loss of MLVSS from the system (mg)	Cumulative solids (mg)
	Ave-MLSS	Ave-MLVSS	Ave-MLVSS /MLSS	Ave-MLSS	Ave-MLVSS	Ave-MLVSS/ MLSS							
92	11	9	0.82	-	-	-	-	-	54	-	205	259	26304
93	11	9	0.82	2000	1680	0.84	1647	1111	54	33.6	210	298	26602
94	10	8	0.84	-	-	-	-	-	48	-	210	258	26860
95	9	7	0.82	2020	1656	0.82	1719	1166	42	33.13	207	282	27142
100	-	-	-	2120	1696	0.80	1762	1247	-	33.92	212	246	27388

* Sludge wastage was performed every day. It is assumed that missing values were estimated as same as previous day.

Table A.5 : Daily solid concentrations in the OSA-SBR and its effluent, and calculation of cummulative solids.

Days	Effluent of the OSA-SBR			In the OSA-SBR			TS	TVS	Daily mount of lost MLVSS from the effluent (mg)	Lost VSS from the SBR by sampling (mg)	Total daily loss of MLVSS from the system (mg)	Cumulative solids (mg)
	Ave-MLSS	Ave-MLVSS	Ave-MLVSS/ MLSS	Ave-MLSS	Ave-MLVSS	Ave-MLVSS/ MLSS						
12	17	12	0.71	5000	3050	0.61	-	-	72	61	133	133
13	76	58	0.76	-	-	-	-	-	348	-	348	481
14	102	69	0.68	-	-	-	-	-	417	-	417	898
15	102	69	0.68	-	-	-	-	-	417	-	417	1315

Table A.5 (continued) : Daily solid concentrations in the OSA-SBR and its effluent, and calculation of cummulative solids.

Days	Effluent of the OSA-SBR			In the OSA-SBR			TS	TVS	Daily mount of lost MLVSS from the effluent (mg)	Lost VSS from the SBR by sampling (mg)	Total daily loss of MLVSS from the system (mg)	Cumulative solids (mg)
	Ave-MLSS	Ave-MLVSS	Ave-MLVSS/ MLSS	Ave-MLSS	Ave-MLVSS	Ave-MLVSS/ MLSS						
16	102	69	0.68	-	-	-	-	-	417	-	417	1732
17	19	14	0.75	-	-	-	-	-	84	-	84	1816
18	21	15	0.71	5100	3300	0.65	5336	3198	90	66	156	1972
19	132	88	0.67	-	-	-	-	-	528	-	528	2500
20	14	11	0.79	5350	3400	0.64	5382	3425	66	68	134	2634
21	15	13	0.85	-	-	-	-	-	75	-	75	2709
22	15	13	0.85	-	-	-	-	-	75	-	75	2784
23	15	13	0.85	4300	2800	0.65	4679	2998	75	56	131	2915
24	18	15	0.83	-	-	-	-	-	90	-	90	3005
25	21	16	0.74	3800	2800	0.74	4314	2743	93	56	149	3154
26	19	15	0.76	-	-	-	-	-	87	-	87	3241
27	21	15	0.73	4050	2850	0.70	4169	2613	90	57	147	3388
28	19	16	0.84	-	-	-	-	-	98	-	98	3486
29	19	16	0.84	-	-	-	-	-	98	-	98	3583
30	19	16	0.84	4350	2850	0.66	4336	2705	98	57	155	3738
31	25	21	0.81	-	-	-	-	-	123	-	123	3861
32	22	16	0.74	3800	2600	0.68	3938	2632	96	52	148	4009

Table A.5 (continued) : Daily solid concentrations in the OSA-SBR and its effluent, and calculation of cummulative solids.

Days	Effluent of the OSA-SBR			In the OSA-SBR			TS	TVS	Daily mount of lost MLVSS from the effluent (mg)	Lost VSS from the SBR by sampling (mg)	Total daily loss of MLVSS from the system (mg)	Cummulative solids (mg)
	Ave-MLSS	Ave-MLVSS	Ave-MLVSS/MLSS	Ave-MLSS	Ave-MLVSS	Ave-MLVSS/MLSS						
33	19	14	0.75	-	-	-	-	-	84	-	84	4093
34	23	18	0.77	3800	2900	0.76	3688	2492	107	58	165	4257
35	16	12	0.74	-	-	-	-	-	72	-	72	4329
36	16	14	0.86	-	-	-	-	-	84	-	84	4413
37	16	13	0.80	4100	3100	0.76	4088	2799	78	62	140	4553
38	22	16	0.73	-	-	-	-	-	96	-	96	4649
39	19	14	0.75	4050	2950	0.73	487	2787	86	59	145	4794
40	16	12	0.75	-	-	-	-	-	72	-	72	4866
41	18	15	0.83	4150	3150	0.76	4533	3127	87	63	150	5016
42	33	26	0.78	-	-	-	-	-	153	-	153	5169
43	33	26	0.78	-	-	-	-	-	153	-	153	5322
44	33	26	0.78	3900	2850	0.73	4163	2795	153	57	210	5532
45	39	30	0.79	-	-	-	-	-	182	-	182	5713
46	31	25	0.81	3550	2750	0.77	3315	2270	150	55	205	5918
47	33	26	0.79	-	-	-	-	-	155	-	155	6073
48	33	26	0.79	3950	3050	0.77	3894	2670	155	61	216	6288
49	24	21	0.88	-	-	-	-	-	128	-	128	6416

Table A.5 (continued) : Daily solid concentrations in the OSA-SBR and its effluent, and calculation of cummulative solids.

Days	Effluent of the OSA-SBR			In the OSA-SBR			TS	TVS	Daily mount of lost MLVSS from the effluent (mg)	Lost VSS from the SBR by sampling (mg)	Total daily loss of MLVSS from the system (mg)	Cummulative solids (mg)
	Ave-MLSS	Ave-MLVSS	Ave-MLVSS/MLSS	Ave-MLSS	Ave-MLVSS	Ave-MLVSS/MLSS						
50	24	21	0.88	-	-	-	-	-	128	-	128	6543
51	24	21	0.88	4300	3450	0.80	4627	3385	128	69	197	6740
52	20	16	0.82	-	-	-	-	-	96	-	96	6836
53	22	18	0.82	4150	3250	0.78	4268	3063	108	65	173	7009
54	22	18	0.82	-	-	-	-	-	108	-	108	7117
55	27	23	0.84	4450	3400	0.76	4440	3160	137	68	205	7321
56	16	14	0.83	-	-	-	-	-	81	-	81	7402
57	16	14	0.83	-	-	-	-	-	81	-	81	7483
58	16	14	0.83	4250	3350	0.79	4953	3745	81	67	148	7631
59	17	14	0.81	-	-	-	-	-	81	-	81	7712
60	18	15	0.83	4400	3450	0.78	4874	3565	88	69	158	7870
61	15	12	0.79	-	-	-	-	-	69	-	69	7939
62	13	10	0.79	4700	3750	0.80	4642	3407	62	75	137	8075
63	12	10	0.80	-	-	-	-	-	58	-	58	8134
64	12	10	0.80	-	-	-	-	-	58	-	58	8192
65	12	10	0.80	4550	3950	0.87	4698	3444	58	79	138	8330
66	20	16	0.81	-	-	-	-	-	96	-	96	8426

Table A.5 (continued) : Daily solid concentrations in the OSA-SBR and its effluent, and calculation of cummulative solids.

Days	Effluent of the OSA-SBR			In the OSA-SBR			TS	TVS	Daily mount of lost MLVSS from the effluent (mg)	Lost VSS from the SBR by sampling (mg)	Total daily loss of MLVSS from the system (mg)	Cummulative solids (mg)
	Ave-MLSS	Ave-MLVSS	Ave-MLVSS/ MLSS	Ave-MLSS	Ave-MLVSS	Ave-MLVSS/ MLSS						
67	15	12	0.82	-	-	-	-	-	75	-	75	8501
68	15	12	0.82	-	-	-	-	-	75	-	75	8576
69	18	15	0.83	4550	3600	0.79	4812	1571	90	72	162	8738
70	18	15	0.82	-	-	-	-	-	90	-	90	8828
71	18	15	0.82	-	-	-	-	-	90	-	90	8918
72	18	15	0.82	4300	3750	0.87	4621	3431	90	75	165	9083
73	18	15	0.82	-	-	-	-	-	90	-	90	9173
74	21	20	0.93	4750	3750	0.79	4482	3366	119	75	194	9366
75	19	16	0.84	4650	3800	0.82	4597	3547	98	76	174	9540
76	24	19	0.81	4600	3600	0.78	4749	3517	114	72	186	9726
77	24	20	0.83	-	-	-	-	-	120	-	120	9846
78	24	20	0.83	-	-	-	-	-	120	-	120	9966
79	24	20	0.83	4500	3600	0.80	4606	3395	120	72	192	10158
80	32	27	0.86	-	-	-	-	-	162	-	162	10320
81	30	24	0.80	4200	3550	0.85	4377	3263	144	71	215	10535
82	28	25	0.88	-	-	-	-	-	147	-	147	10682
83	20	17	0.85	4300	3600	0.84	4422	3356	102	72	174	10856

Table A.5 (continued) : Daily solid concentrations in the OSA-SBR and its effluent, and calculation of cummulative solids.

Days	Effluent of the OSA-SBR			In the OSA-SBR			TS	TVS	Daily mount of lost MLVSS from the effluent (mg)	Lost VSS from the SBR by sampling (mg)	Total daily loss of MLVSS from the system (mg)	Cummulative solids (mg)
	Ave-MLSS	Ave-MLVSS	Ave-MLVSS/ MLSS	Ave-MLSS	Ave-MLVSS	Ave-MLVSS/ MLSS						
84	20	17	0.85	-	-	-	-	-	102	-	102	10958
85	20	17	0.85	-	-	-	-	-	102	-	102	11060
86	20	16	0.80	4400	3700	0.84	4570	3442	96	74	170	11230
87	15	12	0.83	-	-	-	-	-	72	-	72	11302
88	27	22	0.83	4050	3200	0.79	4611	3146	132	64	196	11498
89	21	18	0.81	-	-	-	-	-	105	-	105	11603
90	11	9	0.82	4350	3750	0.86	4354	3349	54	75	129	11732
91	16	14	0.88	-	-	-	-	-	84	-	84	11816
92	16	13	0.81	-	-	-	-	-	78	-	78	11894
93	16	12	0.75	4150	3700	0.89	4400	3330	72	74	146	12040
94	17	14	0.82	-	-	-	-	-	84	-	84	12124
95	17	14	0.82	4200	3550	0.85	4120	3209	84	71	155	12279
100	17	14	0.82	4350	3650	0.84	4354	3384	84	73	157	12436

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